Ecological Economics 96 (2013) 165–172

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

The cost of useful knowledge and collective action in three fisheries

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ARTICLE INFO

Article history:
Received 15 May 2013
Received in revised form 31 August 2013
Accepted 28 September 2013
Available online 14 November 2013

Keywords:
Fisheries
Cost of knowledge
Useful knowledge
Collective action
Cooperation
Competition
Complexity
Sustainability
Coupled natural and human systems
Lobster
Urchins
Groundfish
Social capital
Fishers' ecological knowledge
Social capital

ABSTRACT

In a complex environment knowledge is valuable and its acquisition is costly; as a result people are careful about what to learn and how to learn it. We suggest that the dynamics of the "local" environment strongly influences the method that individuals choose to acquire useful knowledge and is one of the principal determinants of the way they compete and cooperate. We focus on the way different environments lead to different costs, especially the relative opportunity costs, of search and communication and, consequently, to the emergence of different patterns of persistent cooperation and competition. In predictably regular and in predictably random environments, the cost of autonomous search is low and little social structure emerges. In complex environments, the relative costs of communication are high, leading to persistent social structure. Our presumption is that the characteristics of the emergent, or informal, social structure are a major determinant of successful collective action. We investigate the hypothesis through a comparison of three fisheries in which the costs of acquiring useful knowledge are different. Because of these differences, fishers' acquisition of useful knowledge leads to different social structure and different preconditions for successful collective action in each fishery. The lobster fishery is characterized by strong collective action and appears sustainable; the urchin and groundfisheries, worked by the same communities, are not even though almost all their participants are familiar with and often participate in the lobster fishery.

1. Introduction

There are few fisheries in the world where collective action has led to sustainable resource management. The Maine lobster fishery is one example often cited. In the early part of the last century, the lobster fishery was thoroughly depleted (Acheson, 2003; Acheson and Gardner, 2010); in response, a long negotiation between the state of Maine, scientists and the industry led to effective and well-enforced rules restraining fishing and conserving the resource. However, the same fishing communities that have conserved lobster with such success have also pursued and thoroughly extirpated local populations of several other species, including groundfish and sea urchins. The key question is, what is it about the lobster fishery and the way it is conducted that leads to successful collective action and sustainable resource use while other fisheries worked by the same communities are overexploited?

In 1990 Elinor Ostrom published her famous list of the preconditions for successful collective action. Her list includes a number of items that presuppose the existence of a viable civil society, i.e., collective choice arrangements, boundaries defining who is in and who is out of the institution, congruence with local ecology, monitoring, conflict resolution, and graduated sanctions. Why these social–economic attributes arise in some and not other situations is not clear. In 2000 she advocated "further work to explain why some contextual variables enhance cooperation while others discourage it" (Ostrom, 2000). In this paper we argue that the attributes Ostrom lists,[2] especially those that are the self-organized product of individuals' interactions with each other and with the environment, are sensitive to the costs individuals incur while acquiring knowledge that is useful to their self-interest. We assume that the social and ecological environments in which individuals reside are complex and that economic opportunities are patchy in space and variable in time. We also assume that learning about those opportunities requires either costly individual search or costly communication with other individuals. Thus, we argue that the costs of acquiring useful knowledge are one of the principal determinants of the way individuals compete and cooperate. We focus our argument on the way different environments lead to different

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[2] Along with those listed by others building on her work (e.g., Agrawal, 2002; North, 1990, 2007; Wade, 1994).

0921-8009/$ – see front matter
http://dx.doi.org/10.1016/j.ecolecon.2013.09.012

costs of search, communication, and learning, and consequently, to the emergence of different social structure.[3] Our presumption is that the attributes of this emergent social structure are an important determinant of the likelihood of successful collective action.

This theoretical perspective is based on the evolutionary computational model of learning and adaptation in Wilson et al. (2013) and is explained in the next section of the paper. We then turn to a description of the way the problem of learning and adaptation affects the emergence of informal social structure and the likelihood of collective action in the three fisheries. We believe that this focus on the problem of learning and adaptation leads to a better understanding of the ways natural and human systems interact and, thereby, adds to the literature concerning the success and failure of collective action.

2. Learning and Adaptation

In a complex world, the acquisition of useful, usually mundane, practical knowledge is a necessary and continuing part of life. By useful knowledge, we mean knowledge about the order and regularity in complex social and natural environments (Valiant, 2013). The usefulness of this knowledge lies in the guidance it offers about the likely outcome of the alternative actions an individual might take. Presumably, the choices that individuals make about what actions to take are strongly biased towards actions that they believe will lead to beneficial outcomes.

