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## SHELLFISH AQUACULTURE MAP VIEWERS: AN ASSESSMENT OF DESIGN, DATA, AND FUNCTIONS TO INFORM PLANNING AND SITING IN THE UNITED STATES

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**ABSTRACT** Shellfish aquaculture in the United States contributes to the global seafood supply, provides habitat and restoration opportunities, and enhances the economic sustainability of coastal communities. Most marine aquaculture production (two-thirds by value) in the United States comprises bivalve shellfish (oysters, clams, and mussels). As the marine aquaculture footprint grows, so too does the potential for negative environmental and space–use interactions. To streamline shellfish aquaculture permitting, many states have developed web-based aquaculture map viewers to communicate critical regulatory, space–use, and natural resource information. In this study, 18 state-level shellfish aquaculture map viewers were reviewed for common design approaches, important data considerations, and useful tools and functions. Key characteristics of a successful shellfish aquaculture map viewer include a user-friendly interface, instructional guidance, the ability to assess both opportunity and risk, inclusion of authoritative data, and a long-term maintenance plan for the viewer and data. The most common design approaches reviewed were Esri Web AppBuilder and Google. Viewers ranged from having 3–27 layers, with “view orthoimagery” (94%) as the most commonly occurring function. This review provides valuable information on using map viewers and technological innovation to communicate shellfish aquaculture planning and permitting information to a variety of stakeholders.

**KEY WORDS:** marine spatial planning, shellfish aquaculture, shellfish map viewer, review, siting

### INTRODUCTION

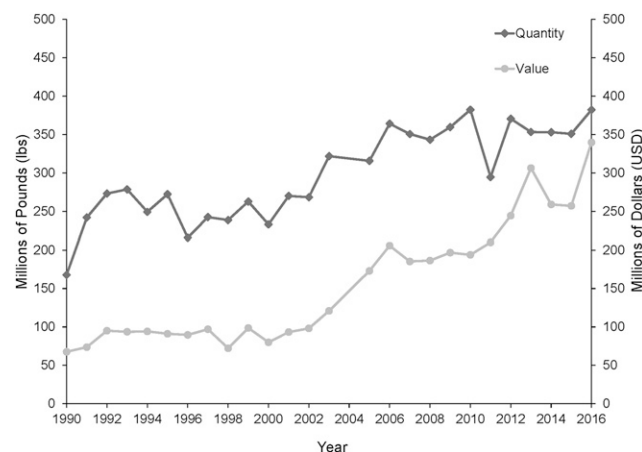
With an annual growth rate of approximately 13%, marine aquaculture is the fastest growing fisheries sector in the United States, and globally aquaculture has surpassed capture fisheries in the total seafood production (NMFS 2017, FAO 2018). Industry growth in U.S. waters is viewed as a mechanism to meet the demand for fresh, local seafood (Knapp & Rubino 2016, Lester et al. 2018), while also decreasing the seafood trade deficit (\$US16.1 billion in 2017–NMFS 2017, 2018). The opportunity for continued sustainable aquaculture expansion in U.S. waters requires coastal managers to evaluate where the aquaculture industry fits within the context of existing coastal, estuarine, and ocean uses (e.g., transportation, recreation, fishing, mining, military, and energy) and ecosystems (e.g., protected species, sensitive habitats, and water quality) (Calado et al. 2010, Aguilar-Manjarrez, Kapetsky & Soto 2010, Anderson et al. 2015, Aguilar-Manjarrez et al. 2017, Gentry et al. 2017). Aquaculture production of oysters, clams, and mussels in the United States, herein referred to as bivalve shellfish, has been an area of significant industry growth over the past decade (Fig. 1; O’Connell 2018). This trend is expected to increase, with Massachusetts and Washington states now cleared to export shellfish to Europe (e.g., the Netherlands and Spain) (FDA 2018). Beyond contributing to the U.S. seafood supply and enhancing the economic viability of working waterfronts, a growing body of evidence suggests shellfish aquaculture can provide valuable ecosystem services, including water filtration (i.e., nutrient and particulate reduction) and

provision of important habitat critical to life stages of fishery species (Shumway 2011, Gentry et al. 2019).

Most marine aquaculture production (by value) in the United States comprises bivalve shellfish aquaculture within estuarine and coastal ocean areas (Fig. 1) (NMFS 2017). Many coastal states have shellfish aquaculture industries, government agencies tasked with sector management, and established regulations to protect both ecosystem and human health (NSSP 2015). Increasingly, zonal and other spatial planning approaches for aquaculture management are being evaluated domestically and internationally to improve sector performance and minimize risks to human and environmental health or social conflict (Aguilar-Manjarrez et al. 2017). One long-standing example of spatial management of shellfish aquaculture within the United States is designation of harvest areas and rainfall-driven closures to reduce human health risks (NSSP 2015). Recent technological innovations allow managers to better communicate human health risks and rainfall-driven closures in a timely manner, where other environmental or spatial use conflicts are likely to arise (Conte and Ahmadi 2017, USEPA 2018), or where ecosystem service benefits of aquaculture may be realized (Carlozo 2014).

Implementation of marine spatial planning and web-based communication tools can improve aquaculture management and industry development processes—enhancing sector performance, minimizing negative interactions, and maximizing potential for ecosystem and community benefits (Longdill et al. 2008, Pınarbaşı et al. 2017, Stelzenmüller et al. 2017). One of the most important spatiotemporal elements to shellfish aquaculture management is designation of shellfish harvest areas (SHA), with the goal of sanitary control of shellfish produced and sold for human consumption (NSSP 2017). Shellfish

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**Figure 1. Growth in U.S. shellfish aquaculture production between 1990 and 2016, measured in millions of pounds and millions of U.S. dollars per year. Source: Food and Agriculture Organization (FAO) of the United Nations: Fisheries and Aquaculture Department (2016). Query for data search: United States; Marine areas; Marine environment; Oysters, Mussels, Clams, Cockles, Ark shells; Years selected: 1990–2016. Note that the 2004 statistics were omitted from this figure because they represent “FAO estimates” or estimated data from the available source, or are calculated based on specific assumptions not applicable to the remainder of the data.**

harvest areas are managed by states using standards and requirements set by the National Shellfish Sanitation Program (NSSP 2017). These areas are regularly sampled for pathogens, toxigenic microalgae, chemicals, and other dangerous substances from the surrounding waters, which may bioaccumulate in filter-feeding bivalves. The SHA program aims to prevent the harvest of contaminated shellfish (NSSP 2017). Tracking the status of these areas requires monitoring for bacterial contamination to make timely decisions regarding an area based on the level, type, and frequency of contamination and to subsequently communicate status to the public and shellfish harvesters, processors, and dealers.

Geographic information systems (GIS) and other spatial planning tools allow aquaculture applicants, coastal managers, and other stakeholders access to spatial information to guide aquaculture business and regulatory decision-making (Stelzenmüller et al. 2017). Increasingly, web-based spatial decision support tools allow this information to be more widely and publicly available—taking the form of easily accessible map viewers. Prospective aquaculture applicants and coastal managers must navigate a myriad of decisions (*e.g.*, harvest area classification, distance to port, current speed, depth, and seawater temperature) to identify a viable location for siting and permitting of an operation (O’Connell 2018). Many planning decisions rely on spatially referenced data, analytical tools, and decision support systems to explore options (Stelzenmüller et al. 2017). Map viewers act as decision support systems to standardize spatial data for decision-making. Potential spatial interactions, including environmental (*e.g.*, distribution of protected species and sensitive habitats), space-use (*e.g.*, fishing, navigational channels, and oil and gas operations), and general compatibility, are incorporated within these planning tools (Longdill et al. 2008), providing instant access to spatial data. These data can be viewed to identify compatible locations

for siting of aquaculture operations, minimizing potential risks and meeting certain parameter thresholds for optimizing aquaculture production.

