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A Social-Ecological System Framework for Marine Aquaculture Research

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Abstract: Aquaculture has been responsible for an impressive growth in the global supply of seafood. As of 2016, more than half of all global seafood production comes from aquaculture. To meet future global seafood demands, there is need and opportunity to expand marine aquaculture production in ways that are both socially and ecologically sustainable. This requires integrating biophysical, social, and engineering sciences. Such interdisciplinary research is difficult due to the complexity and multi-scale aspects of marine aquaculture and inherent challenges researchers face working across disciplines. To this end, we developed a framework based on Elinor Ostrom's social–ecological system framework (SESF) to guide interdisciplinary research on marine aquaculture. We first present the framework and the social–ecological system variables relevant to research on marine aquaculture and then illustrate one application of this framework to interdisciplinary research underway in Maine, the largest producer of marine aquaculture products in the United States. We use the framework to compare oyster aquaculture in two study regions, with a focus on factors influencing the social and biophysical carrying capacity. We conclude that the flexibility provided by the SESF is well suited to inform interdisciplinary research on marine aquaculture, especially comparative, cross-case analysis.

Keywords: marine aquaculture; social-ecological systems; interdisciplinary research; social-ecological system framework; aquaculture; oyster aquaculture

1. Introduction

Aquaculture, or the cultivation of aquatic species, including land-based and open-ocean production, has been responsible for an impressive growth in the supply of global seafood, providing more fish for consumption than capture fisheries since 2014 [1]. The geographic distribution of aquaculture production is uneven, with China accounting for approximately 62% of the global production [1]. To meet future global seafood demands, there is both need and opportunity to expand production in regions both rich and poor outside of China [2,3] As this sector grows, it is imperative that aquaculture be integrated into coastal regions in ways that are both socially and ecologically sustainable.

Marine aquaculture systems represent classic coupled social–ecological systems (SESs) and understanding them calls for integrating biophysical, social, and engineering sciences with stakeholder knowledge [4,5]. Scholars call for a more holistic approach to aquaculture, where the implementation of such systems produce economic, social, and ecological benefit [4–9]. Such an approach should account for ecologically appropriate scale and engineering designs, be economically and socially efficient, and use “farmer first” research and extension methods and a sustainability science toolkit [4,10]. However, SES research is difficult due to the complexity and scope of sustainability problems and the inherent challenges of team science involving multiple disciplines [8,11,12]. A framework providing a common vocabulary can facilitate communication among researchers concerned with SES sustainability [13,14].

Interdisciplinary research frameworks have been developed for analyzing diverse aspects of marine aquaculture covering production technology, socio-economic characteristics, and environmental aspects [15]. A systems approach framework that included ecological, economic, and social interactions has been applied to mussel aquaculture in Italy [16]. An analytical framework to guide context specific, policy-relevant assessments of the social, economic, and ecological dimensions of aquaculture for policy-making underscores the importance of people in aquaculture systems [5]. A number of different modeling tools and approaches have been developed for analyzing complex aspects of aquaculture, e.g., [7,17]. While these frameworks acknowledge the social and biophysical dimensions of marine aquaculture systems, a need remains for a comprehensive framework focused on advancing multi-scale, interdisciplinary research of marine aquaculture as an SES.

Many frameworks have been developed to analyze SESs [18–20]. Of the 10 SES frameworks reviewed by Binder et al. [18], Ostrom’s SES framework [14] (hereafter SESF) is the most general and the only framework that treats social and ecological systems in near equal depth (Figure 1). The SESF conceptualizes the relationship between social and ecological systems as bidirectional, takes an anthropogenic perspective, and is analysis-oriented (i.e., it provides a general language for guiding research) [18]. As such, the SESF is well suited to interdisciplinary, multi-scale research on marine aquaculture.

The SESF builds from scholarly efforts aimed to understand the conditions under which institutions exist for sustainable use of common-pool resources (CPRs) [14,21], and applied to many different kinds of SESs, including marine systems, e.g., [18,20,22,23]. The framework has been used to develop a classification system for small-scale benthic fisheries and lobster fisheries [24,25], and to analyze collective action in pond aquaculture [26] and more complex SESs, such as urban commons and recreational fisheries [27]. In this paper, we use the SESF as a conceptual tool to inform comparative, cross-case, and cross-scale research on marine aquaculture occurring in coastal and offshore regions, excluding land-based systems. Our application of the SESF to marine aquaculture further illustrates its potential utility for analyzing other kinds of systems and resource use settings.

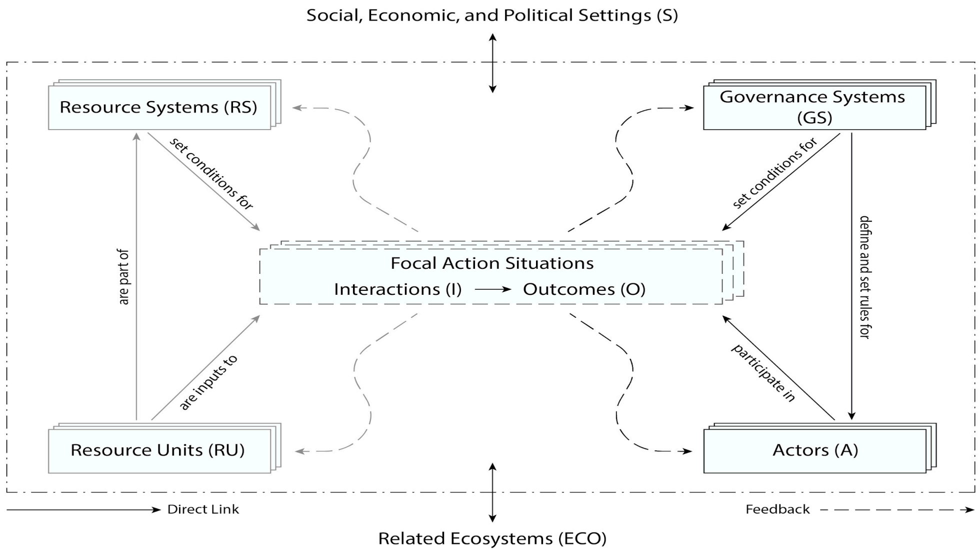


Figure 1. Ostrom's social–ecological systems framework. Adapted from McGinnis and Ostrom [13].

