Seeking sustainability: employing Ostrom’s SESF to explore spatial fit in Maine’s sea urchin fishery

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Abstract: Achieving resource sustainability in complex social-ecological systems requires employing place-based management mechanisms congruent with the underlying temporal, spatial, and functional dynamics of the system in question. However, matching management to system dynamics can prove extremely challenging, as has been illustrated in Maine’s sea urchin fishery where fishery managers have struggled to resolve management spatial scale mismatch for over two decades. In Maine, the spatial scale of management far exceeds the relevant spatial dynamics of the urchin resource and leaves fine-scale urchin aggregations in a de facto open access state. These conditions facilitated the serial overharvest of urchin aggregations, which caused overharvested areas to transition to kelp-dominated ecosystem states that inhibit urchin recruitment. Although fishery actors contemplated adopting a number of fine-scale management alternatives to enhance social-ecological fit in the fishery, to date, no such alternatives have been employed. We adopted an ethnographic research approach and conducted semi-structured key informant interviews, document analysis of archived meeting minutes, and participant observation at co-management meetings and restoration events to explore these fishery dynamics. Following data analysis, we employed Ostrom’s social-ecological systems framework as a diagnostic tool to identify the factors that have influenced management spatial fit in the urchin fishery. Research findings suggest that a number of interacting variables, including harvesters’ heterogeneity and conflicting mental models of the SES, low levels of trust and social capital, and changes in the resource system following collapse impeded the degree of collective action necessary to support fine-scale management.
However, changing leadership characteristics and increasing horizontal collaboration between harvesters and scientists have positively influenced governance outcomes in recent years. These conditions provide a window of opportunity for the urchin fishery to transition towards a more adaptive and collaborative governance arrangement more conducive to addressing problems of fit in the urchin fishery.

**Keywords:** Fishery management, scale mismatch, sea urchins, social-ecological fit, social-ecological systems

**Acknowledgement:** This project was supported by the USDA National Institute of Food and Agriculture, Hatch project number #ME021509 through the Maine Agricultural & Forest Experiment Station. Additional funding was provided by the University of Maine Graduate Student Government. We would like to thank the urchin harvesters, SUZC members, and ME DMR staff who participated in this research. We especially thank Joe Leask and Clint Richardson for inviting us aboard their urchin vessel. We also thank Larry Harris, Keith Evans, Christine Beitl, and three anonymous reviewers for comments on earlier versions of this manuscript.

### 1. Introduction

The widespread decline of global marine resources highlights the vast shortcomings of employing simplified management panaceas in the governance of common pool resources and the complex social-ecological systems (SES) in which they are embedded (e.g. Young et al. 2018). Globally, numerous instances of resource decline have been attributed to problems of fit resulting from a mismatch between the scale of resource management and the scales of the underlying social and ecological processes in a SES (e.g. Folke et al. 2005; Berkes 2006; Wilson 2006; Galaz et al. 2008; Epstein et al. 2015; Lindegren et al. 2018). Scale mismatches may be of a spatial, temporal, and/or functional nature and typically result in the disruption or loss of key system components, the consequences of which can include ecological decline, cascading effects, and threshold shifts that compromise system resilience and stakeholder well-being (Cumming et al. 2006; Galaz et al. 2008).

Spatial scale mismatch, wherein the spatial scale of management is incongruent with the spatial scale of the underlying social and/or ecological processes in a SES, remains a particularly pervasive issue in urchin fishery management and has been described as a primary contributing factor in global urchin decline (Berkes et al. 2006; Johnson et al. 2012; Ouréns et al. 2015). The typical spatial scale mismatch exhibited in urchin fisheries is one in which the scale of management far exceeds the relevant spatial scale attributes of adult urchin populations, thereby leaving the urchin resource in a *de facto* open access state and vulnerable to serial depletion via commercial harvest (Johnson et al. 2012; Wilson et al. 2013).
Sea urchins are a commercially valuable common pool resource harvested for their gonads or “roe” which are commonly exported to Japan for consumption (Brown and Eddy 2015). Following a decline in domestic stocks, Japanese demand for urchins shifted to the global market during the 1970s driving the emergence of a number of boom and bust urchin fisheries around the globe. One example includes Maine’s sea urchin (Strongylocentrotus droebachiensis) fishery (Figure 1), which came to fruition in 1987 only to collapse less than a decade later (Johnson et al. 2012; Figure 2).

Figure 1: Maine (USA) (above) with the two urchin harvesting zones depicted by the dashed line (below).
Scholars suggest that achieving social-ecological fit in complex systems is best accomplished within collaborative, adaptive, and polycentric institutional arrangements, wherein management can be tailored to system dynamics and adapted appropriately as conditions change (Folke et al. 2005; Wilson 2006; Young et al. 2007; Galaz et al. 2008). One such approach widely cited for application in small-scale fisheries is adaptive co-management, wherein resource stakeholders and centralized authorities share management responsibility and “institutional arrangements and ecological knowledge are tested and revised in a dynamic, on-going, self-organized process of learning-by-doing” (Folke et al. 2002, 20). Key features of this approach include a high degree of collaboration, dialogue, and knowledge exchange between diverse actors at various scales and the incorporation of multiple types of knowledge into research and management. These processes enable actors to better cope with system complexity and experiment with alternate pathways to achieve social-ecological fit in complex systems (Folk et al. 2005; Cumming et al. 2006; Olsson et al. 2006; Armitage et al. 2007).