This study provides a synthesis of web-based GIS decision support tools (map viewers) to provide guidance for permitting and development of shellfish aquaculture in state waters across the United States. With the growing trend in online GIS tools, web-based interactive map viewers have become an increasingly important tool for state shellfish farmers and managers to identify opportunity and communicate critical regulatory, space-use, and natural resource information for shellfish aquaculture. Some discontinuity exists among map viewers, as each state not only has varying priorities but also may not have all relevant data for informed decision-making. In this study, 18 shellfish aquaculture map viewers were reviewed to identify architectures, inventory data layers and functionalities, and other considerations for developing these tools. This study offers important insights for coastal managers to consider as they explore new, and potentially improved, methods to best communicate shellfish planning and permitting information for use within their communities. Although the study analyzed shellfish aquaculture map viewers, there are broader implications into how to successfully plan, develop, and execute (in the long-term) an online map viewer for coastal and marine spatial planning.

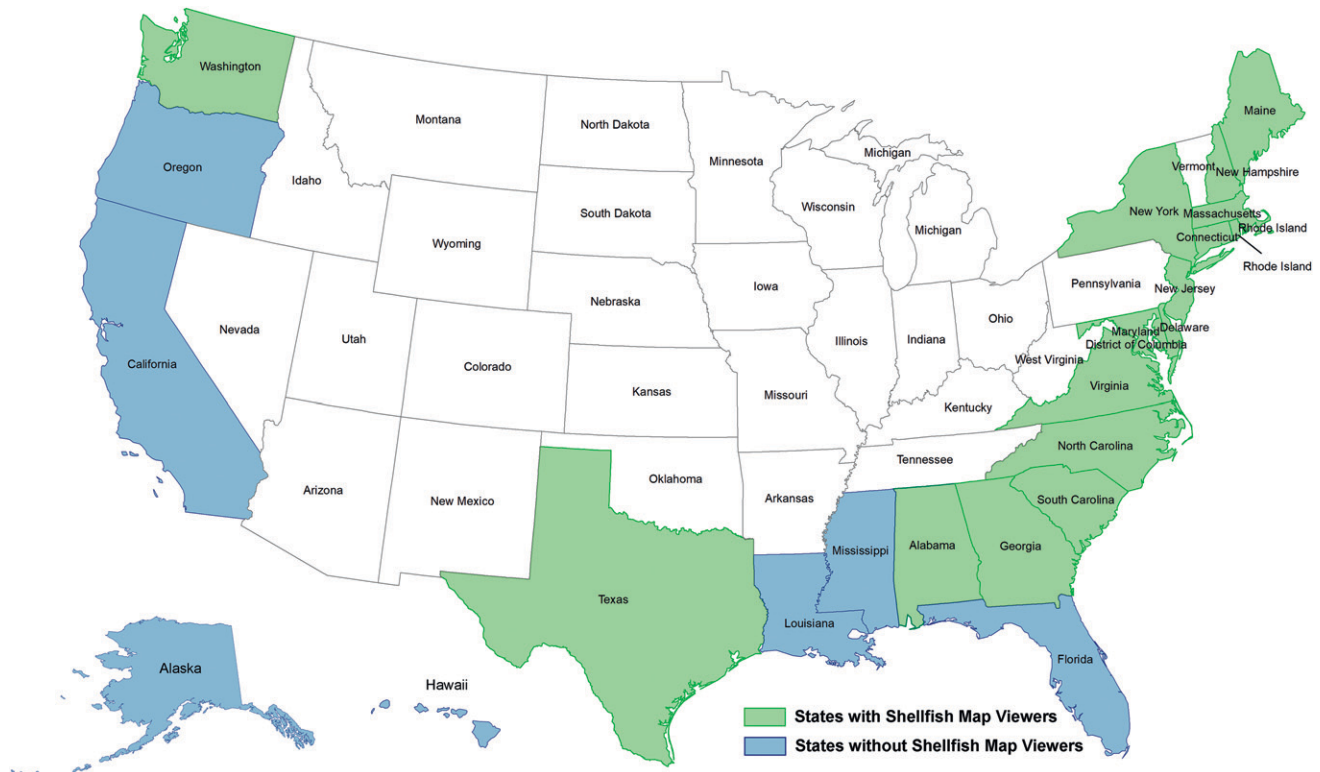
## METHODS

### *Search Methods for State Shellfish Map Viewers*

A detailed web search conducted from January through August 2018 of all U.S. states with marine coastal boundaries to inventory state-level shellfish aquaculture map viewer was in-place and accessible. Search terms included “state name,” “shellfish aquaculture,” “shellfish tool,” “aquaculture shellfish permitting,” “aquaculture shellfish map,” “map viewer,” “map atlas,” “shellfish approved areas,” and “shellfish siting opportunity.” A total of 18 shellfish aquaculture map viewers were identified, as some states had more than one relevant map viewer (*i.e.*, Virginia, Massachusetts). Each map viewer reviewed was specifically targeting shellfish aquaculture in the state. Data were collected on design and architectural approaches, number of layers, types of layers, integrated functions, and overall ease of use (*e.g.*, user tutorials). All data were cataloged in Microsoft Excel, product version 16.0, to perform descriptive statistics for relative comparison of all reviewed shellfish map viewers. Descriptive statistics were needed to determine the relative presence and number of layers, and to determine common and unique functions among shellfish map viewers. Assessment of these shellfish viewers aids states in determining if each viewer has all aquaculture-relevant layers and if additional layers and functions could improve map viewer capabilities for users.

## RESULTS

Sixteen coastal states were identified as having shellfish aquaculture map viewers, whereas seven coastal states did not have shellfish aquaculture map viewers during the period of analysis (*i.e.*, Florida, Mississippi, Louisiana, California, Oregon, Alaska, and Hawaii (Fig. 2). Of those 16 states with viewers, two had multiple viewers that were included in this review. For example, in Massachusetts, the state has shellfish



**Figure 2.** Coastal U.S. states with and without shellfish aquaculture map viewers as of 8/31/2018. Eighteen shellfish aquaculture map viewers were reviewed within this assessment across 16 states. Seven coastal states did not appear to have a shellfish aquaculture map viewer available online. White-colored states do not have a coastal border and thus were not included in this study, light green states have a shellfish map viewer, and light blue states do not presently have a shellfish aquaculture map viewer.

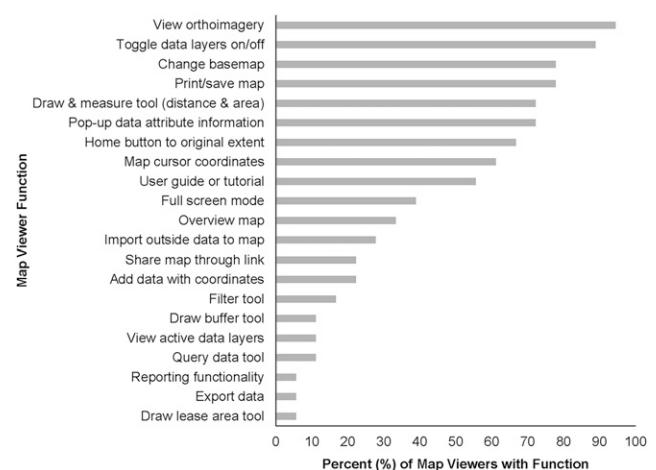
layers embedded into a larger state map viewer and also has a new stand-alone shellfish map viewer. In Virginia, one map viewer focused on the Virginia side of the Chesapeake Bay, whereas the other focused on the Chesapeake Bay as a whole.