2. Materials and Methods

The setting is marine aquaculture research and development underway in Maine, the largest producer of marine aquaculture products in the United States, through the Sustainable Ecological Aquaculture Network (SEANET), a multi-institutional, interdisciplinary research effort currently underway (2014–2019). Embracing a sustainability science approach, the identification of about 50 research projects involved early consultation with stakeholders and experts. The project consists of 83 researchers spanning the biophysical, social, and engineering disciplines relevant to aquaculture.

Ostrom's SESF was selected to support this large, interdisciplinary study and its modification is presented here as we have applied it to marine aquaculture. The team began with a review of existing variables in Ostrom's SESF [13], considering the extent to which they were meaningful (or not) to understanding sustainability (broadly conceived) in the context of marine aquaculture. We then surveyed all SEANET researchers to inventory data collection efforts and mapped research onto the SESF. Industry stakeholders who informed the selection of research projects provided key insights on SES variables and SEANET researchers identified additional variables from their disciplinary perspective and knowledge of the SES. Identified variables were pooled together into a draft framework. We reviewed the variables identified in the draft framework, considered appropriate metrics, and identified gaps and new variables. Throughout the process, we consulted the literature for theoretical and empirical support for selected variables. Thus, the final selection of framework variables (Tables 1 and 2) drew from the rich and diverse expertise across the project, following an iterative process of consultation with experts and stakeholders and a literature review.

Our intent is not that all variables must be analyzed in a single analysis. Instead, researchers can use the framework as a checklist or diagnostic tool to select the variables most relevant to their specific SES investigation. The selection of variables will be dependent on the specific study context, scale, and research questions examined, as is consistent with other uses of the SESF [25]. The framework further provides a tool to facilitate and guide discussion among researchers with expertise related to different aspects of the system, and these conversations can lead to new, interdisciplinary research inquiries. One way this occurs, for example, is through discussions about the meaning, importance, and connections among the SES variables. Although we view the framework as comprehensive, it is our expectation that other researchers applying it to other marine aquaculture systems would add or modify the variables, which again is consistent with how the framework has been used by others, e.g., [26].

SEANET researchers used the framework to identify new interdisciplinary research questions and hypotheses for investigation focused around the topics of carrying capacity, siting, efficiency, and resilience of marine aquaculture. Section 3.2 illustrates one application of this framework to oyster aquaculture in Maine with investigation of the SES factors influencing the social and biophysical carrying capacity in two study regions, Damariscotta River and Bagaduce River estuaries (Figure 2).

This comparative analysis draws on existing biophysical (water quality buoy monitoring network; maine.loboviz.com) and socioeconomic data sources (e.g., US Census/American Community Survey), publicly available aquaculture lease data from the Maine Department of Marine Resources, and SEANET generated oceanographic and social science research findings, including published studies. Biophysical variables were obtained from SEANET Land-Ocean Biogeochemical Observatories (LOBO) deployments in 2017 in the Damariscotta and Bagaduce River estuaries. Each buoy is equipped with an array of sensors that monitor physical and biogeochemical properties on an hourly basis (e.g., photosynthetically active radiation (PAR), nitrate, chromophoric dissolved organic matter (CDOM), salinity, chlorophyll-α, temperature, pH, dissolved oxygen (DO), turbidity, and current speed and direction). We summarized monthly averages for the 2017 season for chlorophyll-a and temperature in the two estuaries (Figures 4a and b). To measure the biophysical carrying capacity of the oyster aquaculture in each estuary, we used a weighted regression approach for determining the suitability of the habitat for oyster aquaculture. This model is heavily weighted toward the effects of temperature because oysters are at the northern extent of their range in Maine. To provide a measure of the social carrying capacity, SEANET social scientists analyzed aquaculture lease hearings to quantify and understand conflicts in each region and conducted key informant interviews to provide additional context on the history and context of aquaculture development in these two areas.

3. Results

3.1. The SES Framework Applied to Marine Aquaculture

This section presents the key variables of the nested, multi-scale framework identified as significant to marine aquaculture. A key element of the SESF is the focal system, composed of four subsystems (Figure 1): The resource system (RS); resource units (RU); governance system (GS); and actors (A). This focal system affects and is affected by two sets of broader, exogenous factors that make up the social, economic, and political setting (S) and the related ecosystems (ECO). The focal action situation represents the interactions (I) between actors in the focal system and their outcomes (O), with feedbacks to other parts of the system. Identifying the scale of the focal system is key to the nested, multi-scale aspects of the framework and the analyses it enables. We decompose these eight system components into second-tier variables that represent their key characteristics and illustrate why they are important to research on marine aquaculture (Tables 1 and 2).

Table 1. The social-ecological system framework applied to marine aquaculture. Four subsystems make up the focal system: The resource system, resource units, actors, and the governance system.

Resource System (RS)	**Actors (A)**
RS1—Resource Sector: Marine Aquaculture	A1—Number of relevant actors
RS2—Clarity of system boundaries	A2—Socioeconomic attributes
RS3—Size of resource system	A3—History or past experiences (of actors)
RS4—Human constructed facilities	A4—Location in relation to resource & market
RS5—Productivity	A5—Leadership/entrepreneurship
RS5.1 Stock status	A6—Norms/Social capital
RS5.2 Biophysical factors	A6.1 Trust and reciprocity
RS6—Predictability of the system	A7—Knowledge of SES/mental models
RS7—Connectivity	A8—Importance of resource
RS8—Location	A8.1—Economic importance of resource
	A8.2—Cultural importance of resource
	A9—Characteristics of the technologies used

Resource Units (RU)	**Governance Systems (GS)**
RU1—Mobility of the resource units	GS1—Policy area
RU2—Growth or replacement rate of RUs	GS2—Geographic range
RU3—Interaction among resource units	GS3—Size of Population
RU4—Economic value of the resource	GS4—Regime type
RU5—Number or size of units produced	GS5—Organizations
RU6—Distinctive characteristics	GS5.1 Government organizations
RU7—Spatial and temporal distribution	GS5.2 Non-government organizations
	GS6—Rules-in-use
	GS6.1 Operational rules
	GS6.2 Collective choice rules
	GS6.3 Constitutional Rules
	GS7—Property rights
	GS8—Norms and strategies
	GS9—Network structure
	GS10—Historical continuity