Beyond fostering flexible governance arrangements that encourage learning and adaptation to changing conditions, achieving spatial fit in urchin fisheries requires targeting management mechanisms (i.e. rules, norms, and/or property rights) at a fine spatial scale congruent with the spatial attributes of the urchin resource. Researchers who have explored spatial scale mismatch in urchin fisheries have typically recommended employing spatial management mechanisms

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Figure 2: Maine sea urchin landings by zone in millions of pounds on the left axis and price on the right axis (1987–2017). Data source: Maine DMR 2017.
(e.g. small-scale harvesting zones, rotational closures, no-take reserves) and allocating the property rights and/or management responsibilities for these areas to urchin harvesters (Wilson 2006; Miller and Nolan 2008; Johnson et al. 2012; Ouréns et al. 2015). In theory, small-scale zones would focus management at the scale of discrete urchin aggregations and tighten system feedbacks, thereby encouraging harvesters to recognize the consequences of overharvest (Wilson 2006; Wilson et al. 2013). In turn, granting harvesters property rights to harvesting grounds would reduce competition and enable harvesters to reap the benefits they generate via sustainable harvest or by participating in restoration activities (Johnson et al. 2012; Wilson et al. 2013). One mechanism that meets this criterion is territorial use rights in fisheries (TURFs), which have been shown to facilitate the sustainable management of other marine benthic resources (e.g. Gelcich et al. 2012; Steneck et al. 2017) and have been considered an ideal management alternative by many influential actors in Maine’s urchin fishery. However, operationalizing fine-scale management requires a high degree of collective action that is not always supported in a SES (Ostrom et al. 2002; Schlager 2004). This was the case in Maine, where although actors contemplated employing a number of management alternatives, no transition to fine-scale management was achieved. Below, we employ Ostrom’s social-ecological systems framework (SESF) (McGinnis and Ostrom 2014) to diagnose why fine-scale management failed to emerge in Maine’s urchin fishery and explore how changing dynamics may provide new opportunities to address the persisting spatial scale mismatch in urchin management.

2. Background

The state of Maine (Figure 1), located in the Northeast corner of the United States, is a highly marine resource-dependent region. Despite the state’s long-standing commercial fisheries for groundfish, lobsters, and clams, urchins largely evaded commercial extraction until the late 1980s when trophic cascades and global market forces prompted the emergence of the urchin fishery. During the 1970s, the overharvest and collapse of groundfish populations (urchin predators) created conditions that resulted in the rapid increase of urchin abundance throughout Maine’s coastal zone (Harris and Tyrrell 2001). Just several years later, harvesters across Maine’s coast began competitively extracting urchins to meet Japanese demand (Johnson et al. 2012).

Green sea urchins have a circumpolar distribution and commonly inhabit rocky substrates, often referred to as ledges, in the subtidal zone between 0 and 50 m of depth. Urchin larvae spend 4–21 weeks suspended in the water column prior to settling on the substrate and post settlement, exhibit relatively sedentary tendencies (Scheibling and Hatcher 2007). Maine’s urchin stock comprises many discrete aggregations that function semi-independently and a typical aggregation spans one to several subtidal ledges, ranging in size from 10 to 200 m² (Johnson et al. 2012). Urchins and kelp exhibit a strong inverse relationship as urchin abundance and grazing determines the dominant ecosystem state of the surrounding habitat. When urchin abundance is high and predation or harvesting is low, urchin aggregations...
destructively transform kelp beds into urchin barrens (a state characterized by highly abundant urchins of low roe quality and commercial value) (Steneck et al. 2013); subsequently, removing too many urchins from an aggregation allows for the rapid regrowth of kelp and causes the habitat to “flip” to a kelp-dominated state. The latter state becomes locked in place as kelp cover provides habitat for micropredators (e.g. crabs and lobsters) that prey on juvenile urchins and prevent their recruitment (Harris and Tyrrell 2001; Steneck et al. 2013). For commercial harvesters, an ideal ecosystem state is an intermediate one, characterized by the co-occurrence of kelp and urchins at various stages of maturity. To maintain this state, harvesters must selectively extract high roe-quality urchins from aggregations before they can overgraze available food sources, while leaving behind a sufficient abundance of smaller urchins to prevent the habitat from flipping and locking in a kelp-dominated state (Johnson et al. 2012). These characteristics ultimately necessitate that urchin management be employed at an extremely fine spatial scale to prevent the overharvest of discrete aggregations.

Despite high levels of entry and effort in the early fishery, urchin harvest went unregulated until 1992 when the Maine Department of Marine Resources (DMR) established a license requirement and limited entry. Thereafter in 1993, the state established the Sea Urchin Zone Council (SUZC), an advisory co-management body and the following year, managers divided Maine’s coastline into two harvesting zones (Figure 1).1 Facing continuing decline, managers employed additional measures to curb urchin harvest over subsequent years, including size limits, harvesting seasons, daily catch limits, mandatory reporting for harvesters and buyers, and a moratorium on new entry (Hunter 2015). However, these broadscale measures left discrete urchin aggregations in a de facto open access state that enabled their serial depletion (Johnson et al. 2012). To date, few if any, cooperative relationships or informal rules promoting sustainable harvest have evolved amongst urchin harvesters to bolster the state’s urchin management (Johnson et al. 2012; Wilson et al. 2013). At present, the future of Maine’s urchin fishery depends on whether actors can collectively devise and implement finescale management mechanisms that incentivize sustainable harvest and prevent the loss of additional urchin habitat across Maine’s coast. In recent years, fishery actors have also asserted that maintaining a viable commercial fishery is contingent upon restoring urchin biomass to depleted areas, requiring that actors collectively devise and test novel restoration mechanisms.

3. Social-ecological systems framework application

Ostrom’s SESF is a conceptual framework that outlines a set of generalizable variables that interact to influence outcomes in coupled SESs (Ostrom 2009) (Figure 3). This set of variables is supported by extensive commons scholarship that has explored the conditions under which resource stakeholders have been

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1 Harвестers can be licensed to harvest in Zone 1 or Zone 2 but not both.
able to act collectively to achieve sustainable common pool resource governance in a variety of settings (Partelow 2018). To date, this framework has been applied in the study of a wide-range SESs, including various coastal and marine fisheries (e.g. Partelow and Boda 2015; Guevara et al. 2016; Partelow et al. 2018) and increasingly, is being used as a diagnostic tool that enables researchers to identify the source of environmental dilemmas in coupled systems (Ostrom and Cox 2010; Partelow 2018).