As discussed in greater detail in the following text, the most common architectural approaches reviewed were from Esri and Google platforms. There were also more sophisticated custom-scripted architectures used for some state's viewer(s). On average, each viewer contained about 16 data layers, with Connecticut having the most layers (27 layers), followed closely by New Jersey (26 layers), Alabama (22 layers), the stand-alone Massachusetts viewer (22 layers), Washington (21 layers), North Carolina (21 layers), and Maryland (20 layers). The viewer with the least number of data layers (3 layers) was Delaware. "View orthoimagery," "toggle data layers," "change basemap," and "print and save" were the most common functions, occurring in 94%, 89%, 78%, and 78% of viewers, respectively. More refined functions, such as "draw lease area tool" and "query data tool," were only present in one or two viewers.

#### Map Viewer Functions

During the review process, data were gathered on the basic functions found in each map viewer (*e.g.*, view orthoimagery and toggle layers) and those unique to certain tools (*e.g.*, export data and query). The frequency of these functions within the reviewed shellfish aquaculture map viewers (*i.e.*, percentage of map viewers possessing a giving function) is presented to convey

common versus more rare functions available within these viewers' occurrence of function among viewers (Fig. 3). The more basic functions, such as a "basemap selection," "pan," or a "draw and measure" tool, are found in most of the viewers



**Figure 3.** Percent occurrence of functions in the shellfish aquaculture map viewers reviewed. Pertinent functions were captured here, but basic functions such as "zoom" were not included as these are generally included as default functionality within the software infrastructure used to create these tools. *View active data layers* refers to a separate list showing only the layers currently turned on in the map viewer. An *overview map* is a map inset that shows where the user is currently exploring as viewed within a pop-up window.



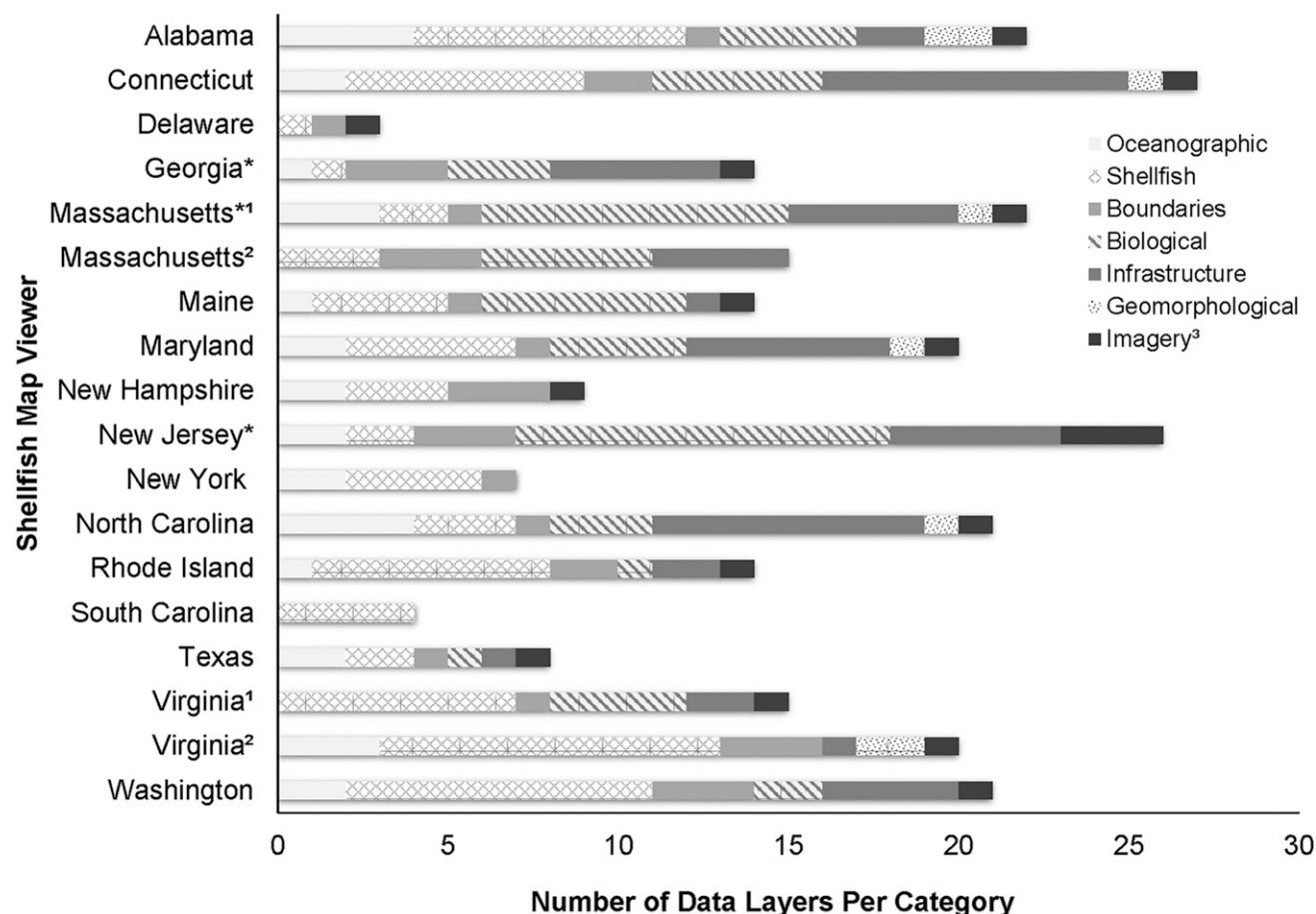


Figure 4. Categories and proportion of different types of aquaculture-relevant data layers within each state shellfish map viewer. An asterisk (\*) indicates that this state's shellfish map viewer is embedded into a larger map viewer. The data layers represented in this figure are only those that were found to be relevant to shellfish aquaculture. Massachusetts<sup>1</sup> refers to the OLIVER map viewer, where shellfish data are embedded into a larger map viewer, whereas Massachusetts<sup>2</sup> refers to the MA-shellfaST map viewer. Virginia<sup>1</sup> represents the Virginia Marine Resources Commission Chesapeake Bay Map Viewer and Virginia<sup>2</sup> refers to the NOAA Chesapeake Bay map viewer.

and are essential for creating a user-friendly map viewer. More advanced tools included data analytical tools, such as an “export data” or a “draw lease area” tool, and were only available in some of the more sophisticated viewers. Other examples of more advanced map viewer tools include the ability to import or export data to and from the viewer, the ability to query individual data layers and draw prospective lease areas, and the ability to share map information *via* a link or automated report. These tools provide users with the opportunity for a higher level of engagement, analysis, and synthesis of geospatial data pertinent to shellfish aquaculture siting and permitting.