3.1.1. Four Subsystems: Resource System, Resource Units, Actors, and the Governance System

For the marine aquaculture context, the resource system (RS) includes the coastal waters in which farms are situated, including the intertidal, subtidal, and offshore ocean regions, depending on the kind of cultured species. The resource sector (RS1), marine aquaculture, could be interpreted more specifically (e.g., oyster aquaculture), depending on the study. The clarity of system boundaries (RS2) indicates a potential level of ambiguity about where the RS begins and ends, which influences actors' abilities to evaluate positive and negative externalities associated with aquaculture farms. The size of the RS (RS3) refers to the total available area within the RS appropriate for aquaculture, or its physical carrying capacity [28]. Human constructed facilities (RS4) located within the RS refer to the built infrastructure enabling production (e.g., fish pens, oyster cages, lines). The productivity of the system (RS5) refers to the amount of organic matter generated within the RS that cultured species need for growth. Sea vegetable aquaculture will be limited by some of the same factors that control planktonic production, including nutrient and light availability. The productivity of the RS has little influence on finfish aquaculture since fish grown in pens are supplied with feed, illustrating important differences to consider when comparing different marine aquaculture sectors. In wild capture seafood production, the productivity of the RS is determined by the stock status of the wild population (RS5.1), but this is rare for aquaculture species. An exception is aquaculture requiring seed supply from wild populations, such as scallops [29,30] and tuna ranching [31]. Key biophysical factors (RS5.2) that influence productivity include water temperature, salinity, grazing, transport processes, and water quality [32,33]. RS predictability (RS6) refers to the degree of environmental variability impacting aquaculture production, including stochasticity or uncertainty of driving forces, which could include disturbance events, e.g., harmful algal blooms [34]. RS connectivity (RS7) captures the flow of water between farms and growing areas, and the resulting transport of genes, waste, food, and disease. In near shore systems, growing areas can be linked by tidal processes, estuarine circulation, and wind [35]. Increasingly, farmers use hydrodynamic models that account for these processes to minimize connection between farms [36,37]. Location (RS8) refers to the spatial and temporal placement of the species grown by actors (A). Siting aquaculture farms is typically influenced by rules set out by the governance system (GS), the productivity of the RS itself (RS5), conflicts among actors, and infrastructure support [38]. Effective utilization of productive sites has implications for the number of resource units that can be grown (RU5), time to market (RU2), and conflicts among actors (I4).

In the type of SES examined here, we recognize that depending on the question or sustainability challenge and the scale at which it is examined, the resource units (RU) could be interpreted in different ways [27]. The resource units (RU) could refer to the products (i.e., shellfish, sea vegetables, or finfish) grown on farms. Each type of aquaculture species should be considered separately in light of distinct grow-out methods, gear used, and nutrients/feed requirements for production. Since farmers have reasonably secure lease rights over their farm, they do not experience the exclusion or subtractability problems associated with other CPRs. If the RU is viewed as the physical space used by the farmers to grow aquaculture species, marine aquaculture does pose a classic CPR problem associated with needing to control access to the resource (i.e., the exclusion problem) and confront the physical limits of the common area to support unconstrained growth (i.e., the subtractability problem). Similarly, the RU could be considered the stock of ecosystem services provided by the resource system. A farm can consume a disproportionate amount of available primary production and/or otherwise reduce water quality in ways that reduce the provision of other ecosystem services; in this way, the RU is subtractable. Bivalve and seaweed aquaculture can improve water quality, effectively increasing the stock of RU [39,40]. In our attempt to make this framework flexible and applicable to different situations, we include diverse attributes of RUs, with the caveat that not all will be applicable for all analyses and/or some may require alternative interpretations depending on the research question and how the RU is characterized.

The mobility of aquaculture resource units (RU1) in most cases will be minimal. In contrast to wild fisheries, aquaculture RUs grown and maintained on ropes or in bags, cages, or pens allow for little mobility. Bottom planted species (e.g., mussels and oysters) also exhibit little mobility. In some cases, however, RUs are manually moved within or between sites, for example, to accommodate different life stages, over-wintering, or depuration sites [41]. Operations that collect wild spat or seed avoid dependence on hatcheries, but rely on the transport of larvae by coastal currents from sites to growing areas [42]. Escape from pens is a major concern for finfish aquaculture [43,44]. Restoration aquaculture, or fishery enhancement, where RUs are grown and then released into the wild, is another special case in which RU mobility is relevant [45,46]. The growth or replacement rate of resource units (RU2) refers to the absolute or relative changes in quantities of aquaculture units over time and is influenced by the system's productivity (RS5). Interactions between RU life stages (RU3) are typically minimal due to artificial separation on farms or through the use of hatcheries. An exception is integrated multi-trophic aquaculture, where the farmer deliberately manipulates the relationship between different kinds of RUs to improve production outcomes [47]. The potential economic value of the RUs (RU4) and the number or size of RUs produced (RU5) (i.e., the production carrying capacity [48]), influence actor decisions, local and non-local investment, and ultimately the system's economic efficiency [49]. Distinctive characteristics (RU6) of the RU can influence actors' behavior, and include aspects like texture, appearance, smell, branding, packaging, labeling, and the overall terroir of the RU. The spatial and temporal distribution of the RUs (RU7) refers to distribution patterns of RUs across an area in a particular time period. For aquaculture, this refers to the placement and distribution of cages, bags, or lines as aggregates of RUs, with different marine aquaculture sectors exhibiting different distribution requirements based on size and species' suitability.

Important actors (A) in the focal system that influence marine aquaculture are the farmers and others utilizing the RS, primarily riparian landowners, local residents, and commercial seafood harvesters. Actors can be collective entities, but in most cases, specific individuals act as agents on behalf of those entities (13). The number of relevant actors (A1), their socioeconomic attributes (A2), and their history or past experience (A3) with aquaculture have implications for siting aquaculture farms [50] and for general perceptions of the role aquaculture plays in a community [51,52]. The location of actors (A4) in relation to the resource can influence conflicts [50]. Local leadership (A5) can play an important role in spurring innovation and the growth of new industries, including aquaculture [53]. Norms and social capital (A6), including trust and reciprocity (A6.1), are important variables that influence the success of an aquaculture operation [26]. Knowledge of the SES (A7), including the environmental conditions influencing the growth and health of the target species, is critical to sustainable aquaculture [26,54]. This knowledge is often specialized, even hyper-localized since farm siting is made on the scale of a few acres. The importance of the resource to the actors (A8), or their economic (A8.1) and cultural (A8.2) dependence, can influence the resilience of the actors facing environmental and social change [54]. The historic and cultural role aquaculture has played in a community is often acknowledged as important in balanced support of the industry, although jobs at the expense of environmental quality is not desirable [55]. The characteristics of the technology used (A9) have implications for multiple components of the SES, e.g., social acceptance, growth rate of the RUs, and labor requirements [26,56].