The SESF depicts an SES as consisting of four subsystems, each constructed of decomposable nested tiers. These subsystems, or first-tier variables, include the Resource System (in this context, the urchin fishery), Resource Units (urchins), Actors (urchin harvesters, buyers, scientists, and managers), and the Governance System (the formal management mechanisms established by the DMR and Maine State Legislature with advisory input from the SUZC), and each can be decomposed further into additional tiers. Actors within focal systems interact to produce outcomes that influence and are influenced by exogenous Social, Economic, and Political settings and Related Ecosystems (McGinnis and Ostrom 2014). We employed the SESF because of its utility for conducting temporal analyses and exploring governance challenges in marine SESs using qualitative data (e.g. Basurto et al. 2013; Lozano and Heinen 2016; Partelow et al. 2018) and operationalized the framework to diagnose contributing factors to ongoing spatial scale mismatch in urchin management.

Figure 3: Revised social-ecological system framework (SESF) diagram adapted from (McGinnis and Ostrom 2014).
4. Methods

We adopted an inductive qualitative research approach (Bernard 2011; Cox 2015) that included key informant interviews, participant observation, and document analysis of archived co-management meeting transcripts. In total, we conducted 14 semi-structured interviews with key informants between February and November of 2016. Each participant possessed extensive experience in the urchin fishery and substantial knowledge of relevant system dynamics. Participants were selected using a purposive snowball sampling strategy (Bernard 2011) and we began by interviewing DMR personnel and SUZC members who were particularly active in co-management processes. In total, we interviewed seven harvesters (six divers and one dragger), one tender, one urchin buyer, three DMR staff scientists, and two academic scientists involved with the fishery. Of the harvesters who participated in interviews, two were licensed to harvest in Zone 1 and five were licensed in Zone 2; however, the majority of these individuals possessed SES knowledge related to both zones (Figure 1).2 Interviews followed a semi-structured interview guide (Appendix A) that we devised following a review of relevant literature and co-management meeting transcripts. This guide was further informed by the second author’s experience as a SUZC science advisor. Interviews spanned 1.25 to 2.5 hours in length, all were recorded with the participant’s permission and were transcribed verbatim.

Participant observation occurred at 14 co-management meetings between July 2015 and March 2017 and throughout the design and implementation of the Cat Ledges Restoration Project (CLRP), a harvester-led habitat restoration effort in the Sheepscot River, Maine. We observed various stages of project planning and assisted with three implementation days by volunteering to measure and record a sample of urchins harvested for relocation. In addition to conducting interviews and participant observation, we also reviewed archived transcripts obtained from 129 SUZC and Research Subcommittee meetings held between 1999–2016. These transcripts provided us with critical insight into past fishery dynamics and into actor perceptions that were underrepresented in key informant interviews (i.e. draggers and urchin buyers).

Qualitative data consisting of interview transcripts, observation notes, and meeting minutes were entered into an NVivo 11 database and analyzed using a two-step coding process (Saldaña 2015). The first coding cycle consisted of applying descriptive inductive codes to the qualitative data. For instance, if an interview participant described a dispute between divers and draggers over preferred management strategies, we applied the code Past Conflict to that section of text; other examples of codes applied during this phase included Mistrust Between Actors, Collective Learning, Fine-scale Management, and Experience-based

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2 224 harvesters were active during the 2014–2015 season, this included 130 divers, 92 draggers, and 2 rakers; 43 of these individuals were licensed to harvest in Zone 1 and 181 were licensed to harvest in Zone 2 (Maine DMR 2017).
Knowledge. Upon the completion of this cycle, we performed a secondary coding cycle wherein we used axial coding to condense our first-round inductive codes and generate a succinct list of emergent themes. Thereafter, we matched these themes with existing second-tier variables under the SESF (McGinnis and Ostrom 2014). For instance, we matched the inductive code Past Conflict with the SESF’s Conflicts (I4), Experience-based Knowledge with the second-tier variable Knowledge of the SES (A7), and so on.

We present the results of our temporal analysis of the urchin fishery in the following section. The first period extends from approximately 1987–2011 and corresponds with the fishery’s early to intermediate phases. The second period extends from approximately 2012–2018 and corresponds with several major changes in the urchin fishery SES, including a decline in the number of harvesters, the emergence of new leaders and boundary spanners, and the implementation of a highly collaborative restoration pilot project (Tables 1–3). Second-tier variables of the SESF are noted in-text (e.g. “A1”) refers to the number of actors in the urchin fishery SES.

5. Results

5.1. Period 1: Attributes of the early and intermediate fishery

Despite increasing entry and effort during the late 1980s and early 1990s, the Maine DMR (GS1) refrained from actively managing the urchin resource until 1992 when it established a limited entry license requirement (GS6). One scientist described this as typical for the region, which he asserted “has a long history of laissez-faire management, especially in new fisheries.” Word quickly spread on the opportunity to amass large profits in the urchin fishery, drawing in 2725 new entrants (A1), many of whom were first-time harvesters with minimal local ecological knowledge or preexisting relationships with other urchin fishery actors (A7/A6). These dynamics ultimately contributed to the low levels of leadership

Table 1. Temporal analysis of ecological variables in the urchin fishery utilizing the SESF.

| Ecological system variable | Early to intermediate fishery (approx. 1987–2011) | Fishery at present (approx. 2012–2018) |
|----------------------------|--------------------------------------------------|----------------------------------------|
| Resource system (RS)       |                                                  |                                        |
| RS3 Size of the resource system | Coast-wide; rapidly shrinking with overharvest during height of fishery | Comparatively smaller but relatively stable, concentrated in Zone 2 |
| RS6 Equilibrium properties | Urchin-dominated stable states prevail | Kelp-dominated stable states prevail |
| Resource units (RU)        |                                                  |                                        |
| RU5 Number of units        | Low biomass post-collapse                       | Stable over time                       |
| RU7 Spatial and temporal distribution | Patchy coast-wide distribution; concentrated in Zone 2 post-collapse | Patchy, low biomass in Zone 1 |
Table 2: Temporal analysis of social variables in the urchin fishery utilizing the SESF.

