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research paper

Marine spatial planning and best siting practices to achieve an ecosystem approach to aquaculture in the United States

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ABSTRACT.—Marine aquaculture, defined here as aquaculture that takes place in coastal, nearshore, and offshore environments, has great potential for sustainable development in the United States. While the United States' exclusive economic zone supports many ocean uses and socioecological systems, an ecosystem siting and management approach is imperative for aquaculture to develop sustainably. An ecosystem approach to aquaculture (EAA) is a broadly recognized strategy for developing aquaculture with minimal disruption to other ocean uses and environmental attributes. An ecosystem is defined here as the totality of environmental and human dimensions in which an aquaculture operation can interact. The United States can achieve an EAA by adhering to a suite of marine spatial planning techniques that are adaptive to scale, carrying capacity, and stakeholder preferences. In this paper, we discuss how the United States can better utilize marine spatial planning protocols to develop an EAA and grow the aquaculture industry with optimal efficacy. Ultimately, this paper is intended to serve as a blueprint for implementing an EAA for marine aquaculture in the United States. We first review the state of marine aquaculture within the United States, including state and federal regulatory frameworks and then discuss the principles of EAA and tools of marine spatial planning, including analyses that are pertinent to the scale of planning and for assessing carrying capacity. We conclude with a discussion on how marine spatial planning can lead to the successful implementation of an EAA.

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The Food and Agriculture Organization (FAO) defines an "Ecosystem Approach to Aquaculture" (EAA) as a strategy for the integration of aquaculture within the broader ecosystem context to promote sustainable development, equity, and resilience of interlinked socioecological systems (Soto et al. 2008, FAO 2010). According to Soto et al. (2008) and Aguilar-Manjarrez et al. (2017), three principles govern the implementation of EAA, including: (1) aquaculture should be developed in the context of ecosystem functions and services with no degradation of these beyond resilience; (2) aquaculture should improve human well-being with equity for all; and (3) aquaculture should be developed in the context of other sectors, policies, and goals, as appropriate. Under these three guiding principles, the EAA acts as a conceptual guideline for spatial planning and management based on a balance between production, ecological, regulatory, and social carrying capacities (Byron and Costa-Pierce 2013, Aguilar-Manjarrez et al. 2017).

An EAA requires the application of marine spatial planning (MSP) techniques to ensure equitable shared use of natural resources (Ross et al. 2013). Planning for sustainable aquaculture development among current ocean use sectors (e.g., transportation, recreation, military, fishing, mining, and energy) is challenging, especially given the economic scale, global need, and operational space requirements of these other industries. To meet food security and economic growth goals, allocation of space for aquaculture, based on relative compatibility with other ocean uses, must be analyzed to integrate this growing industry amongst competing uses. Given that marine aquaculture is typically a fixed-location industry, it is not transient or easily relocated. Long-term sustainability requires adequate and predictable environmental conditions and compatible interactions with other users over both space and time (Costa-Pierce 2010). Spatiotemporal planning for different types of aquaculture must also balance tradeoffs among environmental, social, economic, cultural, and management considerations—a central aim of EAA. Balancing tradeoffs is complex, especially at the ecosystem-level where expanded datasets and broader scale determinations are required, but are often limited. As Gifford et al. (2001) suggested, there are no ideal sites for aquaculture, and compromise will always be required. Thus, when and how to prioritize aquaculture in a given location is social, economic, and ecological challenge. Comprehensive and transparent spatial conflict assessments and advanced visualizations within an MSP framework can support identification of compromise and best fit locations for new aquaculture operations (Stelzenmüller et al. 2017). In this study, we set out to review the pertinent literature and available tools and approaches for spatial planning for sustainable aquaculture in the United States (US). This review is intended to be a reference for how MSP can be a key component for achieving EAA in the US. Specifically, we cover (1) the current obstacles to sustainable aquaculture in the US, (2) principles of an EAA, (3) MSP tools including carrying capacities, scale of planning, and hierarchical spatial analysis protocols, and (4) how MSP techniques can lead to implementation of an EAA.

United States Aquaculture Planning

With one of the largest exclusive economic zones in the world, the US has considerable opportunity for commercial aquaculture development (Kapetsky et al. 2013). To date, and in part due to the nascent scale of the US aquaculture industry, marine spatial planning for aquaculture development has received relatively little effort nationally (Lester et al. 2022). One often cited reason for the lack of marine aquaculture development in the US is the lack of a comprehensive regulatory framework for federal waters, leading to regulatory uncertainty (Engle and Stone 2013, Anton and Hupp 2021, Otts 2021).

Regulatory uncertainty has several implications for aquaculture development including time-consuming permitting processes, less clarity for aquaculture businesses on how to operate (Falconer et al. 2023), and no federal agency congressionally authorized as the lead regulator for aquaculture in US federal waters. The mix of laws and regulations are perceived to impose a significant barrier to industry entry by means of deterring investments for offshore aquaculture development (Knapp and Rubino 2016, Rubino 2008, Upton 2019, Rubino 2023). In addition, complicated regulations have resulted in uncertainty for how to obtain exclusive use of space in federal waters (US Commission on Ocean Policy 2004). With no agency possessing statutory authority as the regulatory lead on aquaculture in US federal waters and no explicit direction for how agencies would coordinate, prospective developers may be left without a clear understanding of when and where they could even begin aquaculture operations.