The governance system (GS) includes both formal and informal institutions that drive actor behavior in the SES. The policy arena (GS1) consists of the rule systems tailored for a particular area of knowledge, geography, or time, which is analogous to the resource sector variable (RS1). For example, the resource sector and policy arena of focus might be shellfish, finfish, or sea vegetable aquaculture. Scale is an inherent characteristic of nested SESs, and the framework includes two kinds of scale deserving attention: The geographic range of the governance rules (GS2) and the size of the population (GS3) on which the rule system has jurisdiction [13,57,58]. The governance regime type (GS4) refers to the logic upon which the broad GS is organized, i.e., whether it is democratic or autocratic, and this can influence how aquaculture develops and what, if any, decision-making processes will be instituted [4,59]. Different types of organizations (GS5) play significant roles in aquaculture development trajectories, such as by providing funding, knowledge, and expertise, technical support, education, developing community networks, lobbying, and conservation and environmental monitoring [59]. These include both government organizations (GS5.1) and non-government organizations (NGOs) (GS5.2) that operate at multiple scales, underscoring the importance of considering scale. NGOs include for-profit, non-profit, community-focused, and science organizations. Rules in use (GS6) are the formal and informal rules guiding human behavior and social interactions, and include, operational rules (GS6.1), collective choice rules (GS6.2), and constitutional rules (GS6.3). Property rights (GS7) define particular relations among people and things [60]. As property rights are formed and strengthened around aquaculture, farmers have greater control and are expected to establish a longer-term perspective of the system [61]. However, significant debate arises regarding property rights and ownership of the marine commons related to aquaculture [59]. Norms and strategies (GS8) drive social interactions without formal sanctioning. The network structure (GS9) refers to the connections among the rule-making organizations and the population subject to these rules. Historical continuity (GS10) refers to how long a GS has been in place, including whether it exhibits entrenchment or flexibility.

Table 2. The social-ecological system framework applied to marine aquaculture: External exogenous influences include the social, economic, and political context and related ecosystems. The focal action situation includes interaction and outcomes.

Exogenous Influences	Focal Action Situation
Social, Economic, and Political Setting (S)	**Interactions (I)**
S1—Economic development trends	I1—Farming (Harvesting)
S2—Demographic trends	I2—Information sharing
S2.1 Urbanization	I3—Deliberative processes
S2.2 Gentrification	I4—Conflicts between/among actors
S3—Political stability	I5—Investment activities
S4—Non-local govt. org mandates	I6—Lobbying activities
S5—Markets	I7—Self-organizing activities
S5.1 Demand	I8—Networking activities
S5.2 Suppliers of industry inputs	I9—Monitoring and sanctioning activities
S6—Media	I10—Evaluation activities
S7—Technology available	
S8—Perceptions of other marine users	
Related Ecosystems (ECO)	**Outcomes (O)**
ECO1—Climate patterns	O1—Social performance measures
ECO1.1 Ocean acidification	O1.1.1 Economic carrying capacity
ECO2—Pollution Patterns	O1.2 Social resilience
ECO3—Flows into/out of focal system	O1.3 Efficiency
	O1.3.1 Technical efficiency
	O1.3.2 Economic efficiency
	O1.3.3 Social efficiency
	O2—Ecological performance measures
	O2.1 Ecological carrying capacity
	O2.2 Ecological resilience
	O3—Externalities to other SESs

3.1.2. Exogenous Influences: The Social, Political, and Economic Setting and Related Ecosystems

The social, political, and economic setting (S) represents the exogenous, socially relevant influences that can affect any component of the focal SES. Components of the social, economic, and political setting are dynamic, and they shape actor decision-making and behavior within the SES. Most SES researchers have not explicitly incorporated the social, political, and economic settings through case studies or data analysis [62]. Instead, researchers address these briefly in the introduction, background, or case descriptions [26]. Marine aquaculture development is often driven by regional, national, and global economic trends (S1), including declines in wild capture fisheries [1,52]. Shifts in regional demographics (S2) can influence local aquaculture decision-making, and we add to the framework urbanization (S2.1) and gentrification (S2.2) as key demographic changes that have been observed to influence the acceptance of aquaculture [50,51,63]. Non-local governmental organization mandates (S4) prescribing specific management actions (e.g., national public health and sanitation requirements) can be significant, as well as the global role of environmental NGOs in driving public awareness and action about aquaculture through organized education and political campaigns [64]. Changes in political stability (S3), such as new policies that alter traditional property rights, can create tensions across actors [65]. Markets (S5), including the availability of global and niche markets, influence the investment and expansion of marine aquaculture. More specifically, we added to the framework demand (S5.1), including the availability of consumers, buyers, dealers, and processors of resource units, as a key variable influencing farmer behavior and choice of technology [66,67]. Suppliers of industry inputs (S5.2), including the availability of non-local capital and labor, were added to the framework given their importance to economic sustainability [68]. News media (S6) recount specific frames that can influence social understanding and acceptance of aquaculture [69]. Technologies available (S7) to aquaculture farmers can influence their willingness to invest [70] and can drive the formation of rules regarding development in an area [50]. The perceptions of other marine users (S8) variable, including public perception, was added to account for actors outside the focal SES whose opinions about the relative risks and benefits of aquaculture may influence farmer practices and decision-making [71]. While the public may recognize local economic contributions of aquaculture, they sometimes question its impacts on the environment related to pollution and the depletion of wild stocks [72,73].

The related ecosystems (ECO) component of the framework represents the exogenous environmental influences that can affect any component of the focal SES. Climate patterns (ECO1) have important implications for marine aquaculture sustainability, particularly extensive or non-fed aquaculture systems [74,75]. We identified ocean acidification (ECO1.1) as a significant threat to shellfish farms [75]. Ocean acidification can change which species are viable in certain locations, based on their life history [76]. Low pH can affect metabolism, development, growth, mineralization, and membrane/ion homeostasis in invertebrates [75]. Increased precipitation and freshwater runoff resulting from warming waters reduces salinity in growing areas and this can contribute further to acidification [77]. Relevant pollution patterns (ECO2) impacting marine aquaculture include nutrient loading from point and nonpoint sources, which can cause eutrophication [78]. In turn, eutrophication can cause or enhance hypoxia and toxic harmful algal blooms. Heavy metals, PCBs, and other refractory and bioaccumulating inorganic compounds are also of concern for aquaculture [79,80]. Notable flows into/out of the focal SES (ECO3) relevant to marine aquaculture include disease [81], invasive species [82], biofouling organisms [83], escapement [84], and feed [85,86].