| Social system variable | Early to intermediate fishery (approx. 1987–2011) | Fishery at present (approx. 2012–2018) |
|------------------------|---------------------------------------------------|----------------------------------------|
| Governance system (GS) |                                                   |                                        |
| GS1                    | Government organizations                          | Stable over time                       |
|                         | Maine DMR and state legislature began managing in 1992 |                                        |
| GS2                    | Non-government organizations                      | Stable over time                       |
|                         | SUZC founded in 1993; harvesters, buyers, processors, and scientists represented on council |                                        |
| GS4                    | Property rights                                   | Stable over time                       |
|                         | State divided into two harvesting zones, broadscale property rights create *de facto* open access conditions at the scale of urchin ledges |                                        |
| GS6                    | Rules in use                                      | Stable over time                       |
|                         | Absent until 1992; rules in use determined by DMR with advisory input from SUZC | Aforementioned rules plus daily catch limits |
| Formal                 | License requirement, size limits, harvesting seasons, mandatory reporting, zone restrictions, moratorium on entry |                                        |
| Informal               | Non-existent                                      | Stable over time                       |
| GS8                    | Network structure                                 | Stable over time                       |
|                         | Vertical, top-down                                |                                        |
| Actor variables (A)    |                                                   |                                        |
| A1                     | Number of relevant actors                         | Under 300 licensed harvesters in 2018  |
|                         | 2725 licensed harvesters at peak in 1994          |                                        |
| A3                     | History or past experiences                       | Relations improving                    |
|                         | Extremely contentious relations between harvesters and state actors |                                        |
| A4                     | Fishery duration                                  | Fishery active for several decades    |
|                         | Newly emerged fishery                             | Stable over time                       |
|                         | Harvesters dispersed across state; draggers often live and harvest in coastal communities; many divers reside inland and are highly mobile throughout their harvesting zone |                                        |
| A5                     | Leadership                                        | Harвестers take on leadership roles, power sharing more evident |
|                         | Leadership roles dominated by scientists and state personnel, absence of power-sharing |                                        |
| Boundary spanners       | Largely absent in early fishery; sporadic in intermediate fishery | Present and embrace collective learning and knowledge exchange |
| A6                     | Norms                                             | Prosocial behaviors and cooperation increasing |
|                         | Antisocial and competitive behavior prevalent     | Increasing cooperation; interpersonal relationships more common |
| Social capital          | Low cooperation; interpersonal relationships uncommon |                                        |
| Conservation ethic      | Absent                                            | Growing conservation ethic (harvesters feel inclined to maintain viable ledges despite absence of fine-scale property rights) |
| A7                     | Knowledge of the SES                              | Increasing; RBK generated through collaborative biological monitoring; EBK accumulated through prolonged experience in fishery |
|                         | Limited by recent emergence of fishery and absence of biological monitoring until 2001 |                                        |
(A5) and social capital (A6) exhibited during this period of the fishery and inhibi-
ted the evolution of informal norms and governance mechanisms that could have
supported resource sustainability (A6/GS6). It was only after the resource col-
lapsed in 1993 that the DMR (GS1) employed a suite of command and control
measures to curb harvest (GS6), and it wasn’t until 2001 that the DMR began
actively monitoring the urchin resource (GS8).

Following collapse, resource managers (GS1) and SUZC members (GS2) con-
sidered alternatives they felt could enhance management and promote the longev-
ity of the fishery. Of primary interest was implementing a fine-scale area-based
management system, which they referred to as local zones. According to actors,
local zones would loosely mirror the TURFs systems employed in the Chilean
urchin fishery (Steneck et al. 2017) and would more closely match the spatial
attributes of the urchin resource. Actors also contemplated employing small-scale
closures and urchin relocation mechanisms to restore urchin biomass in the region
and manage urchin aggregations at a finer-spatial scale. From 2002–2013, local
zones remained a primary discussion topic at co-management meetings and sev-
eral bills to establish local zones were considered in the state legislature. However,
to date, no formal fine-scale management alternatives have been implemented.
Below, we elaborate on the dynamics that influenced these outcomes.

5.1.1. Factors constraining the adoption of local zones
Harvesters’ rejection of local zones can be partly attributed to the dynamics of
commercial extraction in the early fishery and the state of the urchin resource post-
collapse. In the years following the fishery’s emergence, harvesters indiscriminately
extracted massive amounts of urchin biomass from Zone 1, while harvesting more
sporadically from Zone 2 (I1) (Figures 1, 2). This concentrated effort, wherein
harvesters extirpated whole urchin aggregations from Zone 1, caused overhar-
vested habitat to flip to kelp-dominated states thereby resulting in the widespread
loss of urchin habitat throughout the zone (O2). By 1994, urchin biomass (RU5)
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and the functional size of the urchin resource system had decreased substantially (RS3) as the remaining urchin biomass became concentrated in Zone 2 (RU7) where it remains today. By the time actors initially proposed adopting local zones, Zone 1 was already considered commercially extinct, which rendered the concept a non-viable one for many harvesters (O1).