The US Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), and Food and Drug Administration (FDA) are each authorized to regulate certain activities pertinent to aquaculture in federal waters of the US. NOAA asserts authority over management of offshore aquaculture under the Magnuson-Stevens Act (MSA) and works to avoid conflicts with protected species, sensitive habitats, and fisheries. Meanwhile, the USACE regulates construction activities to ensure minimal impacts to navigation and other conflicts, the EPA regulates benthic and water quality impacts, and the FDA regulates matters related to human health (NMFS 2022). While federal agencies have acknowledged the role of regulatory uncertainty in constraining the growth of sustainable aquaculture (USDA 2022), clearer definition of federal agency roles in offshore aquaculture governance and implementation would help standardize MSP into decision-making workflows, thus reducing time and costs and increasing understanding of permitting processes.

In addition to enhanced coordination among federal agencies in the permitting process for aquaculture in US federal waters, the US has taken steps to improve the efficiency of establishing aquaculture through Presidential Executive Order 13921, Promoting American Seafood Competitiveness and Economic Growth (7 May, 2020). E.O. 13921 called for NOAA to designate certain US federal waters as "Aquaculture Opportunity Areas" (AOAs), which are areas that contain suitable environmental characteristics for sustainable aquaculture and minimize conflicts with other ocean uses. In carrying out the Executive Order, NOAA is identifying AOA options using multicriteria spatial analysis, best available spatial data, and robust stakeholder engagement. In 2021, NOAA released the first two atlases to inform siting of AOAs for the Gulf of Mexico and Southern California Bight (Morris et al. 2021, Riley et al. 2021). At the time of release, these atlases represented the most comprehensive regional-scale marine spatial planning studies conducted in US federal waters.

Inconsistent planning efforts among states is another obstacle to expansion of the US aquaculture industry (Wickliffe et al. 2019). While only eight marine coastal states have developed aquaculture use zones (e.g., Florida, New York, New

Jersey) and four have non-aquaculture-specific marine spatial plans (Lester et al. 2022), the majority lack existing spatial analysis-based approaches to guide siting and permitting (Wickliffe et al. 2019). Continued omission from regional planning efforts now requires coastal managers and farmers to evaluate where the aquaculture industry fits within the context of existing coastal uses on a case-by-case basis. Lack of baseline suitability understanding in a given region or state likely reduces effectiveness and efficiency, equity, and predictability of the rule of law for potential aquaculture—all central principles of good aquaculture governance essential to reconcile ecological and human well-being (Hishamunda et al. 2014). Without a clear, spatially explicit plan, aquaculture faces significant challenges in navigating this landscape of conflict. To determine where suitable space does exist, planning at various spatial and temporal scales is necessary to minimize user conflicts and ensure compatibility of aquaculture within the existing ecosystem.

Marine spatial planning helps stakeholders visualize and understand the socioeconomic, environmental, and industry context of a planned farm, and can be particularly valuable to inform the permitting process. Permitting can be different for shellfish, finfish, and algae aquaculture in state and federal waters; thus, MSP can provide regional context related to other ocean users and environmental sensitivities for industry and regulators during project scoping, permitting, and permit renewal stages. The whole ecosystem receives consideration during permitting at various stages and levels depending on the level of environmental review. For example, habitat and fishery managers and the Regional Fishery Management Councils will consider aquaculture impacts to both water quality and benthic habitats as both falling under the purview of Essential Fish Habitat provisions of the Magnuson-Stevens Fishery Conservation and Management Act (MSA). This review occurs multiple times by the agencies involved during each phase of the permitting process as more information becomes available. Another example is the types of environmental reviews federal agencies conduct under the National Environmental Policy Act (NEPA). NEPA allows federal agencies to use a programmatic approach to reviewing and planning future actions. A programmatic approach evaluates the effects of broad proposals or planning-level decisions that may include a wide range of individual projects, implementation over an extended period of time, and/or actions across a large geographic area. The level of detail in a programmatic NEPA review is sufficient to allow informed decisions among planning-level alternatives and to develop holistic mitigation strategies. Collaboration among all levels of government and tribes is especially important to have an effective process and outcome. This NEPA-based programmatic approach does not evaluate individual project-level issues such as precise project impacts or specific design details that are not appropriate for decisions at the planning level. Instead, a programmatic NEPA approach is a tool for examining the interaction among proposed projects or plan elements, and for assessing cumulative effects. Ultimately, the goal of any marine permitting process is to make the best decision regarding use of public trust waters through selection of space that is the best alternative for the activity being permitted. Marine spatial planning can provide alternative siting scenarios that integrate the often complex socioeconomic and ecosystem spatial context of aquaculture to inform and assure industry and regulators that the right kind of aquaculture is sited in the right place.