Although advanced tools are beneficial in the site screening process, they are not essential for creating a functional map viewer for users. Many of the advanced tools reviewed (Fig. 3) are available through the Esri Web AppBuilder, a common platform for building map viewers. Although 7 of 18 map viewers (39%) were developed using Esri Web AppBuilder, very few have implemented advanced tools. As described within “Section four Case Studies” in the following text, the Connecticut Aquaculture Mapping Atlas included a custom-developed tool for drawing prospective lease area boundaries. Development and incorporation of custom tools can add value to the functionality of shellfish aquaculture map viewers to inform the siting and permitting process.

User guides or tutorials are a vital component of any map viewer to ensure users are able to readily access and use the map viewer and its functionalities (Fu 2016). Although online GIS tools are becoming increasingly prevalent, many of the users of these web-based map viewers may not have a strong foundation of GIS knowledge or experience. About half (56%) of the reviewed shellfish aquaculture map viewers include a tutorial in some format. User guides within some of the reviewed map viewers included those in the form of a downloadable PDF, a tutorial video, or an Esri Story Map. It is also recommended that the map viewer developers state the best web browser to use the tool in, and it should only be viewed on the computer, not additional smart devices.

#### Data Layers

Data layers within map viewers were identified, synthesized, and divided into eight distinct planning categories: (1) infrastructure, (2) shellfish resources, (3) oceanographic/biophysical, (4) biological, (5) geomorphological, (6) cultural, (7) administrative, and (8) imagery (Fig. 4). The most common data layer themes were biological, industrial, and shellfish-specific layers (*i.e.*, related to shellfish aquaculture rules and regulations in that state). Examples of common shellfish-specific layers include SHA and commercial shellfish-growing

areas. Oceanographic (*e.g.*, depth and sea surface temperature) data layers were present in 78% of reviewed map viewers. Infrastructure or industry-related data were identified within 78% of map viewers. Administrative boundaries, including those specific to shellfish regulation or sanitation or those delineating state waters, were present in 100% of viewers. Biological data layers (*e.g.*, distribution of essential fish habitat, hard bottom habitat, and submerged aquatic vegetation) were also commonly found in the reviewed map viewers. Aerial imagery (in some cases, IR imagery) was present within 95% of map viewers. Few shellfish aquaculture map viewers contained geomorphological data, and none contained cultural data (*e.g.*, archeologically sensitive areas and tribal areas).

Other important data constraints within shellfish aquaculture map viewers include those related to recreation, transportation, commercial fishing, dredging, beach nourishment, and other existing aquaculture operations. Data representing regionally specific considerations (*e.g.*, special use areas for certain regional industries or activities) require adequate representation within map viewers, as well. Incorporation of existing infrastructure and other space-use factors imposing risk to shellfish aquaculture development also deserves consideration for inclusion.

Oceanographic, biological, and geomorphological data layers can also be included within shellfish aquaculture map viewers to provide additional utility in the siting process for prospective shellfish permit applicants. Oceanographic data are not necessary for determining if shellfish aquaculture can be sited in a particular area, but these data can be useful in determining the types of conditions shellfish aquaculture operations may face. For example, the range of salinity, food availability (*e.g.*, chlorophyll *a*), current speed, and dissolved oxygen concentrations present at a particular site can inform compatibility for cultivation of specific shellfish species (Cho 2012). Geomorphological data, such as surficial sediment type (*e.g.*, sand and mud), aid determination of seafloor composition for basic gear compatibility (Longdill et al. 2008). Biological layers can reveal species occurrence in an area, particularly in the case of critical or important habitat for threatened or endangered species. In some cases, areas such as marine protected areas or essential fish habitat may have fishing restrictions pertaining to aquaculture. For example, commercial and recreational fishing-prohibited areas may exclude aquaculture from occurring in those areas.

Shellfish-specific resource data are often included in map viewers to display other existing shellfish aquaculture infrastructure, SHA, commercial shellfish leases, or other regulated areas for shellfish aquaculture (*e.g.*, Texas Shellfish Harvest Area Viewer, Virginia Chesapeake Bay Map; Appendix 1). This improves the efficiency in management, ascertaining opportunity, and planning and permitting.

Importantly, data integration into a map viewer may be completed using data on a local server or data that are served through map services. Map services have a different host, which may be limiting if services are unstable or stops responding, rendering the layer useless in the map viewer. Most software allows for easy integration and organization of data layers, but some have limitations as to the amount of data you can input or the type of data (raster or vector) in the development. For instance, if a data layer has a high number (>100,000) of point files associated with it, then the developer must work to optimize

how the layer is served (*e.g.*, tiled and cached) to improve map viewer performance. This highlights the benefit of integrating custom data or data obtained from other sources, and serving from a known stable server.

#### *Map Viewer Architecture and Design*

All of the map viewers examined in this study incorporated similar design characteristics including a flexible interface. Developers may interact with the map viewer tool overtime concerning maintenance, performance, technical support, design updates, errors, and reporting options. Many architectures are built to allow for developers to work toward increased speeds and performance, and allow for easy integration of needed data to make the front-end component highly functional for the user. It is recommended to determine upfront if the map viewer will be displaying data with a depth component, as a unique way to visualize the data may need to be scripted in. Finally, choosing a program to track user statistics, and integrating a feedback mechanism are important for improving and monitoring the map viewer built over time.

If an Esri license is available (Esri 2018), one of the most user-friendly and cost-effective map viewer tools available is the Esri Web AppBuilder—the largest percentage (39%) of the reviewed shellfish aquaculture map viewer platforms currently use this framework. In addition to Esri Web AppBuilder, other Esri products, including ArcGIS Server and ArcGIS API (*i.e.*, Application Programming Interface) were used for 28% of the map viewer platforms. Prepackaged development tools, such as the Esri Web AppBuilder, may reduce the need for maintenance and associated costs, as much of the maintenance to the underlying software infrastructure is conducted by the software provider in an automated fashion. Other platforms available to develop a map viewer include Google-based platforms, private websites such as Maptive (<https://www.maptive.com/>) or Mapbox (<https://www.mapbox.com/>), or open-source software (*e.g.*, R Shiny and PostGIS) applications. Google-based and custom applications constitute 33.3% of the reviewed map viewer platforms. Custom applications—which offer the advantage of a more customizable and flexible design for map viewers and associated features—generally require a higher level of technical expertise, requiring in many cases increased maintenance needs and associated costs in the long term.

#### CASE STUDY EXAMPLES

The case studies described in the following texts, including the Connecticut Aquaculture Mapping Atlas and the Massachusetts Shellfish Aquaculture Siting Tool (MA-ShellfAST), represent diverse examples of state-level shellfish aquaculture map viewers that vary in age, architecture and design, data types included, and overall map viewer objective. Comparisons of these two differing approaches illustrate how flexible shellfish aquaculture map viewers can be while still conveying important permitting information.

##### *Connecticut Aquaculture Mapping Atlas*

The Connecticut Aquaculture Mapping Atlas (CLEAR 2018) is a sophisticated example of a stand-alone map viewer built specifically for aiding in shellfish aquaculture site selection and permitting decisions within Connecticut state waters



**Figure 5.** A screenshot of the Connecticut Aquaculture Mapping Atlas, for reference. The data layer displayed on the map represents shellfish classification areas, illustrating where and which areas are approved, conditionally approved, recreational, conditionally restricted, or prohibited. The map viewer also allows visualization of current aquaculture operations and the shellfish jurisdictional line. The “Draw Lease & Area” tool is highlighted here, illustrating the user can draw a custom polygon or input coordinates, and the area and perimeter are automatically calculated. The viewer also gives the user the projection that is needed to determine proper measurements. Once the polygon is drawn, the user can gain more detailed information on the SHA the polygon has been drawn in. Please visit the website to more closely review the application (CLEAR 2018).