In addition to the aforementioned resource attributes, several actor characteristics contributed to the rejection of local zones. In Maine, urchin harvesters are licensed to employ dive gear or drag gear but not both and the type of gear a harvester employs strongly shapes their preferred management alternatives and their harvesting strategies (I1). Divers typically extract urchins from shallow rocky...
substrates using SCUBA gear and work in groups of 2–3 aboard small vessels (averaging 28 ft.). In contrast, draggers typically harvest aboard larger fishing vessels (averaging 37 ft.) and extract urchins from sandy substrates at greater depths using specialized urchin drags (Hunter 2015). While draggers tend to reside in the coastal communities where their vessels are moored (A4), many divers reside inland and trailer their fishing vessels to different ports throughout their zone engaging in a highly mobile harvesting strategy (A4/I1). In interviews and management meetings, divers and draggers also expressed divergent mental models of the SES with regards to the root cause of urchin decline (A7). Draggers typically regarded diver mobility as a key source of resource decline (i.e. a roving bandit strategy, Berkes et al. 2006). Alternatively, divers communicated that mobility prevented unsustainable harvest and suggested that local zones would limit effort to a smaller area, thereby driving the localized overharvest that causes flipped ledges. As a result of these dynamics, local zones were widely supported by draggers who already operated at a local scale but were opposed by divers who felt that local zones would conflict with their learned harvesting strategies and result in resource deterioration. To date, these conflicting perceptions remain a longstanding conflict in the fishery (I4) and continue to shape harvesters’ opinions on management alternatives (O1).

5.1.2. Experimenting with other fine-scale management alternatives
In addition to local harvesting zones, fishery actors also experimented with other fine-scale management and restoration mechanisms including small-scale closures and urchin relocation. One major experiment consisted of implementing a three-year multi-species closure in Cobscook Bay located in Zone 2 (Figure 2). This closure effectively restored urchin biomass within closed-area boundaries, however, interview participants suggested that the closure persisted for too long as by the time it reopened, the habitat had transformed into an urchin barrens (where urchin abundance is high but food availability and commercial value is low). Prior to reopening this area to harvest, the DMR publicly reported on the substantial increase in biomass at the site (I2). Worried that this would attract a high degree of fishing effort, harvesters local to the closed area petitioned the DMR to implement protections that would limit catches. Despite their requests, the area was reopened to all Zone 2 harvesters without special regulations (GS4/GS6) and commercial harvesters decimated the resource within several days. This outcome generated widespread criticism from the local harvesters whose harvesting grounds had been destroyed and spurred resistance towards implementing small-scale closures in the future or collaborating with the DMR to experiment with other management alternatives (I4/A3).

Another example dates back to 2000 when harvesters called for research testing the effectiveness of urchin relocation, a fine-scale management and restoration mechanism that harvesters had been employing informally for a number of years. Urchin relocation involves moving urchins from urchin barrens to kelp-dominated habitat where they can feed. Harvesters pursue this activity to
improve the roe quality and commercial value of their catch and restore urchin populations to kelp-dominated ledges that were previously commercially viable (RS6). Several formal experiments testing this approach followed, including one high-cost University-led experiment funded by harvesters but predicated on scientists’ research-based knowledge (RBK) (I7). One harvester reported attempting to share their experience-based knowledge (EBK) during the planning phases for the University-led study, recommending that the relocation should happen in winter months when lower water temperatures and predation levels would improve success (I2). Contrary to this harvester’s advice, the first relocation was implemented in the late summer, the results of which were described to us by a scientist who observed these proceedings:

[The urchins] went down live but weakened for sure… everything was dead and was starting to wash away with tidal cycles. It was a full on failure; it also happened to coincide with a peak Jonah crab population, so [it was] pretty abysmal timing on that front.

Although these results appear consistent with the harvester’s suggestion that relocation be tested in colder water temperatures, the DMR Commissioner became convinced that urchin relocation was an ineffective restoration tool. Later, he dismissed harvesters’ calls for additional projects during an SUZC meeting as documented in the following transcript:

[A harvester] spoke about the history of the fishery, the lack of DMR involvement early on, and the need for enhancement today. He suggested areas like Cobscook Bay be treated as experimental zones for reseeding and grow out studies. [The Commissioner] acknowledged [the harvester’s] devotion to the industry but pointed out that some of these things had already been tried and had not been successful.

According to several interviewees, the inclusion of RBK over EBK in industry-funded research and management during this period and the state’s rejection of proposals calling for additional testing of urchin relocation suppressed potential opportunities for cross-boundary collaboration and knowledge exchange (I2). Although both aforementioned projects were implemented at a fine spatial scale, they ultimately lacked important collaborative and adaptive qualities and created further barriers to enhancing social-ecological fit in urchin management (O1).

5.1.3. Additional factors influencing actor capacity to address social-ecological fit
Several other characteristics have constrained the degree of collective action and adaptive capacity observed in the fishery and thereby, the extent to which actors are able to resolve spatial scale mismatch. In particular, the vertical top-down management structure (GS1/GS8) and the purely advisory role of the SUZC co-management
body (GS2) offered few opportunities for harvesters to meaningfully contribute to deliberation and decision-making processes (I3). Furthermore, several interview participants stated that the DMR commonly advanced policy decisions without the support of urchin harvesters and on several occasions directly undermined collective action by unilaterally overturning recommendations generated through co-management processes. These actions eroded trust between harvesters and state actors (A6) and created an extremely volatile management context (I4). Despite a turnover in state actors over the past decade, interview participants suggested that this history of contention and mistrust, or what Johnson and McCay (2012) refer to as latent distrust, still lingers amongst harvesters today (A3/A6). These dynamics further inhibited the collective action that would have been necessary to support fine-scale management and generated a maladaptive and inflexible governance system poorly equipped to address problems of fit in the fishery (O1/O2).