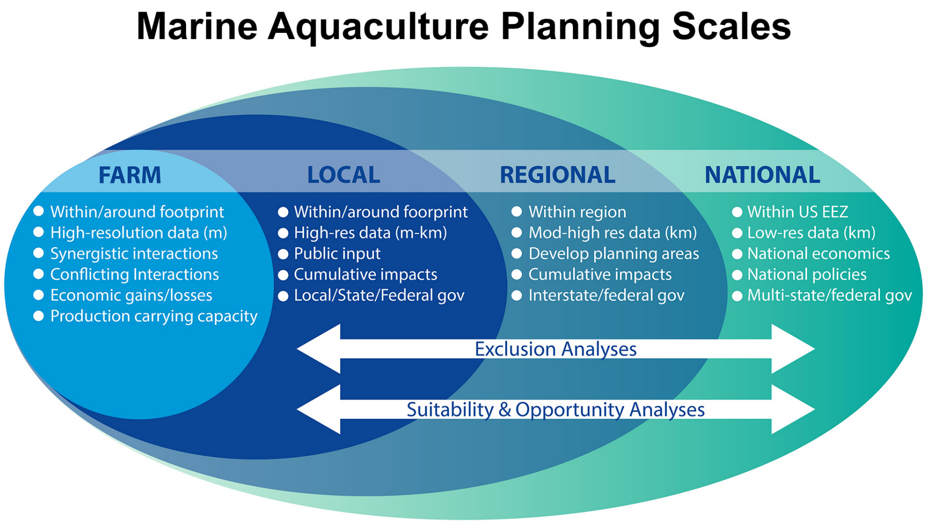

Figure 1. Various marine aquaculture planning scales, the associated characteristics of planning at each scale, and the types of geospatial analyses that are generally conducted at each scale.

Aquaculture Spatial Planning at the Ecosystem Level

Planning for aquaculture development while considering an entire ecosystem of data and interactions can be challenging given data limitations and complexity of interactions. However, there are benefits such as ecosystem services that may enhance the surrounding ecosystem (Alleway et al. 2019) making trade-off assessments a likely fruitful exercise. Further, the transparent nature of MSP approaches to aquaculture siting can contribute to needed improvements to US public perceptions about potential ecosystem impacts and benefits of aquaculture. While an EAA provides useful guidance to managers and industry, it is cumbersome to implement without clear national policy and regulatory frameworks capable of weighing allocation based on public interest costs and benefits. Formal adoption of EAA, including in North America, is relatively limited (Brugère et al. 2019).

Defining the spatial extent or scale of an "ecosystem" is an important first step in determining the appropriate MSP approach and the spatiotemporal resolution of data required to understand aquaculture impacts and interactions at the ecosystem-level. This decision should depend on environmental and socioeconomic components, and it should seek both the best available science and broad stakeholder participation. Involving stakeholders from the onset of planning is a key component of the EAA, as the result is more effective integration of aquaculture within communities (FAO 2010). In the same way that including environmental components elucidates what is ecologically sustainable, rigorous stakeholder involvement helps establish planning objectives that are appropriate for a community, resulting in support for the planning process and participatory engagement across all community sectors.

The priorities of aquaculture planning will also depend on whether planning occurs at the farm, local, regional, or national ecosystem levels (Fig. 1). Often, many of the concerns related to environmental or social challenges appear insignificant at the farm or local level, but can compound and become significant at the regional or national ecosystem scale. For example, nutrient levels associated with one finfish farm may not seem problematic, but if more cages or farms are added over time without adequate spatial planning (e.g., depositional modeling), the ecological carrying capacity of a waterbody may be exceeded (Beveridge 1984, Strain and Hargrave 2005, Aguado-Giménez et al. 2006, Price et al. 2015). If this occurs, ecosystem trophic structure and function can degrade and secondary impacts, such as algae blooms, can impact other ocean-use sectors (e.g., tourism, recreational and commercial fisheries), yielding conflicts among stakeholders (Filgueira and Grant 2009, Price and Morris 2013). Under the EAA, MSP incorporates and thereby mitigates many potential deleterious ecosystem-level impacts of aquaculture. For example, adjusting the mix of aquaculture types to optimize enhancements to ecosystem function can only be done by considering ecosystem level factors by using MSP in conjunction with environmental models (e.g., Integrated Multitrophic Aquaculture, Granada et al. 2018). Some evidence indicates that well-sited marine aquaculture could contribute to coastal ecosystem conservation and restoration goals (Theuerkauf et al. 2019). Aquaculture spatial planning also improves the effectiveness of management interventions to increase production and improve emergency preparedness and mitigation options (e.g., planning for disease outbreaks), thereby reducing long-term farm risks (Meaden et al. 2016, Hobday et al. 2018).