(Fig. 5). The shellfish industry in Connecticut generates about \$30 million annually and 300 jobs for the state (CDA 2011). The application was developed by the University of Connecticut’s Center for Land Use Education and Research and the Connecticut Sea Grant Program, in collaboration with the Connecticut Department of Agriculture, Bureau of Aquaculture. This is an example of moderately custom-built application, using GEOCORTEX Essentials, allowing for expansion of options for Esri products, including Web AppBuilder. The site is hosted through Connecticut Environmental Conditions Online. Intended to be a resource for local and state government industry managers and aquaculture farmers, the data and the tools integrated into the application are specific to shellfish aquaculture siting, rules, and regulations for Connecticut (CLEAR 2018).

In addition to emphasizing data that are particularly relevant to the state’s shellfish industry, the application has custom-built tools to aid in the planning process for shellfish aquaculture siting. Examples of shellfish-specific data layers include mapping existing shellfish beds by category (state-managed, town-managed, recreational, and natural), shellfish restriction classification areas, and shellfish jurisdiction lines. A tool unique to this viewer is the “Lease & Gear Area” toolset, which allows the user to (1) plot unique coordinates or areas, (2) draw area, and (3) print maps for required figures for shellfish lease applications. Other unique features include data filter, query, upload functions, and a function to export graphics to a GIS shapefile (Fig. 5).

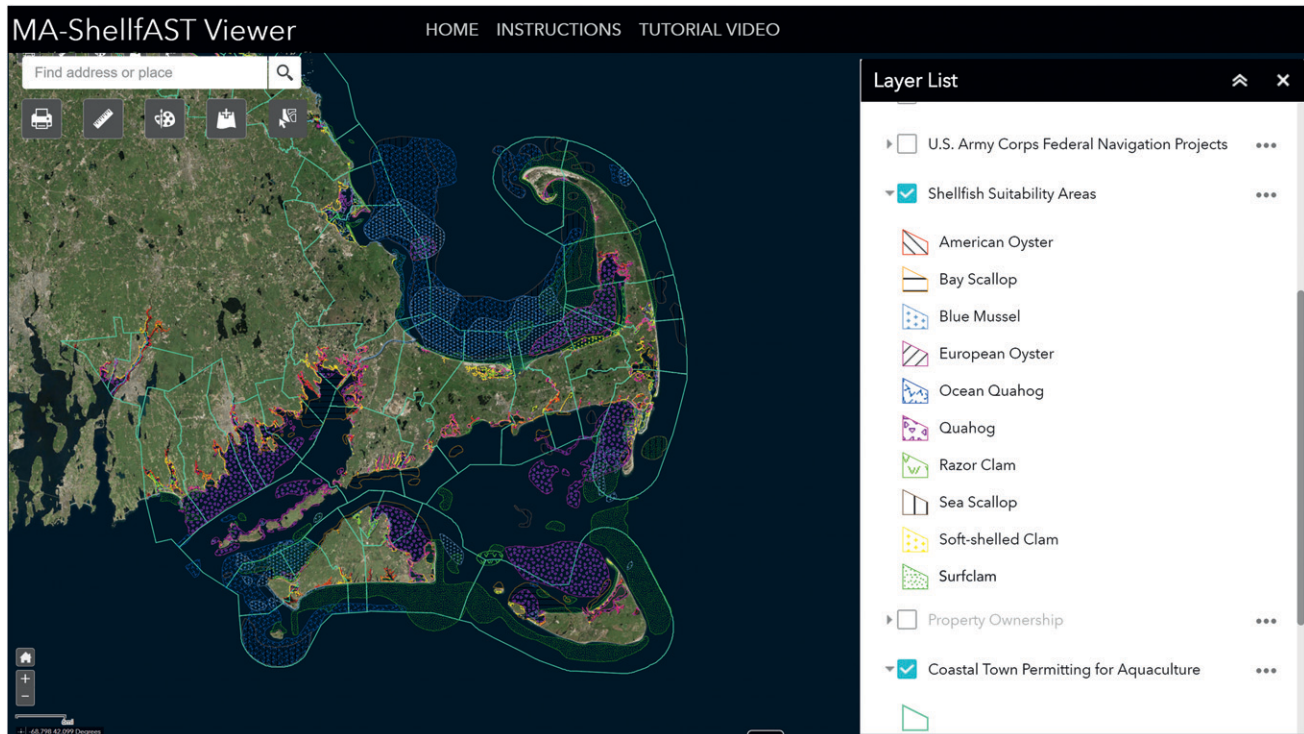
#### MA-ShellfAST

The MA-ShellfAST (NEAQ 2018) is a recently released (2018) shellfish web application that was created collaboratively and with a steering committee with numerous members from

government and nongovernmental agencies, and those who had constructed shellfish map viewers previously (Fig. 6; CLEAR 2018). The goal of the web application is to provide integrated spatial information and guidance to shellfish growers and agencies to inform siting and permitting decisions. MA-ShellfAST allows users to evaluate potential shellfish aquaculture sites based on geospatial data relevant to environmental factors, human use constraints, and regulatory information. The application was built using the Esri Web AppBuilder, similar to many other state shellfish viewers across the country. In addition to using the Web AppBuilder, the user is introduced to the map viewer using an Esri Story Map, which creates a dynamic and interactive web-based guide to the application.

MA-ShellfAST focuses on boundaries and management zones important for consideration when siting and permitting shellfish aquaculture operations, integrating both relevant data for aquaculture site screening and also policy information specific to a given county or area of interest to aid the user in navigating the permitting process. Some integrated layers include historic and current eelgrass bed distribution, coastal boat launch locations, submarine cable locations, areas of critical environmental concern, and North Atlantic right whale critical habitat distribution. Shellfish aquaculture-relevant layers in this application include shellfish suitability areas, designated shellfish-growing areas, and onshore and offshore boundaries for coastal town permitting for aquaculture. In addition to providing relevant data, the map viewer also provides legal documentation to educate and assist users in the planning process before applying for a permit. The intention of providing an accurate and accessible description of relevant laws and regulations for shellfish aquaculture within MA-ShellfAST is (1) to provide prospective growers the legal and regulatory context for shellfish aquaculture permitting in Massachusetts and (2) to aid in





**Figure 6.** A screenshot of the MA-ShellFAST. In Massachusetts, shellfish permits are issued at the municipality level, with varying rules for permitting. MA-ShellFAST allows the user to select their municipality of interest and for all pertinent legal information to be presented to the user (e.g., Coastal Town Permitting for Aquaculture layer in light green). In addition, this map viewer incorporates shellfish biophysical suitability areas for multiple candidate aquaculture species and the locations where they are most probable to grow. Please visit the website to more closely review the application (NEAQ 2018).

understanding shellfish aquaculture licensing, navigation, and wetlands requirements in Massachusetts coastal municipalities. Within the map viewer, shellfish aquaculture-relevant data layers (e.g., designated growing areas) have pop-ups with the specific laws and regulations for each municipality.

The MA-ShellFAST provides a variety of similar functions as the Connecticut Aquaculture Mapping Atlas that enhances usability and relevance of the information provided by the tool for siting and permitting decisions. For example, the tool allows the user to draw an area within the integrated map viewer and export the coordinates to a spreadsheet file—this functionality allows users to save this information for inclusion within a permit application.