5.2. Period 2: Changing dynamics and their implications for urchin governance

Although numerous attributes in the fishery remained stable across the two periods we studied, including the top-down governance structure (GS8), the scale of property rights, (GS4), the rules-in-use (GS6), and the state of the urchin resource (RU5/RU7/RS3), several notable changes have transpired in recent years. In particular, the number of licensed harvesters steadily declined from 2725 to 300 following collapse (A1). Those who have continued to harvest urchins have accumulated substantial EBK (A7), have built personal relationships with other actors in the fishery (A6), and have come to view harvesting urchins as a long-term income source they wish to sustain and pass on to their children. Furthermore, the fishery experienced a gradual turnover in state managers and science advisers who had heavily influenced management decision-making in prior years. These individuals were replaced by new leaders and boundary spanners (A5) (Johnson 2011) who inspired increased collaboration between harvesters and scientists (I7/I9) and promoted the integration of EBK into industry-funded research, management, and monitoring activities (I2/I7). Although the urchin fishery remains on an unsustainable trajectory under spatial scale mismatch (O2), small increases in collective action have been achieved in recent years by diverse actors who have come together to explore possible ways to sustain and restore urchin biomass in the region (O1/O2). One way collective action has manifested is in the Cat Ledges Restoration Project (CLRP), a highly collaborative pilot project that tests urchin relocation as a fine-scale management and habitat restoration measure, which we elaborate on below.

Frustrated with the lack of resource recovery nearly two decades after collapse, urchin harvesters called for new measures that could restore urchin biomass and enhance resource sustainability. In 2011, one harvester emphasized that “now is a critical juncture—if we don’t do something concerted to increase our biomass, it may never recover, we can be proactive,” and in 2014 another expressed:
We all want this industry to continue to thrive and [to] hand [it] off to our kids someday. If we take care of the resource now, there will be something to pass along. It’s time to give something back. We need to experiment with the restoration of an area to show it will work and document how.

Despite the resistance encountered from the former DMR Commissioner several years earlier, urchin harvesters continued to express a willingness “to do reseeding and restocking for their own future” at management meetings, described urchin relocation as “a last hope for Zone 1”, and continued to informally test relocation mechanisms without the knowledge or direct support of the SUZC, the DMR, or urchin scientists.

This influx of harvester interest in urchin relocation coincided with a turnover in state actors and the appointment of new urchin research subcommittee (RSC) members who brought with them different histories (A3) and increased levels of trust with harvesters (A6). These new leaders and boundary spanners posited harvesters as experts on urchin dynamics and opened opportunities for knowledge exchange between epistemic communities (I2). With limited research funding, the SUZC and resource managers turned their attention towards low-cost projects that would promote urchin restoration and draw directly from harvesters’ EBK to inform project design and implementation. Shortly thereafter, the CLRP began in 2014 to once again test urchin relocation but for the first time using a harvester-designed and led approach. One scientist and long-time fishery participant described this as the first time key DMR personnel were really receptive to harvesters’ ideas, whereas another described how the idea for the project first emerged:

Nothing that [was happening] was beneficial to the industry itself, just regulation after regulation. It was handcuffing everybody instead of allowing a free thinker to think. I thought it would work because [we’ve] moved urchins and had them survive very well for as much as a year. I just saw no future in the urchin council going in the way it was going because it wasn’t accomplishing anything.

During the project, the RSC acted as a bridging organization wherein harvesters and scientists shared perspectives and discussed project design and implementation, including preferred habitat and substrate types, locations for source populations, and conditions for promoting urchin survival. During these exchanges, harvesters drew from their EBK (A7) to define project parameters, which presented a new form of horizontal deliberative processes (I3) previously unseen in the fishery. Unlike prior relocation attempts, the CLRP promoted knowledge exchange (I2) and trust-building between actors (A6), as described by one resource manager associated with the effort:

[The project evolved] organically. It wasn’t driven by the Department [or] by any of the scientists on the council. It was a constructive conversation where all the conversations that I had in the past leading up to that were just fighting
over days, trays, and access. It’s kind of trying to be adaptive. It’s a way that we’ve been able to build trust, have good conversations with people, and build the relationships with the industry. It’s identified a group of very constructive stakeholders who want to help the resource.

After significant discussion and planning, a small-scale closure was implemented around the Cat Ledges area for which the DMR granted a special license to participants to harvest and relocate urchins at the site, a phenomenon which one scientist said would not likely have been supported earlier in the fishery:

It’s only now, [with the current state actors] that it’s been possible for this kind of operation like Cat Ledges to even be tried. In the past, the DMR would come up with excuses as to why it couldn’t be done and [back then] fishermen wouldn’t have wanted to set an area aside for only a few.

The CLRP was initiated and supported by a core group of six urchin divers, two of which embraced direct leadership roles (A5), as well as state and council scientists and two graduate students. After the urchins were harvested and relocated to the closure, harvesters continued to conduct site visits and monitor the status of the relocated urchins until the closure was reopened (I9).

Project participants and other harvesters shared their perspectives on the CLRP with us in interviews. One scientist expressed his opinion that “true co-management is when everybody’s working towards a common goal, like Cat Ledges [which is] the closest thing in all the time I’ve been here where there is a willingness to work together on a project like that.” Furthermore, several harvesters described the effort as a creative alternative to the top-down management they felt had been stifling management innovations (GS8). Another diver expressed his support stating: “I’m all for it, because we’re learning, we don’t need it today but we might tomorrow, so it’s good to do it before you need it,” (A7) suggesting that the knowledge generated from these activities can be applied to overcome future challenges and adapt to changing conditions. Although other management pilot projects have been implemented in the past, the CLRP is the first to involve truly horizontal collaboration and deliberation between harvesters and scientists, mobilize harvester’s EBK into industry-funded research, and foster social learning on system dynamics. Despite persisting spatial scale mismatch, the changing dynamics described above have ultimately generated small increases in collective action in the urchin fishery and create a platform from which to foster a more adaptive and collaborative urchin governance regime (O1).

6. Discussion

Achieving social-ecological fit and resource sustainability in complex coupled SESs requires targeting management at the appropriate temporal and spatial scales and fostering flexible governance arrangements that promote learning and adaptation to changing conditions (Folke et al. 2005; Wilson 2006; Galaz et al.
2008; Armitage et al. 2007). However, shifting away from conventional management towards arrangements more conducive to achieving social-ecological fit can prove extremely challenging. This is illustrated in the case of Maine’s sea urchin fishery where SES conditions and dynamics during the fishery’s early to intermediate stages (Tables 1–3) inhibited collective action and prevented the adoption of proposed fine-scale management strategies.