Principles of Marine Spatial Planning

The term “marine spatial planning” can describe planning at small and large spatial (meters to kilometers) and temporal (daily to multidecadal) scales across single or multiple ocean use sectors and various aquaculture types including shellfish, algae, and finfish aquaculture practices. For the purposes of this discussion, the ecosystem-based MSP approach is a process which informs the spatial distribution of activities in the ocean such that existing and emerging uses can be maintained, use conflicts reduced, and ecosystem health and services protected and sustained for future generations (Foley et al. 2010). MSP is often regarded as the first reconnaissance-level step in implementing EAA (Ross et al. 2013). This guiding framework informs science-based tools that can be used to address site-specific aquaculture infrastructure management challenges, building and strengthening community resiliency and promoting logical siting of a variety of aquaculture types in the appropriate environmental conditions. Analytical approaches conducted through MSP efforts can vary widely; from simple mapping of existing uses (e.g., Commonwealth of Massachusetts 2009) to sophisticated geospatial modeling approaches that synthesize and integrate environmental, social, economic, cultural, and management considerations (Battista and O’Brien 2015). While historical spatial planning analytical approaches and efforts largely were terrestrially focused, there are a few notable oceanic examples of planning efforts in US waters for multiple infrastructure uses [e.g., military compatibility analyses, Bureau of Ocean Energy Management (BOEM) wind energy areas] and industry/ecosystem interactions (e.g., shipping, cetacean density in shipping fairways) that serve as model case studies for siting and planning commercial aquaculture (Benassai et al. 2014, Christie et al. 2014, Garavelli et al. 2022).

Regardless of the complexity or scale of the planning objective, the planning process often follows the general workflow of (1) identifying the planning objective through multistakeholder engagement, (2) inventory of available, relevant data, (3) analysis and mapping of data, (4) interpretation, and (5) delivery of map products and reports to coastal managers and other end-users.

A lack of adequate planning for marine aquaculture can constrain industry growth. When aquaculture is poorly sited, problems routinely arise with animal health, environmental sustainability, production, social conflict, post-harvest processing services and product marketing, risk financing, and a lack of adaptability to external threats such as natural disasters and environmental change (Sanchez-Jerez et al. 2016, Aguilar-Manjarrez et al. 2017). Aquaculture requires consideration of unique sets of environmental and physical conditions, including factors such as water quality, depth, temperature, salinity, current speed and direction, substrate type, and wave energy to ensure facility security and health and quality of cultured species. In addition, farms need access to land-based infrastructure capable of supporting delivery of supplies and ensuring efficient processing and distribution occur. Poor site selection can not only result in failure of farm sustainability (both economical and ecological), but can leave a lasting social stigma against aquaculture development across local and regional communities.

Carrying Capacities, Models, and Site Selection

The carrying capacity of an ecosystem is the maximum production that can be maintained within a given space based on the environmental and social limits of aquaculture to avoid "unacceptable change" (Ross et al. 2013, Weitzman 2019, Weitzman and Filgueira 2020). In order to achieve site selection under the EAA, consideration must be given to the upper bounds of aquaculture production (production carrying capacity), ecological assimilation (ecological carrying capacity), regulatory compliance (regulatory or governance carrying capacity), economic capacity (ability to sell products produced and general profits), and societal acceptance of aquaculture (social carrying capacity; Byron and Costa-Pierce 2013). Production carrying capacity refers to the maximum sustainable aquaculture yield and is usually considered at the farm-scale irrespective of ecosystem function (McKindsey et al. 2006). Ecological carrying capacity refers to the ability of the waterbody in which the farm resides to provide the factors or requirements necessary for successful production. Ecological carrying capacity takes into account how the environment supports aquaculture production while balancing the assimilative capacity of the waterbody (Tett et al. 2011, McKindsey 2013, Fisher et al. 2023) but should also consider the whole ecosystem including all processes involved in aquaculture production (Filgueira et al. 2015). Regulatory carrying capacity refers to the upper limit of aquaculture infrastructure and production permissible under existing regulations. Social carrying capacity of aquaculture is built through stakeholder engagement in the planning process to avoid unacceptable change to both social functions and the natural ecosystem (Ostrom 2009, Kluger and Filgueira 2021). Numerous limiting environmental, ecological, social, and economic parameters must be considered to sustainably and responsibly support new commercial-scale marine aquaculture endeavors (Fig. 2). All four categories of carrying capacity intersect and overlap to define the optimal ecosystem and societal context for marine aquaculture. Although the overarching concepts of production, ecological, regulatory, and societal carrying