Practical knowledge is usually acquired through personal experience and communication; its acquisition is costly. There are the direct costs of time and resources expended, but there are also important opportunity costs, especially the loss of the knowledge that might have been gained if another action had been taken. Over time, the accumulation of things learned and things not learned strongly affects the knowledge an individual chooses to acquire, focusing her knowledge about both the natural and social environment. This focusing narrows her view of the world and strongly affects her subsequent decisions about where and how she might effectively compete and cooperate. A simple, repeated path-dependent decision process drives this focus. At any moment, an individual must decide whether her interests are best served through the continued reliance on already existing knowledge or through actions that might generate new useful knowledge, i.e., through autonomous exploration or communication with others. That decision is strongly influenced by the individual's assessment of the net benefits of alternative actions which is strongly dependent on the individual's experience — that is, her focused, usually tentative, and always somewhat aged knowledge of a complex, dynamic environment.

For example, in a local part of a complex environment, a search conducted by someone who is already knowledgeable about that particular part of the environment is likely to be more directed and more likely to produce more accurate information than a search conducted by a person unfamiliar with that place. Thus, local experience can be the source of relative advantage in a competitive dynamic environment and is likely to make an individual even more strongly disposed to search familiar places again. The cost of this familiarity, however, is the loss of the knowledge that might have been acquired if other places had been searched. Similarly, repeated communications among familiar individuals are likely to be more nearly complete and less ambiguous than communications among individuals who do not know one another or the local context, leading to more informed decisions. Consequently, communications are likely to be strongly biased toward familiar individuals (Crona and Bodin, 2006). However, in a way that is similar to the results from autonomous search, the repetitive acquisition of knowledge from familiar individuals also comes at the cost of not acquiring other knowledge that might have been available from communications with and better understanding of other people.

Thus, the path-dependent effects of an individual's decisions tend to focus her knowledge towards areas and people with whom she is already familiar.[4] Within those areas and among those people, the individual can develop reasonably informed expectations about the likely outcome of her actions. These expectations are valuable and encourage the restrained behavior needed to maintain relationships with the individuals who are their source. Outside that particular environment her lack of experience creates pervasive uncertainty, making it more difficult for her to anticipate the outcome of her actions and, consequently, less likely to take them.

The benefits of familiarity are not unlimited, however. Familiarity feeds on itself and in the process erases some of its own benefits. That is, the more individuals know one another, the more they share a similar mental model of their environment and the less new, valuable information they can acquire from one another. In a dynamic environment, this kind of closeness creates high opportunity costs, shutting off opportunities and generating incentives for the acquisition of different knowledge from other, less familiar individuals and places. Thus, an individual has to find a balance between the benefits of communication with familiar people, which tends to diminish as her knowledge becomes too much like that of the people she works with, and the benefits of acquiring different knowledge through autonomous search and communications with unfamiliar people. The result of all individuals pursuing a similar strategy is a heterogeneous population in which each individual holds much of her knowledge in common with others, but at the same time actively differentiates herself from those others. The extent of commonality and differentiation depends largely on the costs of acquiring useful knowledge.

For an individual, the magnitude of the cost of new knowledge depends largely on his experience – i.e., what he already knows – and the complexity of his environment. For example, in a simple, i.e., a regular or a random environment, the knowledge an individual acquires in one place is easily transferable to other places. If the individual leaves a place, his absence is not particularly costly because when he returns the value of his previously acquired knowledge is largely intact. Thus, in the extreme instances of predictably regular (even with stochastic variation) and predictably random environments – two states almost universal in mathematical and statistical models of resource systems (Weaver, 1948) – both search and communication carry no opportunity cost (Fig. 1). Therefore, all individuals hold the same knowledge and there is little to gain from communications with any other individual. Consequently, social structure does not develop. The theoretical circumstances of perfectly competitive markets for homogeneous products are a good example of the social and economic outcomes that might be expected with low or zero information costs.

In a patchy, irregular and dynamic environment, on the other hand, an individual bears a higher cost when leaving a place. When he returns after an extended absence, he is likely to find that the practical value of his previously acquired knowledge is greatly diminished and that the cost of becoming current again is high. In this kind of environment, it is worthwhile for an individual to remain close to home, maintaining persistent communications with individuals and a group if other circumstances permit.