3.1.3. Focal Action Situation: Interactions and Outcomes

The focal action situation involves multiple actors whose interactions lead to particular outcomes. Farming (I1), i.e., the addition of farmed species into the ocean (or movement from wild to farmed locations), their husbandry, and subsequent harvest, is perhaps the most critical interaction in the system. Farmers often share information (I2) about their farms with landowners and residents, fishers, and government officials through mandatory public hearings [50]. Technology transfer and extension can promote the expansion of aquaculture and improve farmers' efficiency (O1.3) [87]. Deliberative processes (I3) among actors or between different groups of actors, such as those occurring at public hearings or marine spatial planning efforts [88], allow farmers, government officials, and other stakeholders to discuss and mitigate potential impacts [50]. Conflicts (I4) occurring between actors, including among farmers or between farmers and other stakeholders, can influence social carrying capacity [89]. Investment (I5) in aquaculture, by public or private entities can dictate the success of an industry [90]. Lobbying activities (I6) by specific actors or groups can influence outcomes, such as when residents demand local ordinances that restrict certain activities [91]. Self-organization (I7), e.g., farmers who organize into cooperatives or associations, can be effective for achieving mutually beneficial outcomes [92]. Networking activities (I8) among or between farmers and other stakeholders can aid knowledge transfer and social acceptance. Monitoring and sanctioning activities (I9) related to potential social–ecological impacts and for regulation compliance is another important activity that can impact acceptance [93,94]. Similarly, evaluative activities (I10) of the outcomes allow for the capture of feedback in relation to the environment and other components of the system [73], e.g., when government organizations review farms for lease renewal [95].

Outcomes (O) emerging from these interactions identified by Ostrom and others [14] include social performance measures (O1—efficiency, equity, and accountability), ecological performance measures (O2—overharvested, resilience, diversity), and externalities to other SESs (O3). We applied these specifically to marine aquaculture, focusing on four concepts: Carrying capacity, resilience, efficiency, and externalities.

The traditional definition of carrying capacity has been expanded into different types of carrying capacity for application to marine aquaculture [28,48]. Ecological carrying capacity (O2.1) refers to the level of farm development that causes unacceptable ecological impact. We use this as an ecological performance measure (O2), recognizing it as a social construct since society ultimately decides what is “acceptable” [96]. Following others [48], we analytically distinguish ecological carrying capacity from social carrying capacity (described below), placing a focus on the changes to ecological processes that can be measured as defining significant change, or rather the yield that can be produced without significant impact to ecological processes, species, populations, and communities found within the focal resource system. This can be quantified through a modeling framework using lower trophic level models (e.g., [97] or complete food web models, e.g., [17,96]. In practice, implementation approaches that integrate social and ecological carrying capacity would be ideal [98].

The social carrying capacity, a social performance measure (O1), refers to the biomass or space of aquaculture that the community is willing to allow. Methods for evaluating the social carrying capacity of aquaculture are still being developed [99], but it is typically inferred from measures of social acceptance and conflicts via focus groups, surveys, and interviews [48,51,56,63]. Economic carrying capacity (O1.1.1) refers to the biomass that farmers are willing to establish and maintain [48]. Prospective farmers are expected to investigate the limits of aquaculture in a place, although prediction is difficult and there are significant incentives for farmers to overestimate potential when seeking investments and subsidies [48]. Like ecological carrying capacity, social carrying capacity is dynamic and will change as a result of internal and external SES influences, e.g., climate change and invasive species, new knowledge of environmental impacts gained through monitoring over time, technological changes that reduce environmental impacts or increase production, and broader economic forces that influence the gate price of the product that lie external to the farming location (e.g., regional and global markets, transportation costs, and trade policies).

Ecosystem resilience (O2.2) refers to the capacity of the ecological system to continue functioning in the face of shocks or a disturbance [100,101]. The resilience of marine ecosystems typically derives from characteristics, such as the variety of genotypes and species, the availability of nutrients, or the level of pollution. Multi-trophic aquaculture practice represents an innovation that can positively influence ecological resilience as macroalgae have the ability to take up and remove dissolved inorganic nutrients from bivalve or finfish aquaculture, in effect reducing the probability of eutrophication [102]. Similarly, co-locating macroalgae production with bivalves has the potential to locally mitigate the negative aspects of coastal acidification on growth rates of calciferous species, given that marine vegetation utilizes carbon, acts as a CO_2 sink, and therefore can contribute to carbon sequestration if eventually harvested [103]. Selectively breeding bivalves for higher resistance to diseases is another example of how aquaculture can contribute to ecological resilience [104,105]. A production system can depend on internal transport of nutrients, food, and waste for bivalve or macroalgae production, although anthropogenic inputs can be fundamental in determining the overall structure, function, and outputs from production systems [37,106]. Thus, depending on its configuration, marine aquaculture can reduce or enhance ecosystem resilience [107].