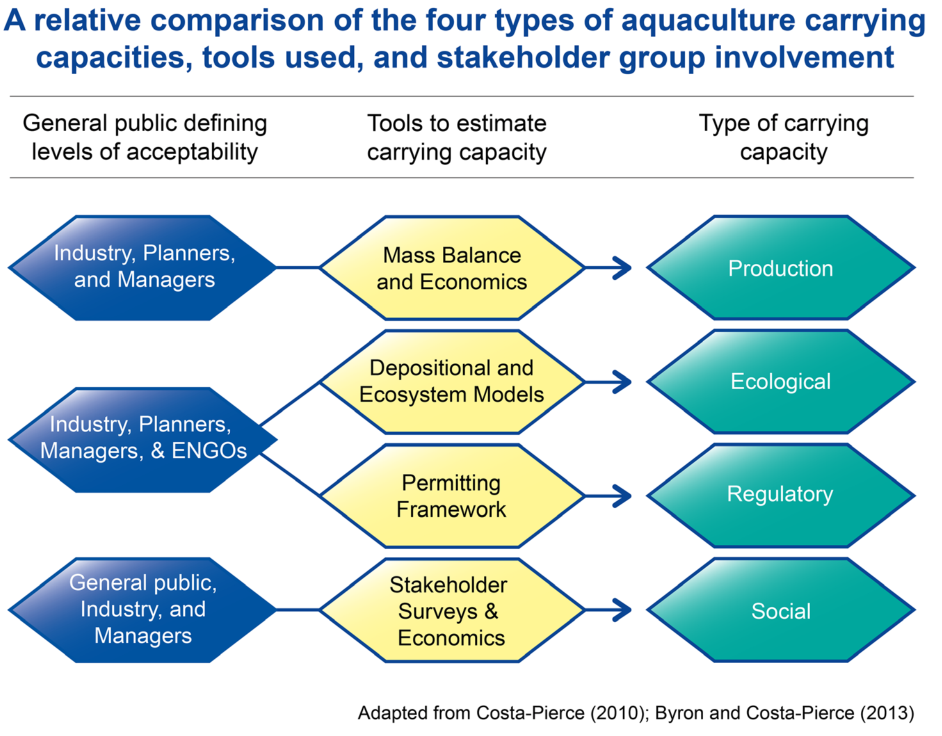

Figure 2. The highest aquaculture farm yields occur when models are utilized to predict the maximum production carrying capacity with ecological, regulatory, and social variables considered.

capacities are globally inclusive, tailoring of regional- or local-scale carrying capacity concepts on a case-by-case basis may be required during the site selection process.

Regulatory carrying capacity refers to the upper limit of aquaculture infrastructure and production permissible under existing regulations, and requires rigorous MSP, environmental impact assessment, and environmental modeling (Fig. 2; Byron and Costa-Pierce 2013). Social carrying capacity is the maximum level of aquaculture infrastructure development that does not negatively impact or disenfranchise local communities (Aguilar-Manjarrez et al. 2017). Even prior to reaching these regulatory and social thresholds, there is potential for ecological degradation, negative societal impacts, and general incompatibility of aquaculture with other ocean uses. To minimize social incompatibility, it is important to engage key stakeholders throughout the planning process through meaningful discourse and timely sharing of information (Gopnik et al. 2012). Economic carrying capacity is determined by not only the ability to grow aquaculture products but the ability to sell at a volume and value for the business to be profitable.

Multiple models and analytical frameworks exist to estimate these aquaculture carrying capacities (Table 1). Production and ecological carrying capacity models integrate hydrodynamic, biogeochemical, and ecological factors with oxygen consumption, sources and sinks of organic matter, and nutrients derived from, or taken up by farm activity, to determine upper biophysical threshold limits for aquaculture infrastructure, and examples of related modeling tools are provided in

Table 1. Examples of modeling tools to estimate carrying capacities of aquaculture. This table is adapted from Byron and Costa-Pierce (2013) and is used here for example purposes only. The authors do not endorse or promote the use of one product over another.

Tool	Purpose	Carrying capacity estimated	References
Geographic Information Systems (GIS) software	First tool to be applied in planning area site selection before the application of more specific local- and farm-scale models which assess likely site-specific impacts from varied production levels.	Ecological	ESRI, Google, Manifold, Geosoft, Hexagon Geospatial, etc.
Statistical models	Assimilation capacity of the environment is calculated based upon farm discharges; Assessments of aquaculture carrying capacities are made on levels of unacceptable water quality and/or benthic environmental impacts.	Production, ecological	Beveridge 1984, Huiwen and Yinglan 2007
3D tidal model	Calculates site placement, spatial distribution of cages, and number of cages.	Production	Geček and Legović 2010
AquaModel	Determines fish cage biomass impacts on pelagic and benthic ecosystems.	Ecological, regulatory	Rensel et al. 2007
NewDEPOMOD	Site evaluation using current velocity and direction, depth, feed input, and cage layout. Predictions of waste fecal and feed deposition and benthic impact.	Ecological, regulatory	Cromey et al. 2002, Fox et al. 2023
FARM	Allows ecological and economic optimization of culture practice including timing and sizes for seeding and harvesting, densities, and spatial distributions.	Production, regulatory	Ferreira et al. 2009, Cubillo et al. 2016, Bayer et al. 2024
AkvaVis	Site selection, carrying capacity, and management monitoring.	Production, ecological	Ervik et al. 2008, 2011