## CONCLUSIONS

### *Recommended Best Practices for Shellfish Aquaculture Map Viewers*

#### **General Considerations before the Development of a Shellfish Aquaculture Map Viewer**

When effectively implemented, online interactive map viewers support sound planning decisions, can offer timely risk-based updates to the public, and can enhance the likelihood of success of commercial aquaculture management initiatives. Any web-based communication tool—particularly in the case of map viewers—needs to have a clearly predefined target audience to ensure the tool is most effective and includes useful information and data that are well conveyed (Greenhawk 2013). Functionality and data layers require definition and discussion with key stakeholders and potential users before development, with all

data obtained from authoritative sources (e.g., state and federal government sources). With regard to selection of a platform or interface to build the map viewer on, this decision should be guided by funding availability (both short term and long term), necessary expertise, and requirements for long-term maintenance. Need, cost, time, and resources, and upkeep requirements are all important considerations when deciding what type of map viewer is appropriate for a given application or audience.

#### **Architecture and Development Platform**

When developing a shellfish aquaculture map viewer, the platform, and architecture for application development, the build structure can be determined through consideration of (1) funding availability, both in the short-term and long-term; (2) availability of GIS and programming expertise for the development and maintenance; and (3) the plan for maintenance of the viewer. Funding availability impacts which software platforms will be accessible for development of the map viewer in the short term. The availability of long-term funding sources is important for determining if the development platform can have more complexity, as custom designs are often more costly to maintain. In addition to funding considerations, the availability of GIS and software development skills of employees or partners on the project will define the components of the tool's development that will need to be outsourced to GIS and programming specialists. It is recommended the map viewer's level of intricacy should be scaled depending on human capital available to facilitate routine maintenance of the map viewer, associated data, field technical questions from users, and get alerts when issues occur with the map viewer.



## Need

Depending on the target audience for a given shellfish aquaculture map viewer, the need can be multifaceted or can be targeted toward communication of a single theme (*e.g.*, shellfish closures). Often, need can be assessed through surveys and focus groups comprising vested stakeholders (*e.g.*, prospective leaseholders). Outlining and defining the need for a map viewer can inform the required level of complexity for a given viewer, the data included, and the tools available within it. In some instances, shellfish aquaculture data are embedded into broader, more general map viewers or those that are regional in nature (*e.g.*, Northeast Ocean Data Portal—<https://www.northeastoceandata.org/>). In these instances, the assumed need is relatively small as data of relevance to shellfish aquaculture that are incorporated within these tools are often difficult to find and use for decision-making, or the need is simply to view aquaculture in the context of other ocean uses. If the actual planning need is greater, this may represent a communication gap between managers and stakeholders. Shellfish aquaculture map viewers themselves vary depending on the identified goal and need, with some map viewers integrating data layers focused on mitigating and minimizing human health and environmental risk and/or interactions with protected species and biologically important coastal and ocean areas (*e.g.*, Delaware Shellfish Advisory Map; Appendix 1), whereas others emphasize opportunity for aquaculture (*e.g.*, Alabama Shellfish Aquaculture Siting Tool; Appendix 1). Assessing need helps to determine the complexity and operational layers within the viewer.

## Cost and Budgeting

Costs are an essential consideration when determining how best to develop a shellfish aquaculture map viewer to meet the expected user's needs. Many states have tried to deliver the benefits of a map viewer with sophisticated GIS data with a limited budget for construction and maintenance activities. For most, the amount of available funding dedicated to the project and the number of years of available funding will ultimately dictate the possible scope of the map viewer. Priorities in terms of functionality, data, and tools should be used to define the overall project budget to ensure the parameters deemed most important are included in the map viewer. If integration can occur within another larger map viewer with long-term funding, it may be possible to develop more powerful custom-built applications, tools, and shellfish aquaculture-relevant datasets that will require a higher level of maintenance and upkeep. For example, the Connecticut Aquaculture Mapping Atlas has integrated macroalgae aquaculture into their viewer because much of the original data used to build the viewer are now on local servers.

## Resources

As previously described, different development architectures have differing construction costs and maintenance plans. Custom-built map viewers are generally the most expensive and time consuming, whereas prepackaged development interfaces yield rapid map viewer development. Prepackaged interfaces may limit flexibility though, concerning data integration and functionality. Regardless of available funding level, ease of use, simplicity of the user interface, accuracy of the data and information,

and provision of user guides should be prioritized within any map viewer development plan (Fu 2016). As users may have shellfish aquaculture and/or map viewer experience spanning the spectrum from novice to expert, clear instructions, tutorials, and user guides are an essential component to be included within the map viewer. Accurate estimation of time required to fully develop the tool and needed functional components should be prioritized in early stages of tool planning. In doing so, the map viewer development team can establish a phased time line for the viewer, informing decisions regarding key functions, operational data layers, pop-ups, and integrated tasks that are reasonable within the available resources.

## Upkeep

Map viewer maintenance in the short term (months) and long term (years) should be discussed during early stages of map viewer development. Questions to be asked among the project team include “How will the map viewer and associated data be maintained and updated?” and “Is further funding available if the map viewer is being built through a grant?” Without a long-term maintenance plan, map viewers can become outdated, obsolete, or exhibit reduced functionality because of updates or changes in the underlying software. These challenges apply not only to the map viewer application but also to associated data layers and data web services. Before developing an online map viewer, establishment of a long-term maintenance plan for all aspects and components of the tool is essential. A plan for customer inquiries, technical support, and outreach with industry and regulators are all important to the long-term success of the map viewer.

## Data Requirements

The types of data layers within shellfish aquaculture map viewers can provide insight into the type of information regulatory agencies need to know with regard to permitting decisions. Some shellfish map viewers may have data gaps (*e.g.*, sea turtle movements), making shellfish permitting and opportunity assessment a more complex process, which may reach beyond the scope of the viewer. In this review, supplementary data layers were present in some map viewers and added additional value to shellfish permitting, serving as an additional site screening aid for prospective applicants. For example, some states include oceanographic data for parameters that could influence where shellfish aquaculture could be sited based on biophysical considerations, such as seasonal salinity or water temperature (*e.g.*, Alabama Shellfish Aquaculture Siting Tool; Appendix 1). By contrast, some states incorporate fewer data layers, focusing only on boundaries, management areas, and other constraints, which convey where shellfish aquaculture operations may not be sited (*e.g.*, Rhode Island Shellfish Harvest Restrictions Map; Appendix 1).

After reviewing the data layers found in each shellfish aquaculture map viewer, a comprehensive list of operational data layers was developed detailing the most relevant data to include within a shellfish aquaculture map viewer (Table 1). This list is based on the results of this review and the literature reviewed, in addition to the authors' related shellfish aquaculture siting expertise regarding which spatial data layers best address opportunity and risk for shellfish aquaculture development. Administrative boundaries are a necessary category of data to include within a shellfish aquaculture map viewer for site

TABLE 1.

Layers that were identified as the most necessary and useful data layers to include in a shellfish map viewer, based on analysis and professional knowledge and expertise.