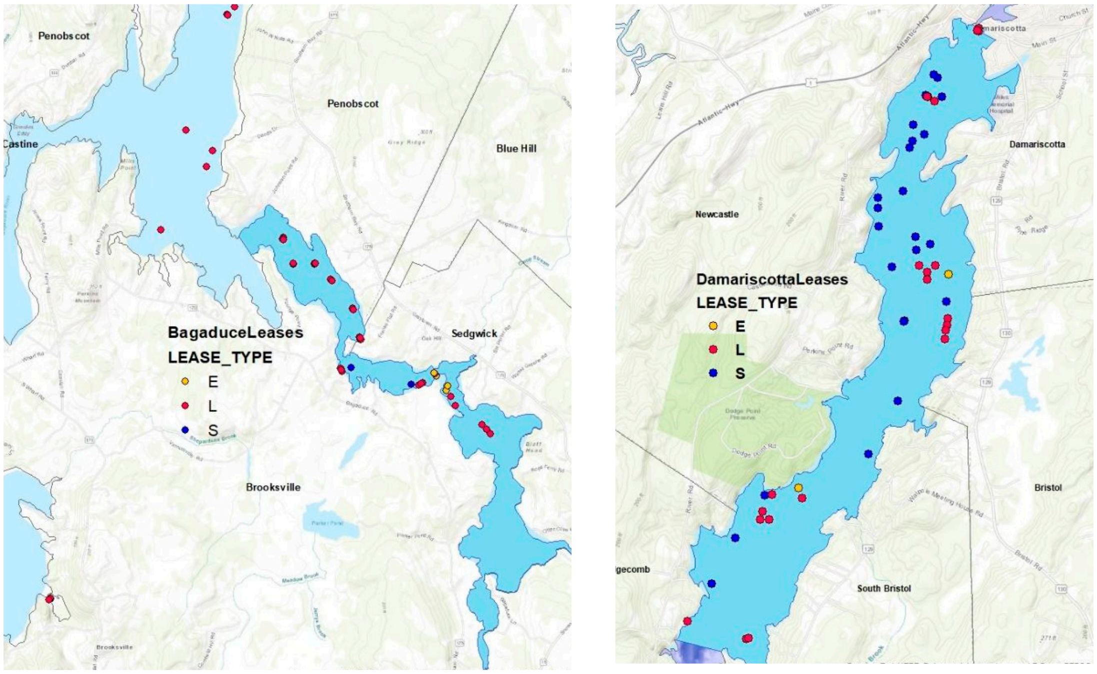
The concept of resilience has been applied to social systems, albeit with some notable limitations, caveats, and discomforts [108,109]. Social resilience (O1.2) is defined broadly as the ability of individuals or groups of people to respond to external threats or change [108]. In the context of marine aquaculture, this refers to actors’ ability to deal with both social (e.g., changing markets, community demographics, etc.) and ecological changes (e.g., ocean acidification, invasive species, disease, etc.). Vulnerability, resource dependence, and factors enabling collective institutional responses are all important aspects of social resilience [108]. We suggest that responses of actors to generic yet anticipated changes in marine aquaculture will be similar to those important in other SESs, and will be influenced by the perception of risk associated with the change; perception of the ability to plan, learn, and reorganize; perception of the ability to cope; and level of interest in change [110]. Marine aquaculture can make wild fish harvesters more resilient, e.g., [87]. Farmers and aquaculture industries with a diversified aquaculture portfolio and/or additional non-aquaculture-based income may enhance SES resilience, as long as alternative employment is not equally vulnerable to the same threats as aquaculture. Similarly, aquaculture can enhance social resilience if it reduces pressures or impacts on threatened coastal resources, but it can reduce social resilience when it impacts local ecosystems [111].

Another important social performance measure in the context of marine aquaculture is efficiency (O1.3), e.g., [112]. Economists identify three types of efficiency as important—technical, economic, and social [113]. Technical efficiency (TE) (O1.3.1) relates the amount of output produced given levels of inputs (e.g., feed, labor, seed) and technology (e.g., bottom-growing of oysters versus surface cages) used in production [114]. The goal is usually to maximize TE. Economic efficiency (EE) (O1.3.2) relates the amount of total revenues generated by the output minus the total costs of inputs generating that level of output [113]. The goal is to maximize net revenues. In most cases, maximizing TE will not maximize net revenues. TE and EE only consider the farmer's benefits and costs; however, there are benefits and costs for other actors in the SES. Social efficiency (O1.3.3) takes into account the costs and benefits of an action to the entire society. Two special conditions prevent social efficiency: 1) When social costs are different than private costs (negative externality) and 2) when social benefits are different than private benefits (positive externality). Some coastal property owners dislike having farms nearby that impact their waterfront view or recreational activities [50]; this is a negative externality to property owners because they are not compensated by the farmer for degrading their home experience. An example of a positive externality is that an oyster farm in an area of poor water quality (eutrophied) may filter excess nutrients and organic matter, and this cleaner water would benefit swimmers via improved water clarity or fisheries due to improved dissolved oxygen conditions [115]; this is an external benefit to swimmers or fishers since they are not asked to compensate the farmer for improving water quality. The problem is the incentives in the market (S5), set by the governance system (GS), do not internalize all costs or benefits in the decision-making process.

Other important outcomes are externalities to other SESs (O3) outside the focal system. In marine aquaculture systems, we interpret this as those flows that have potential impacts outside the focal system, such as fish escapements, debris from lost aquaculture gear, disease, or pollution, that go beyond the focal system. Externalities are impacted by the size (employment) and spatial concentration of the regional industry [116]. Such outcomes can then further influence aspects of the social, economic, and political setting, including perceptions of other users and media [55,59,117].

3.2. Application: Marine Aquaculture in Maine (USA)

SEANET used the framework described above (summarized in Tables 1 and 2) as a checklist for researchers when developing hypotheses for investigation related to marine aquaculture. To illustrate one use of the SESF, we used it to diagnose SES factors influencing the social and biophysical carrying capacity in two aquaculture study regions: The Damariscotta River and Bagaduce River estuaries (Table 3, Figure 2). The resource sector (RS1) is oyster aquaculture and the resource unit (RU) grown and harvested (I1) in both estuaries is *Crassostrea virginica* (eastern oyster; hereafter referred to as oyster).



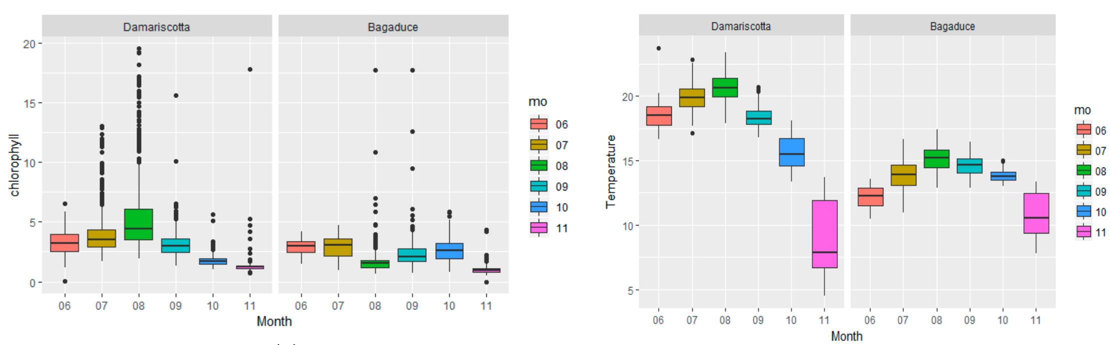
(**a**) (**b**)

Figure 2. Locations of standard leases (blue), limited purpose aquaculture licenses (red), and experimental leases (yellow) within each study region: (a) Bagaduce Estuary; (b) Damariscotta Estuary.