Table 1. Regulatory carrying capacity can be estimated through the siting process with associated risk analyses. Here, exposure to potential natural and human-caused hazards (e.g., storms, disease, etc.) can negatively affect aquaculture infrastructure and should be rigorously quantified. Social carrying capacity can be estimated through stakeholder analysis, wherein attitudes of diverse stakeholders are analyzed at the initiation of, and throughout aquaculture infrastructure expansion, to track if and how stakeholder perceptions change (Budhathoki et al. 2024). Other methods to estimate social carrying capacity include qualitative network modeling (Reum et al. 2015, Ferriss et al. 2022), which can elucidate how social and ecological values are related within an aquaculture system. Modeling efforts to calculate production and ecological carrying capacity ideally should be combined with insights from regulatory and social carrying capacity estimation (e.g., risk and stakeholder analyses) as the resulting outcomes are often more powerful in aquaculture management (Byron et al. 2011).

Marine Spatial Planning for Aquaculture: Approaches and Possibilities.—Marine spatial planning has different considerations, data needs, and planning approaches at varying scales (i.e., farm, local, regional, and national) and the appropriate scale and approach depends on the context of the management issue. We define four hierarchical approaches to MSP for aquaculture that range from

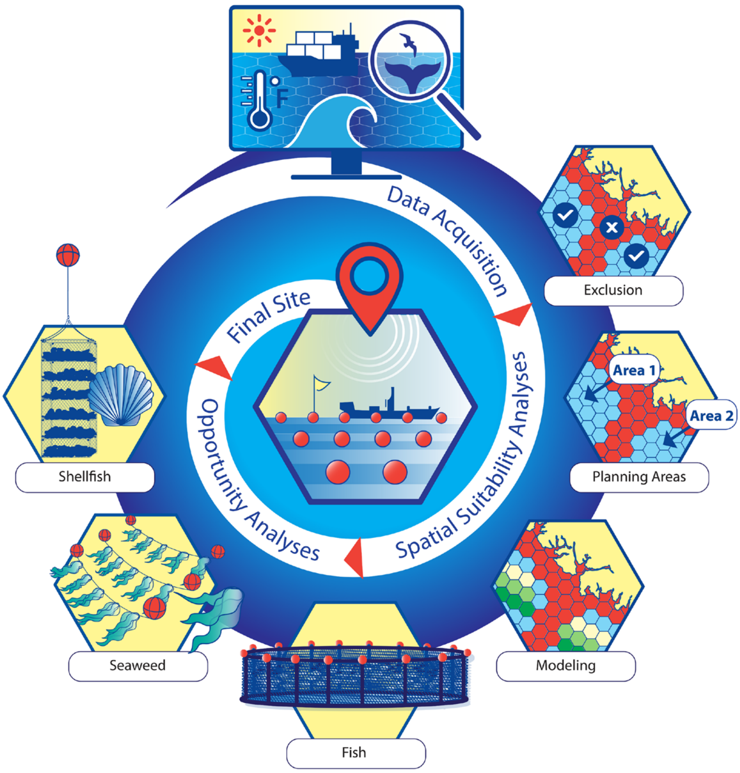

Figure 3. The relationship and interconnectivity of the various analyses from data acquisition through the final site selection. The fish, seaweed, and shellfish panels are not in chronological order as they are three different examples of what one may consider within an opportunity analysis.

ecosystem-scale to site-scale, with each approach requiring varied data requirements and spatial analysis protocols and yielding varied levels of spatial guidance for decision making (Fig. 3). For any ecosystem boundary (hereafter referred to as Area of Interest, or "AOI") the hierarchical process for MSP begins with (1) data acquisition and exclusion analysis to determine areas where aquaculture is potentially suitable, (2) identifying Aquaculture Planning Areas within the AOI, (3) conducting spatial suitability models within the planning areas, and (4) analysis of aquaculture opportunities within the most suitable areas to select final areas for aquaculture. Collectively, these MSP approaches help ensure that aquaculture development meets EAA principles of ensuring ecological resilience, public benefit, and balance with other industry and policy goals.

Spatial Planning Approaches for Marine Aquaculture

1. Data Acquisition and Exclusion Analyses (Scoping).—Defining the AOI in which planning will be conducted is a necessary first step, and this must be completed at the desired spatial, social, and political scales (Aguilar-Manjarrez et al. 2017). This decision (also known as scoping)—at least in the

broader ecosystem context—is usually completed by a panel or coastal manager review group with high-level input from industry and other stakeholder or community groups. Spatial planning within this scoping process generally precedes an exclusion analysis wherein geospatial data (Table 2) associated with major constraining factors (e.g., areas important for national security, shipping lanes, marine protected areas, physical obstructions, etc.) within an AOI are used to exclude areas of known, more absolute conflict from further spatial planning consideration (i.e., binary "yes" or "no" criteria). Constraints are removed from the initial AOI by: (1) removing the occupied or constrained area from the AOI and (2) buffering the occupied areas based on safety considerations if required. Once all areas associated with constraints are removed from the initial AOI, subsequent spatial planning and analyses focus on identification of usable space for aquaculture infrastructure within the remaining AOI. The final usable area can then be assessed for Aquaculture Planning Areas.