Our findings support previous research suggesting that collective action is less likely to emerge in systems with a large number of heterogeneous actors that exhibit low dependence on the resource, low levels of trust and social capital, conflicting mental models of SES functionality, and non-existent norms supporting cooperation, among other attributes (Ostrom et al. 2002; Schlager 2004; Acheson 2006). Furthermore, our research suggests the lack of important social mechanisms facilitating successful governance transformations, including learning networks, bridging organizations, and leaders who identify opportunities for change (Olsson et al. 2006; Gelcich et al. 2010), were also absent from the early fishery. Although a window of opportunity to orient the fishery on a sustainable path emerged with the first indications of resource decline (Figure 2), the DMR failed to act until after unsustainable social norms were established and ecological thresholds were reached. These outcomes underscore the critical importance of investing in proactive management and adaptive capacity as new fisheries emerge and continue to develop.

In contrast to the above, our research suggests that enabling conditions for collective action and adaptive co-management have been emerging in the urchin fishery over recent years (Tables 1–3). This pertains to the decreasing number harvesters (A1), the change in leadership and the emergence of boundary spanners (A5), the increasing levels of trust and social capital in the fishery (A6), and the emergence of the CLRP, a highly collaborative experimental pilot project (I7). Of particular note is the emergence of boundary spanners (A5) who recognize the value of harvester’s EBK (Johnson 2011). In the urchin fishery, boundary spanners have helped to enhance governance outcomes by elevating levels of trust between scientists and harvesters (A6), reducing conflict (I4), supporting constructive deliberation (I3), and mobilizing diverse sources of knowledge for application in research and management (I2). The quality and configuration of leadership has been a key dynamic observed to influence governance outcomes in other marine SESs (e.g. Bruckmeier and Larsen 2008; Basurto et al. 2013; Guevara et al. 2016) and facilitate transformations towards preferred governance arrangements in complex systems (Olsson et al. 2006). Evidence in Maine further supports these notions and suggests that, by embracing boundary spanning roles, leaders can help transition SESs away from unsustainable pathways by finding new ways to make management more collaborative and adaptive.

Beyond embracing flexible and adaptive institutional arrangements, achieving management spatial fit requires implementing management mechanisms at a scale congruent with resource attributes (Wilson 2006; Johnson et al. 2012; Ourèns et al. 2015). Although TURFs remains one prospective alternative linked to sustainability in other benthic fisheries (Gelcich et al. 2012; Steneck et al. 2017), this
system has yielded mixed results in urchin management. In Galicia for instance, TURFs ultimately failed to prevent fishery closures which researchers suggest was partly due to the spatial scale of TURFs in this context exceeding the fine-spatial scale attributes of the urchin resource (Fernández-Boan et al. 2012; Ourén et al. 2015). Similarly, in Nova Scotia, harvesters were allocated property rights and management responsibilities for a small personal harvesting zone, yet even in this case zone size often exceeded what a single harvester could effectively manage (Miller and Nolan 2008). In contrast, researchers studying the small-scale urchin dive fishery in California observed that harvesters participating in a well-functioning cooperative were able to decrease competition, promote selective harvest, and maintain stock productivity without employing an area-based or TURFs system (Gutiérrez et al. 2017). These practices echo a growing conservation ethic described by divers in the Maine urchin fishery, wherein many employ extremely selective harvesting practices to conserve discrete urchin ledges and prevent the flipping and locking of urchin habitat (A6). This suggests that achieving urchin resource sustainability may not require employing a TURFs-system if actors can cultivate a strong conservation ethic and institute harvesting rules that prevent the overharvest of discrete urchin aggregations.

The CLRP, which coupled harvesters’ urchin relocation mechanisms with a fine-scale closure, represents another approach to operationalizing fine-scale urchin management and restoration. Although project participants widely considered this effort a success for its ability to bring together diverse actors to constructively address management dilemmas, this project could prove difficult to scale-up for several reasons. First, CLRP participants tend to be more engaged compared with other harvesters in the fishery, hence this model may not readily transfer to less-engaged harvesters, as has been observed in other cases where actors were either disinterested in or unable to respond to decentralized management responsibilities (e.g. Acheson 2006; Ribot et al. 2006). Second, the transaction costs associated with relocating urchins, project monitoring, and enforcing closures may also discourage participation, especially with urchin harvesters’ low dependence on the urchin resource. Despite these challenges, continuing to collaborate on experiments that test urchin relocation and other potential mechanisms offers opportunities to build trust and acquire knowledge on important system dynamics.

Despite the favorable changes observed in recent years, low urchin biomass, latent mistrust, and continued leadership turnover present ongoing barriers to achieving collective action and resource management at the appropriate spatial and temporal scales. To increase the likelihood that social-ecological fit and sustainable resource management are achieved, the DMR and SUZC should continue to embrace collaborative management approaches that facilitate social learning and cross-boundary exchange between harvesters and scientists. Furthermore, as state and science actors turnover in the future, new leaders should seek to maintain recent momentum towards adaptive co-management and build upon the increasing levels of trust that have emerged with harvesters in recent years.
Overall, we found Ostrom’s SESF to be a highly effective tool with which to diagnose the factors that have contributed to persisting spatial scale mismatch in the urchin fishery. While we refrained from making extensive modifications to the framework, several notable modifications we made included situating boundary spanners as a third-tier variable under leadership (A5) and distinguishing knowledge exchange as a subset of information sharing (I2), both of which are considered enabling conditions for adaptive co-management and governance transformations (Cumming et al. 2006; Olsson et al. 2006). These modifications may prove applicable in other studies that use the SESF to explore social-ecological fit and the factors that shape SES sustainability in other contexts. Provided the nature of complex SESs, the current configuration of the urchin fishery will inevitably change in response to changing ecological conditions and social dynamics. Future researchers are encouraged to use the SESF to explore how changing dynamics facilitate or constrain collective action and social-ecological fit in the urchin fishery.