Oysters (RU) are generally at the northern end of their range in Maine and therefore, farmers seek areas of relatively high temperatures to site farms [118]. The Damariscotta and Bagaduce River estuaries are similar in surface area (RS3) and both have geological or manmade features (e.g., culverts) that increase the residence time and create heterogeneous temperature conditions that farmers use to their advantage. Chlorophyll-a, which can be viewed as a general indicator of the potential food source for oysters (RS5), is generally higher in the Damariscotta compared to the Bagaduce (Figure 3). A comparison of a key biophysical variable (RS5.2) indicates that water temperatures in the upper Damariscotta are on average 1 to 2° C warmer than the upper reaches of the Bagaduce River estuary, which is about 83 km north of the Damariscotta (Figure 3). Because temperature strongly controls the time to market for oysters in Maine (i.e., oysters reach harvestable size within three years), only a limited area of these estuaries is economically viable. Therefore, the physical carrying capacity (RS3) is defined as the total area encompassing the locations (RS8) with temperatures optimal for oyster production, with Damariscotta having a higher physical carrying capacity (7.2 km^2) compared to the Bagaduce region (4.3 km^2).

Table 3. Comparison of select social-ecological system variables for two marine aquaculture regions.

System Component	Variable Name	Variable Metric	Damariscotta	Bagaduce
Resource System				
RS1	Resource Sector	Oyster aquaculture		
RS3	Size of RS/Physical carrying capacity	Area within RS optimal for oyster aquaculture	Higher 7.2 sq km^2	Lower 4.3 sq km^2
RS5	Productivity	Chlorophyll levels	Higher m(3.1) med(2.7)	Lower m(2.2), med(1.9)
RS5.2	Biophysical factors	Water Temperature	Warmer M(16.9) med(18.3)	Cooler M(15.6), med(15.8)
Actors				
A1	# of Actors	# Standard Leases # of LPAs Population	30 49 12,977	2 45 7820
A3	Actor history	# Years experience with aquaculture	<40 Years	<10 Years
Governance System				
GS1	Policy Arena	Oyster Aquaculture		
GS5.2	NGOs	Nature of NGOs involvement in aquaculture	Supportive NGOs impacting discourse	Opposing NGOs impacting discourse
Social, Economic, and Political Setting				
S2.2	Gentrification	Metrics from US Census (Hanes, 2018; Johnson & Hanes, 2018)	Similarly gentrified	Similarly gentrified
Interactions				
I1	Farming	Standard Lease Area LPA Lease Area	More farming 177.83 .49	Less farming 9.5 .45
I4	Conflicts	Level of conflicts at lease hearings (Hanes 2018)	Low	High
Outcomes				
O1.1	Social carrying capacity	Inferred from conflicts and development patterns	Not yet exceeded	At or exceeded



(**a**) (**b**)

Figure 3. Monthly trends for each aquaculture region based on the 2017 observing program: (a) Chlorophyll; (b) temperature.

The policy arena (GS1) for oyster aquaculture (RS1) is the same for both sites, with rules and regulations governing aquaculture (GS6) imposed by the Maine Department of Marine Resources. The state level government organization (GS5.1) recognizes three different aquaculture lease types that establish provisional property rights (GS7): Limited purpose aquaculture (LPA) licenses;

standard leases, and experimental leases. Here, we briefly describe the two most common lease types. LPAs were instituted to facilitate small scale aquaculture operations without requiring a major investment; an LPA license can cover up to 37.16 m^2 of culture equipment and costs $50 USD for a year for the culture of certain shellfish species and marine algae using certain types of gear. Standard Leases can be up to 404,686 m^2 and can be held for up to 20 years, and they require a $1500 USD application fee for shellfish production plus $100 USD per-acre annual rent. Standard leases require public meetings where actors can share information (I2), deliberate on decisions (I3), self-organize (I7), or network (I8). Interviews and observations reveal conflicts (I4) in the Bagaduce region that often involve vocal NGOs (GS5.2) opposing aquaculture, while NGOs in the Damariscotta are reported to be more supportive of the industry [50]. With regards to the GS, a key difference between the two regions is a university research center (GS5.2) with a strong cooperative extension component (I2) that has been present in the Damariscotta region since the first aquaculture lease in the state was granted there in the 1970s. For decades, this organization has had extensive collaborations with other local NGOs (GS5.2). In contrast, without a pre-existing NGO in the region, Bagaduce citizens opposing aquaculture organized the Bagaduce Watershed Association (GS5.2) in response to the first aquaculture lease proposed there in 1999.

Given the comparison of the physical carrying capacity and standard lease density (1.25 vs. .45 leases/ km^2 in the Damariscotta and Bagaduce, respectively), the Bagaduce appears underutilized for oyster aquaculture. The application activity for LPA licenses between the two sites has been similar in number, but the temporal distribution of the LPAs is quite different (Figure 4). The temporal pattern in LPA licenses shows a generally steady increase in the LPAs in the Damariscotta since 2004 (the introductory year for LPAs). LPA license activity in the Bagaduce shows a later start and a generally steady increase through 2014 followed by no new leases since 2015. Because productive aquaculture locations remain in the Bagaduce, we speculate that this system may have reached its social carrying capacity (O1.1) before its physical carrying capacity (RS3). An analysis of lease hearings indicates a difference in the conflicts between different actor groups (I4) in the two estuaries, with the Bagaduce region exhibiting more conflict than Damariscotta [50,63]. This supports our finding that the social carrying capacity may be lower in the Bagaduce compared to the Damariscotta.