2. Aquaculture Planning Areas.—Once the AOI is defined and exclusion analyses are performed, Aquaculture Planning Areas can be responsibly identified within the remaining AOI. Planning area identification requires establishment and analysis of set criteria to define broad areas within which different types of aquaculture may be suitable (Aguilar-Manjarrez et al. 2017). Broadly, planning areas can identify potential areas for aquaculture expansion in new areas and help regulate continued aquaculture development where it already exists. A planning area also implies established legal boundaries for aquaculture, which requires consultation with lawmakers and other stakeholders of interest in defining the planning area. Aquaculture Planning Areas are beneficial for aquaculture site selection to: (1) mitigate and minimize environmental deterioration, (2) provide established areas for estimation of carrying capacities, (3) reduce negative social and environmental interactions, (4) provide coastal managers and regulators with areas to plan for monitoring, (5) increase production and social development, (6) aid implementation of disease risk management, (7) help investors identify prospective sites where long-term investments are possible, and (8) establish clear regulations for activities and behaviors within the zones (Aguilar-Manjarrez et al. 2017). Aquaculture Planning Areas allow for a more efficient and targeted site selection process for all types of aquaculture. The outcomes of identifying planning areas inform the objectives used to shape subsequent spatial suitability models.

3. Spatial Suitability Analyses.—Spatial suitability modeling refers to the spatial overlay and analysis of pertinent geospatial data layers within an AOI to identify and compare areas along a range of continuous suitability (from unsuitable to optimal). This framework allows for identification of suitable potential aquaculture sites based on ecological, administrative, transportation, ocean industry, navigation, among other relevant factors. GIS-based site suitability is one of the most important steps in the MSP process to evaluate potential aquaculture sites (Stelzenmüller et al. 2017). These analyses provide spatially explicit estimations and visualizations of the potential for aquaculture expansion within an AOI. Historically, this approach was used in

Table 2. Example of a data inventory that can be used to define constraining factors within the scoping process for aquaculture.

Constraint Category		Data
Infrastructure Use	Military	Military danger and restricted areas Training areas Operating areas Unexploded ordnance areas Department of Defense sites
	Navigation	Shipping fairways Coastal maintained channels Anchorage areas Lightering zones Aids to navigation
	Industrial	Oil and gas platforms Active lease blocks Significant sediment resources Current and planned dredging activities Ocean disposal sites
Regulatory	Protected Habitats and Species	Essential Fish Habitat Habitat Areas of Particular Concern National Marine Sanctuaries Marine Protected Areas Special designations
	Boundaries and Limits	State waters Federal waters Territorial seas US Exclusive Economic Zone International waters
Biogeochemical and Physical	Geomorphological	Substrate type Hydrocarbon seeps Total organic carbon Sulfides Redox potential
	Biochemical and Oceanographic	Current speed and direction; Significant wave height and wave period Depth Wind speed and direction Water temperature Salinity
	Biological	Distribution of corals, hardbottom, submerged aquatic vegetation, kelp, and other habitat-forming species Artificial reefs Marine mammal densities and migration areas Proximity to seabird nesting colonies Benthic infauna
Socioeconomic	Social and Cultural	Tribal practices and native fishing grounds Perceptions of aquaculture Viewshed impacts Archaeologically sensitive shipwrecks Recreational fishing/subsistence use
	Accessibility	Distance to port Shore-based facilities Skilled workforce Access roads for operations and shipping
	Economic	Capital costs; Insurance cost and availability Cost of labor Cost of farm equipment and maintenance Cost of security Cost of veterinary services and therapeutics

smaller-scale aquaculture planning efforts for in-land, data-rich areas (Nayak et al. 2018, Bandira et al. 2021). In more recent years, as computing power, data availability, and geospatial technologies have advanced, suitability analyses for aquaculture have extended into the offshore environment (Stelzenmüller et al. 2017). High resolution spatial data with the necessary spatial and temporal resolution for offshore planning has taken years of global scientific initiative from many sectors and will continue to be a driver in planning as many data gaps still exist for open ocean areas. GIS-based multicriteria evaluations are a type of suitability analysis where relevant spatial data layers are reclassified according to known relationships between a variable and relative suitability (e.g., reclassification of minimum observed water temperature spatial data based on known species tolerances) and multiple relevant layers are subsequently integrated to generate a final suitability layer. Generally, areas within individual spatial data layers are categorized as not suitable, conditionally or moderately suitable, or highly suitable for aquaculture infrastructure. Multiple layers are subsequently integrated to generate a final suitability layer, such as within a weighted overlay wherein individual layers receive weights based on relative importance and are subsequently summed to generate a single, integrative suitability layer. The layer weights should be a reflection of the objectives of each area of interest. Thus, objectives for a given region need to be evaluated carefully to assign appropriate weights to each layer. This modeling framework aids in identification of optimal, suitable, and unsuitable areas for aquaculture infrastructure development based on all factors considered within the multicriteria evaluation. It is important to recognize some of the limitations of geospatial suitability modeling, especially in areas with limited data and for more complex environmental processes. For instance, rates of change and more nuanced hydrodynamic models may be more difficult to quantify across areas of interest. Thus, comprehensive suitability models need to acknowledge the uncertainty caused by information that is either unavailable or not feasible to incorporate in the model.