Infrastructure	Shellfish resources*	Oceanographic/biophysical	Biological	Geomorphological
Danger zones and restricted areas	Shellfish riparian leases	Bathymetry or depth contours	Critical habitat	Substrate type
Military operating areas	Shellfish management areas	Surface/bottom salinity	Essential fish habitat (EFH)	Slope factor
Unexploded ordnances	Shellfish suitability areas	Surface/bottom water temperature	Habitat Areas of Particular Concern (HAPC)	<b>Cultural</b>
Shipping fairways and ferry pathways	Commercial shellfish-growing areas	Surface/bottom current speed and direction	Marine protected areas (MPAs)	
Energy infrastructure	Closed shellfish areas	Significant wave height	National wetland inventory (NWI)	Tribal resources
Coastal maintained channels	Shellfish patrol areas	Dissolved nutrients (nitrate, phosphate, and silicate)	State reserves	Archaeologically sensitive areas
Anchorage areas and turning basins	Recreational shellfish harvest areas	Chlorophyll <i>a</i>	Harmful algal blooms (HAB) type, concentration, and frequency	National marine sanctuaries (NMS)
Marinas and public boat ramps	Closed recreational shellfish harvest areas	Dissolved oxygen	SAV and/or kelp beds	State parks and state beaches
Ocean disposal sites	Shellfish protection districts	Turbidity and light attenuation	303(d) impairments	<b>Administrative boundaries</b>
Wastewater treatment outfalls and sewer lines	Public oyster reefs	Freshwater inputs (USGS stream gauges)	Water quality—monitoring stations	Federal/ state waters boundary (SLA)
On-site sewage systems	Oyster material—planting areas	Tidal differential and flushing rates	State or local protected species	State counties
Pipelines and pipeline areas	Existing aquaculture leases	pH	Cetacean Biologically Important Areas (BIA)	NOAA raster nautical chart (RNC)
Submarine cables and areas		1,000-ft-high water mark buffer	Sea turtle home ranges	
Shipwrecks and artificial reefs			Seabird nesting areas	
Fixed fishing devices			Protected species population densities	
AIS vessel density				
Beach nourishment				

These layers express both opportunity and risk in terms of identifying potential aquaculture farm sites. An asterisk (\*) indicates the layers presented are specifically related to shellfish management within a state or region. Sources of aquaculture-relevant data in addition to the reviewed shellfish map viewers: Longdill et al. (2008), Ehler and Douvère (2009), Nath et al. (2000), Ross et al. (2013), Bricker et al. (2016), Aguilar-Manjarrez et al. (2017).

screening (Nath et al. 2000). For example, prospective applicants must differentiate between state and federal waters because of the differences in permitting processes, and must also be aware of other regulated zones (e.g., military areas and other restricted areas documented within the NOAA Raster Nautical Chart (RNC) or other authoritative sources). The RNC is the most frequently updated (weekly) ocean use map available for the United States. The RNC provides all major obstructions (e.g., shipwrecks, energy industry infrastructure, rocks, and aquaculture), aids (e.g., lights, buoys, beacons, and signals), routes, and areas to avoid for navigation, depths, danger zones and restricted areas, submarine cables, major pipelines, natural and cultural features, and boundaries and limits (US Chart 1 2018).

### Overall Conclusions

Given the numerous—often competing—uses of U.S. coastal waters, identifying compatible sites for aquaculture

requires compromise and upfront identification of constraints and opportunities for successful siting of operations (Gifford et al. 2011). In the present study, the design architecture, composition of layers and themes, and overall functionality were identified and assessed for 18 state or regional shellfish map viewers across the coastal United States, to identify specific spatial and temporal information presented to stakeholders for decision-making purposes. The review revealed varying levels of complexity and usability, but all reviewed map viewers provided visualizations of geospatial data informing siting of, and permitting decisions regarding, shellfish aquaculture operations. Most map viewers have been developed in the last 5 to 10 years as online GIS tools have become more readily accessible, and the increased rate of aquaculture growth has required enhanced planning tools. Some map viewers have been established for years (e.g., Connecticut Aquaculture Mapping Atlas) and have evolved over time through integration of new data or functions as needs were identified or new technology became

available. Other shellfish aquaculture map viewers only recently entered the public domain (e.g., South Carolina Shellfish Viewer, MA-ShellfaST) and have been developed through partnerships with other states that have shellfish aquaculture map viewers, and further refined through user feedback.

This review of state shellfish map viewers indicates many of the currently available map viewers could incorporate additional useful tools at no additional cost within these platforms. These comprise key characteristics of a functional shellfish map viewer including (1) a user-friendly interface, with a tutorial for how to use the web application; (2) a map viewer that conveys real opportunity, interactions, and risk associated with shellfish aquaculture development in a given area; (3) aquaculture-relevant data and regulatory or legal documentation; and (4) a maintenance plan for sustaining the map viewer's data layers and functions in the short term and long term. General useful functions identified within the analysis include panning, zooming in/out, toggling on/off layers, incorporating a tutorial or user guide, and including pop-ups with additional information and attributes from the data. More specialized functions include the ability to export or print a map, draw a shellfish aquaculture lease area on the map, and import coordinates onto the map.

Application of GIS analysis outputs, or the layers used in decision-making in a map viewer, offers greater confidence to applicants and coastal managers in shellfish siting in state waters (Silva et al. 2011, Bricker et al. 2016). In the case of inclusion of suitability information for shellfish aquaculture, data are intended to further facilitate and direct prospective permit applicants toward selecting sites more likely to be compatible and successfully permitted. Cultural and socioeconomic data can provide useful insights into tribally held areas, as well as culturally or archaeologically important areas (e.g., shipwrecks, National Monuments, and National Marine Sanctuaries), or local economics (WSG 2014). In some cases, areas of use can then be established (e.g., New York Shellfish Aquaculture Lease Program) and easily communicated through a map viewer to stakeholders in a consistent and concerted manner. Map viewers can also convey opportunity for shellfish aquaculture conducive to species-specific parameters (e.g., Alabama Shellfish Aquaculture Siting Tool, MA-ShellfaST) (e.g., depth) and, in some cases, for gear (e.g.,

surficial sediment type and depth). Conveying major constraints or risk (e.g., Delaware Shellfish Advisory Map) for shellfish siting can improve site selection by mitigating potential space-use conflicts before the permitting processes begins. Overall, map viewers can play a major role in providing key information to guide permitting decisions by state resource managers. Notably, state-scale shellfish map viewers act as a screening platform with enhanced transparency and understanding in the process among all stakeholders. After screening, it is just as notable that stakeholders should travel to the preferred siting areas identified through map viewers, to verify conditions. Those seeking shellfish permits in U.S. coastal states with map viewers are now empowered with tools to make important spatiotemporal decisions before investment of time and money into a low suitability site for shellfish culture to occur.

Through provision of a full suite of tools for making informed shellfish aquaculture siting decisions, map viewers offer stakeholders key information needed to guide business investment and regulatory decisions regarding shellfish aquaculture. Given the reduction in cost, money, and time required to develop map viewers within recent years, continued adoption and refinement of these tools are recommended. Although not all coastal states have shellfish aquaculture map viewers at the time of this review, the rapid growth of the industry and concurrent rise in frequency of shellfish aquaculture map viewer tools (described herein) implemented in the last five plus years indicate a growing recognition of the need for online GIS-based decision support tools within the field. Identification of space available for shellfish aquaculture operations requires a complex, multifaceted process and map viewer tools offer a simplified, user-friendly, and cost-effective form of digital communication for education and conflict resolution in the aquaculture siting process. Moreover, these map viewers offer an opportunity to explain the importance of various environmental and space-use factors to the siting process, potentially streamlining the permitting process for coastal managers and applicants.