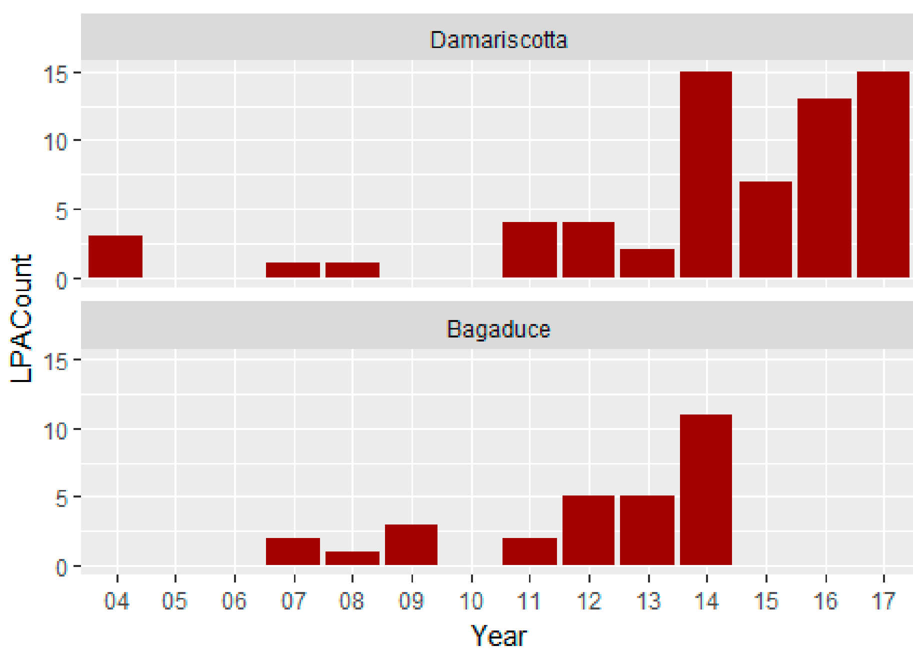


Figure 4. Temporal pattern in limited purpose aquaculture licenses. Data source: Maine Department of Marine Resources.

The social, political, and economic setting (S) of the two sites shows some distinct differences and shifts in demographics (S2), which influence perceptions and acceptance of aquaculture. The American Community Survey five-year estimates for 2005–2010 and 2011–2016 were assembled for the towns abutting the Damariscotta and Bagaduce Rivers. These include five towns surrounding the Bagaduce River and seven towns surrounding the Damariscotta River. In the Damariscotta region, the population is generally aging, showing a 5% increase in the population over 65. The Bagaduce region shows a mixed trend, with one town showing a sizable drop in the population over 65 blended with otherwise small increases in the population over 65 for a slight 10 year decrease in the percent of the population over 65. Both regions show an increase in median income. However, gentrification (S2.2) indicators are relatively similar in these two regions, suggesting that it is not necessarily the demographic trends alone that explain the differences observed in the social carrying capacity [63]. Researchers further hypothesize that the differential social carrying capacity between the two areas may be due to differences in history (A3), actor deliberations (I3), and networking (I8), and the economic and cultural importance of aquaculture (A8), with research underway exploring these additional variables. Given that aquaculture and opposition in the Bagaduce are relatively recent (A3), information sharing (I2), deliberations (I3), and trust (A6.1) remain to be developed.

Our preliminary analysis indicates: (1) There is variation in the social and physical carrying capacity of aquaculture—both higher in the Damariscotta region. (2) Gentrification does not always reduce social carrying capacity. SEANET research on these and four other estuaries in Maine is using the SESF to examine hypotheses around the biophysical and social drivers of carrying capacity, siting decisions, and resilience of marine aquaculture.

4. Discussion

Aquaculture operations are expanding globally at widely divergent scales of operation, from small pond to large scale international operations [1]. Integrating marine aquaculture into coastal regions in ways that are both socially and ecologically sustainable requires thinking about these systems as coupled, social–ecological systems (SESs) requiring interdisciplinary research [4,5,119]. In response to this need, we applied Ostrom's SESF [13] to advance interdisciplinary research on marine aquaculture. The SESF provides an avenue for researchers to understand different disciplinary approaches, languages, and norms while also coordinating the development of interdisciplinary research questions and data collection efforts [120,121].

Our aim was to develop a flexible framework that would guide researchers interested in many different social and ecological aspects of marine aquaculture systems, and like others, our effort demonstrated strengths and weaknesses of the SESF [20,27]. On the one hand, the SESF is comprehensive and provides a guide for interdisciplinary research teams thinking through the complexity of marine aquaculture. On the other hand, the flexibility of interpretation possible within the framework requires that team members commit time and energy to develop a shared interpretation that enables effective use of the tool. In our effort, it quickly became apparent that the team needed to confront more directly (1) the greater than anticipated SES complexity of marine aquaculture and (2) our disciplinary and associated communication barriers. Initially, the team adopted a broad approach, but then shifted the focus to one kind of marine aquaculture (oysters) to constrain the complexity. Overtime, discussions expanded again to include other types of aquaculture resources. It was important to take time to consider the meaning and significance of each variable, and how one would measure it (if need be) using appropriate methods and metrics. The effort allowed a greater appreciation for the complexity of the subject, as well other disciplines. As with other similar interdisciplinary research efforts [11,12], team members required capacity building in interdisciplinarity and trust building before this was possible. Future interdisciplinary teams focused on marine aquaculture can benefit from the framework developed here, even if simply used as a starting point.

A valuable aspect of Ostrom's SESF is its flexibility with respect to the scale of application. Depending on the research question examined and the scale of analysis, researchers can include, exclude, and aggregate or disaggregate variables as needed. A key scale issue to emphasize is the selection of the resource unit relative to the resource system that produces it, and the impact of defining the boundaries of the focal system [27]. In an analysis of different aquaculture outcomes within a very large resource system, one would need to take account of differences in state governance organizations and rules. Actors are important variables in all analyses, but for a large-scale application of the framework, analyses of actors may focus on collective entities rather than individual farmers and landowners. Actors' historical experiences and memories can have a tangible effect on smaller scale interactions, with those effects perhaps diluted at a regional assessment. Local analyses may focus on farmer-to-farmer information sharing or exchanges of information, while a broader scale analysis might focus on information sharing between industry representatives and government or non-government organizations. One could contrast the interaction effects of "coffee shop" exchange versus Internet and mass media delivered information. At the global scale, interactions of relevance may focus on community or corporate interests, mass media dissemination of information and opinion, and actions and dynamics of larger economic flows, such as commodity and financial markets or export and import activities. Given the need to analyze marine aquaculture at multiple scales, the SESF framework offers substantial flexibility for application at local, regional, and global scales.

Our application of the SESF to marine aquaculture brought to the fore the challenge of how to deal with complex SESs where multiple types of actors interact in different ways that depend on and impact multiple resource units within a resource system. Thus, a key choice that deserves further mention is the selection of the resource unit, and consequently the resource system that produces it, as the interaction determines the appropriate boundaries of the focal system, with the choice depending on the question being addressed and whether the situation is represented by appropriation and/or provisioning action situations [27]. We view both kinds of problems as relevant depending on the question and scale of analysis. It is difficult to capture these complex situations and so analyses must be simplified. We chose to simplify by keeping the core focus on the marine aquaculture related uses and impacts, while considering other actors, their RUs, and RSs as part of the broader social, economic, and political context or the related ecosystem. Future applications should consider how to take into account the complexity of these kinds of SESs.

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