4. Opportunity Analysis and Final Site Selection.—Once suitability analyses are performed within the Aquaculture Planning Areas, the extent of optimal, suitable, and unsuitable areas for shellfish, finfish, or algae aquaculture are known. Within these identified areas, subsequent opportunity analyses can determine which species and aquaculture gear combinations are most appropriate for a given location based on known tolerances and thresholds for each combination. Opportunity analyses integrate requirements for aquaculture gear (e.g., substrate, current speed, current direction, significant wave height, depth) and species (e.g., depth, pH, salinity, temperature, current speed, current direction, chlorophyll *a*, dissolved oxygen; Wickliffe et al. 2024). Oceanographic forces such as wave action and currents yield structural stress on aquaculture gear, and maximum stress thresholds for both aquaculture gear and species must be considered within opportunity analyses. These stress thresholds must also scale based on farm size, as hydrodynamic forces will change as the farm structure changes. Furthermore, many species have tolerance thresholds (e.g., maximum/minimum water temperature) above or below which growth and mortality may occur and farm production may decline (Froehlich et al. 2016). While tolerance thresholds

provide reasonable boundaries for a species physiological capacity, other approaches such as dynamic energy budget models may reveal production potential and other metrics that are more nuanced, including for areas where multitrophic opportunities are explored (Sarà et al. 2012, Lavaud et al. 2021). In addition to opportunity analyses, the final site selection process may also include end-user-specific considerations, such as ease of site access by growers or proximity to existing aquaculture infrastructure. All relevant stakeholders (e.g., aquaculture growers, coastal managers) should be engaged throughout the final site selection process.

Conclusions and Recommendations

Marine spatial planning techniques are integral to the planning, siting, and management of sustainable aquaculture industries. Intensive competition for limited ocean space amongst current ocean use sectors demands transparent spatial data analysis approaches and visualizations within a MSP framework to identify compromise, and to find the best fit locations for aquaculture development (Stelzenmüller et al. 2017). Here, we provide multiple MSP approaches of relevance to EAA, ranging from carrying capacity models to hierarchical spatial analysis protocols. Decisions regarding planning should be made at the appropriate scale and use best available data that meet the minimum quality and relevance requirements. Monitoring should be performed on a regular basis to ensure that ecosystem carrying capacity has not been exceeded, and adaptive management should be continually employed to address problems and improve production and efficiency (Froehlich et al. 2021, Fujita et al. 2023).

A spatial plan that uses EAA is wholly robust if it is given the capacity to adapt in light of ecosystem changes. As environmental conditions change (Best et al. 2015), aquaculture plans should consider how all aspects of a farm may respond, including the location, structure, and species. Long-term sustainability of aquaculture can be achieved if planning methods that assess the production stability of a farm to changing conditions are used (Froehlich et al. 2021). As the aquaculture industry innovates, including the development of much larger farms and untethered designs, new challenges with MSP will emerge. Thus, it is prudent for an EAA to include proactive and adaptive marine spatial plans that incorporate scoping for areas where potential emerging technologies are feasible.

It is important during the spatial modeling process to consider the spatial and temporal dynamics of each data layer, especially in areas where there is greater uncertainty. Suitability and opportunity analyses are able to partially account for temporal variation of factors by exploring distributions of values during modeling efforts. Monte Carlo simulations and Bayesian belief networks are both valid ways to explore ranges of relevant environmental and social factors that could be applied to aquaculture suitability (Coccoli et al. 2018). A notable limitation to these dynamic approaches is data availability, which can inform the distribution of input values into the models (Stephenson et al. 2018). In addition, while long-term temporal dynamics models (10+ years) show promise, predictability remains a challenge at higher resolutions that would be of particular interest to aquaculture developers (Chen et al. 2024).

Aquaculture has already become an integrated part of the ocean infrastructure in many regions of the world (e.g. Norway, Chile, China). Currently, the US seafood economy largely relies on imports, and over half is produced from aquaculture (Gephart et al. 2019). As marine and coastal aquaculture operations grow in US waters to meet domestic needs for seafood, it is recognized that more sustainable food production systems require supplemental knowledge about how the ecosystem is already utilized, and how conflicts among stakeholder groups are addressed (Byron and Costa-Pierce 2013, Grebe et al. 2019). A long-term perspective that integrates cultural and economic dimensions is critically important to support realistic growth trajectories (Gentry et al. 2017a,b). With proper planning and resource allocation, the US has the potential to emerge as a world leader in the production of safe and sustainable seafood.

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