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**APPENDIX 1.**  
**Available map viewers and other shellfish resources.**

State-level shellfish aquaculture map viewer	Online URL
Alabama Shellfish Aquaculture Siting Tool	<a href="https://aldcnr.maps.arcgis.com/apps/webappviewer/index.html?id=a32dad8dadc249ea86bcb80dd951a424">https://aldcnr.maps.arcgis.com/apps/webappviewer/index.html?id=a32dad8dadc249ea86bcb80dd951a424</a>
Connecticut Aquaculture Mapping Atlas	<a href="http://clear3.uconn.edu/aquaculture/">http://clear3.uconn.edu/aquaculture/</a>
Delaware Shellfish Advisory Map	<a href="http://dnrec.maps.arcgis.com/apps/OnePane/basicviewer/index.html?appid=bb37754f376349198c76e2cba80732bd">http://dnrec.maps.arcgis.com/apps/OnePane/basicviewer/index.html?appid=bb37754f376349198c76e2cba80732bd</a>
Georgia DNR Outdoor Map	<a href="https://georgiaoutdoormap.com/">https://georgiaoutdoormap.com/</a>
Maine Department of Marine Resources Aquaculture Map	<a href="https://www.maine.gov/dmr/aquaculture/leases/aquaculturemap.html">https://www.maine.gov/dmr/aquaculture/leases/aquaculturemap.html</a>
Maryland Aquaculture Siting Tool	<a href="http://gisapps.dnr.state.md.us/Aquaculture/index.html">http://gisapps.dnr.state.md.us/Aquaculture/index.html</a>
Massachusetts OLIVER MassGIS Online Mapping Tool	<a href="http://maps.massgis.state.ma.us/map_ol/oliver.php">http://maps.massgis.state.ma.us/map_ol/oliver.php</a>
Massachusetts ShellFAST	<a href="https://marinegistest.maps.arcgis.com/apps/Cascade/index.html?appid=fc96cff0ce4247f8bea2fb490327a55a">https://marinegistest.maps.arcgis.com/apps/Cascade/index.html?appid=fc96cff0ce4247f8bea2fb490327a55a</a>
New Hampshire Shellfish Harvest Areas Map	<a href="https://www4.des.state.nh.us/CoastalAtlas/Shellfish_Map.html">https://www4.des.state.nh.us/CoastalAtlas/Shellfish_Map.html</a>
New Jersey DEP GeoWeb	<a href="https://njwebmap.state.nj.us/NJGeoWeb/WebPages/Map/FundyViewer.aspx">https://njwebmap.state.nj.us/NJGeoWeb/WebPages/Map/FundyViewer.aspx</a>
New York Shellfish Aquaculture Lease Program (Suffolk County)	<a href="http://gis3.suffolkcountyny.gov/shellfish/">http://gis3.suffolkcountyny.gov/shellfish/</a>
NOAA Chesapeake Bay Office Oyster Decision Support Tool	<a href="http://science.ncbo.noaa.gov/odst/">http://science.ncbo.noaa.gov/odst/</a>
North Carolina Shellfish Siting Tool	<a href="http://www.arcgis.com/home/webmap/viewer.html?webmap=93a82e7f61e44d59b7c27fae3fcf2491">http://www.arcgis.com/home/webmap/viewer.html?webmap=93a82e7f61e44d59b7c27fae3fcf2491</a>
Rhode Island Shellfish Harvest Restrictions Map	<a href="http://ridemgis.maps.arcgis.com/apps/webappviewer/index.html?id=110a7a4aec914a3492117e9848fe67da">http://ridemgis.maps.arcgis.com/apps/webappviewer/index.html?id=110a7a4aec914a3492117e9848fe67da</a>
South Carolina Mariculture Siting Map Application	<a href="https://scdnr.maps.arcgis.com/apps/webappviewer/index.html?id=d7cce8c8272b4a36a8324fb5cc1833a7">https://scdnr.maps.arcgis.com/apps/webappviewer/index.html?id=d7cce8c8272b4a36a8324fb5cc1833a7</a>
Texas Shellfish Harvest Area Viewer	<a href="https://dshscpd.maps.arcgis.com/apps/View/index.html?appid=742f69f058f444db9a997e2dd3c20954">https://dshscpd.maps.arcgis.com/apps/View/index.html?appid=742f69f058f444db9a997e2dd3c20954</a>
Virginia Marine Resources Commission Chesapeake Bay Map	<a href="https://webapps.mrc.virginia.gov/public/maps/chesapeakebay_map.php">https://webapps.mrc.virginia.gov/public/maps/chesapeakebay_map.php</a>
Washington State Commercial Shellfish Map Viewer	<a href="https://fortress.wa.gov/doh/eh/maps/OSWPViewer/index.html">https://fortress.wa.gov/doh/eh/maps/OSWPViewer/index.html</a>

## Information for shellfish aquaculture for states currently without a map viewer.

Shellfish aquaculture resource	Online URL
Alaska Division of Environmental Health Shellfish Information	<a href="https://dec.alaska.gov/eh/fss/shellfish/">https://dec.alaska.gov/eh/fss/shellfish/</a>
Alaska Department of Fish and Game Commercial Shellfish Area Maps	<a href="http://www.adfg.alaska.gov/index.cfm?adfg=CommercialByFisheryshellfish.shellfishmaps">http://www.adfg.alaska.gov/index.cfm?adfg=CommercialByFisheryshellfish.shellfishmaps</a>
California Shellfish Regulation	<a href="https://www.cdph.ca.gov/Programs/CEH/DRSEM/Pages/EMB/Shellfish/Shellfish-Program.aspx">https://www.cdph.ca.gov/Programs/CEH/DRSEM/Pages/EMB/Shellfish/Shellfish-Program.aspx</a>
Florida Division of Aquaculture Online Resources	<a href="https://www.freshfromflorida.com/Divisions-Offices/Aquaculture">https://www.freshfromflorida.com/Divisions-Offices/Aquaculture</a>
Florida Department of Agriculture and Consumer Services Shellfish Harvesting Area Maps	<a href="https://www.freshfromflorida.com/Business-Services/Aquaculture/Shellfish-Harvesting-Area-Classification/Shellfish-Harvesting-Area-Maps">https://www.freshfromflorida.com/Business-Services/Aquaculture/Shellfish-Harvesting-Area-Classification/Shellfish-Harvesting-Area-Maps</a>
Florida Department of Agriculture and Consumer Services Aquaculture Best Management Practices	<a href="https://www.freshfromflorida.com/es/Business-Services/Aquaculture/Aquaculture-Certificate-of-Registration/Aquaculture-Best-Management-Practices">https://www.freshfromflorida.com/es/Business-Services/Aquaculture/Aquaculture-Certificate-of-Registration/Aquaculture-Best-Management-Practices</a>
Louisiana Department of Wildlife and Fisheries Commercial Harvest License/ Permit Information	<a href="http://www.wlf.louisiana.gov/fishing/commercial-oyster-licenses-and-permits">http://www.wlf.louisiana.gov/fishing/commercial-oyster-licenses-and-permits</a>
Mississippi Department of Marine Resources Shellfish Information	<a href="http://www.dmr.ms.gov/index.php/marine-fisheries/shellfish">http://www.dmr.ms.gov/index.php/marine-fisheries/shellfish</a>
Oregon Department of Fish and Wildlife Shellfish and Estuarine Assessment of Coastal Oregon	<a href="http://www.dfw.state.or.us/mrp/shellfish/seacor/">http://www.dfw.state.or.us/mrp/shellfish/seacor/</a>
Oregon Fishing License Information	<a href="http://www.eregulations.com/oregon/fishing/license-information/">http://www.eregulations.com/oregon/fishing/license-information/</a>