7. Conclusion

This detailed empirical case study contributes to a growing body of literature on problems of fit in SESs and illustrates how the SESF can be employed to diagnose factors that influence scale mismatch and social-ecological fit in a coastal fishery. This case indicates that achieving spatial fit in a SES can be an extremely difficult process, especially in a newly-emerged fishery in which harvesters target a fine-scale and patchy resource. Although fishery actors proposed and tested various management alternatives that they hoped could resolve spatial scale mismatch, the characteristics of the early to intermediate fishery ultimately inhibited collective action and prevented a transition to fine-scale management. In contrast, our research indicates that enabling conditions for collective action and adaptive co-management have begun to emerge in recent years. These changes present a window of opportunity to transition towards adaptive and collaborative governance arrangements more conducive to addressing problems of fit in the urchin fishery.

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Appendix A: Maine sea urchin fishery research semi-structured interview guide (2015–2016)

**Participant Background:**

1. What is your role in the sea urchin fishery? How long have you been involved?
2. Do you or have you participated in other fisheries and/or industries in Maine? Which?
3. Do you identify primarily as an urchin harvester or with another fishery/industry?
4. Can you tell me a little about the emergence and early stages of the sea urchin fishery?

**Participation in Management:**

5. What does co-management mean to you?
6. Do you consider the sea urchin fishery to be a co-managed fishery? Why or why not?
7. Do you participate in urchin management? In what ways?
8. Can harvesters and other stakeholders participate fully in urchin management if they wish?
9. Do you feel that there are any barriers to your or others’ participation in urchin management?
10. Do you feel that you’re listened to at management meetings? Are your opinions taken into account?

Management Evaluation:

11. How well do you think sea urchin management is working in Maine? Please explain.
12. What aspects of management could be improved?
13. Do you propose any specific changes related to how meetings, decision-making, or rule-making work?
14. How well do you think urchin harvesters understand management processes and what goes on at the Council level?

Opinions on Management Rules, Regulations, Permitting, Enforcement:

15. What conservation rules or regulations do you feel are necessary that do not currently exist?
16. What is your opinion on enforcement in the urchin fishery? Is enforcement adequate? Are penalties fair?
17. Do you or others have any concerns regarding licensing or permitting in the urchin fishery?
18. What are the most important differences of opinion that exist regarding urchin management? What are the most controversial topics? Where is there an agreement?
19. What is your opinion about the following rules related to urchin management:

   – Culling on bottom
   – Mesh escape panels (draggers only)
   – Mandatory logbooks
   – Swipe cards
   – Rotating closures (like those utilized in the scallop fishery)
   – Minimum and maximum test-size limits
   – Zones (should the number increase, decrease?)
   – Lease areas (space allocated to individuals/groups for enhancement)
   – Marine protected areas and conservation closures
   – Limited entry (license requirement)
   – CPR certification for divers
   – Seasons
Day regulations
Daily tote limits
Annual quotas (total allowable catches or TAC)
Individual quotas vs. individual transferable quotas
Transferable licenses

20. Are there any other regulations that you would like to discuss?

21. Do you feel that your views are representative of most other harvesters?

22. What are your thoughts on the recent Fishery Management Plan (FMP) draft?

Science Related to Sea Urchin Management:

23. What are the most important differences of opinion that exist regarding the science used to manage sea urchins? Where is there agreement?

24. How much trust is there in the science used to manage the fishery? How important is the science to decision-making in the fishery?

25. From your perspective, what are the most significant threats or challenges facing the sea urchin fishery today and into the future?

26. What do you think are the most important information or knowledge gaps related to managing sea urchins in Maine?

27. Do you have suggestions for research that scientists should be doing to help the fishery?

28. Have you been involved in any research related to sea urchins? Please elaborate.

Harvesting Behaviors:

29. Do you have any concerns regarding other harvesters fishing behavior and practices? (e.g. related to selectivity, compliance, participation?) Do you communicate any of these concerns to other harvesters or at management meetings?

30. Has your harvesting behavior changed from the start of the industry to the present? In what ways? e.g. Are you more or less selective?

31. Have you noticed any changes in harvesters’ opinions towards resource conservation since the onset of the industry?

Urchin Conservation and Restoration Projects:
Cat Ledges Restoration Project (CLRP):

32. Are you familiar with the Cat Ledges Restoration Project?

33. What was your initial opinion of the project? Has your opinion changed?
34. What are your feelings towards urchin restoration, farming, and/or relocation in general?
35. What do you see as the potential outcome of this project?
36. Are you satisfied with the way the project has progressed? Would you implement the project differently in any way?
37. How would you feel about incorporating aquaculture-reared urchins into this type of project?

**Blue Hill Bay Proposed Experimental Area:**

38. Can you tell me more about the origins of the proposed experimental area in Blue Hill Bay?
39. How would you describe the response from harvesters towards this project proposal? Is this response what you anticipated?
40. Would you make any changes in the way that this proposal was introduced?

**Denny and Whiting Bays Closure:**

41. Are you familiar with the zone closure that occurred in Denny and Whiting’s Bays? Do you feel this closure was a success? In retrospect, would you recommend that the closure and reopening be managed differently?

**Wrap-up:**

42. Do you have any urchin harvesting stories that you would like to share (e.g. a story about an exceptionally good or bad fishing day)?
43. Are there any other issues related to management that you think state and local managers or scientists should be paying attention to that we haven’t discussed here today?
44. Can you recommend any other sea urchin fishermen that would be willing to speak with us? In particular, do you know any retired harvesters?