In short, the balance individuals choose between the autonomous search for knowledge and the acquisition of knowledge through communication with others works out in different ways (Fig. 1) depending on the dynamics of the resource they are exploiting. Generally, in simple environments, e.g., the kind of large, predictably regular or predictably random environments of standard fishing theory, the costs of individual search are low; as a result, the benefits of familiarity are low and individuals find little value from associations with others. If groups form, they are large and diffuse. On the other hand, in complex rapidly changing environments in which useful knowledge tends to be localized and ages quickly, the costs of information and the

[3] By social structure we mean persistent individual and group relationships.

[4] Our argument is similar to Williamson's (1985) argument about the importance of asset specificity. The principal difference is that we emphasize knowledge of the resource as the pertinent specific asset.

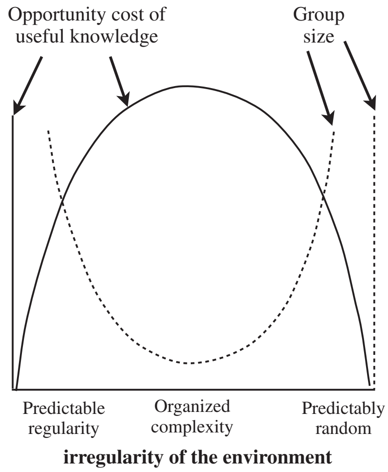

Fig. 1. The opportunity cost of useful knowledge and group size. In simple environments the cost of useful knowledge is low, favoring autonomous search. In complex environments useful knowledge is more costly favoring communication. However, maintaining accurate (trustworthy) communications is, itself, costly. Consequently, complexity creates a tendency for smaller groups.

benefits of familiarity are high, leading individuals to favor smaller groups and close, persistent relationships. Our presumption is that these social relationships are an important foundation for collective action.

As a result, and consistent with Ostrom (1990, 2000), we argue that if the costs of acquiring useful knowledge about the resource leads self-interested fishers to

1. engage in repeated, frequent communications with one another,
2. develop from those communications durable individual relationships,
3. form small groups based on those relationships, and
4. acquire a shared and realistic mental model (or set of beliefs) about the biological dynamics leading to a sustainable resource,

then, the informal, self-organizing social arrangements among fishers will reinforce the likelihood of successful collective action. Consequently, understanding the circumstances in which self-organizing social structure does or does not create a foundation for collective action is important to the development of good resource governance.

In the following sections of the paper, we analyze the way the biophysical and technological circumstances of three different fisheries affect the opportunity costs of search and communication. We pay close attention to the way the particular biophysical and social attributes of each fishery affect the relative costs of search and communication, and how those costs, in turn, affect the intensity and persistence of individual relationships, the size of the groups formed by those individuals and the likelihood of successful collective action.

3. Three Different Fisheries

3.1. Urchins

The Maine sea urchin roe fishery is a classic boom–bust fishery. It started growing rapidly in 1987 after the decline of other supplies to the Japanese market (Berkes et al., 2006). Landings peaked in 1993 when the fishery was the second most valuable fishery in the state after lobster. By 1994, nearly 3000 licensed divers and small draggers were targeting the resource. The rapid increase in landings and effort led to a decline in the abundance of urchins and, eventually, a significant reduction in effort. Today, the fishery remains in this depleted condition.

3.1.1. The Biophysical Domain

Sea urchins (*Strongylocentrotus droebachiensis*) are a sedentary species, moving short distances (tens of meters) primarily to feed. They are generally omnivores, but are most commonly associated with laminarian kelp. They can detect food from a distance of several meters and aggregate around it in response (Vadas and Beal, 1999). Well-fed urchins in kelp-grazing aggregations have high somatic growth rates (Scheibling and Hatcher, 2007). Urchin roe swells in the summer and fall; spawning occurs in the early spring, making the roe most valuable in the late fall and winter when it is the color, texture, and taste favored by the Japanese market.

Sea urchins are prolific broadcast spawners; in Maine, there does not appear to be any shortage of urchin larval production. Even in areas where shallow-water urchins appear to have been extirpated (McNaught, 1999), there is extensive larvae settlement, apparently the result of long-distance drift from probable spawning areas. Once larvae settle to the bottom, they become sedentary and are patchily distributed. They are found most often not only in rocky bottom areas in the subtidal and in tide pools in the low intertidal zone, but also on gravel bottoms in deep water and occasionally on sand (Scheibling and Hatcher, 2007). The relevant spatial scale of these processes leads to typical patch sizes on the order of 100 to several thousand square meters. In an unharvested system, the state of nearby sites can differ substantially due to the differing effects of wave action, storms, and ice.

Scientists have documented a strong interaction between urchins and kelp communities (Harris and Tyrrell, 2001; McNaught, 1999; Meidel and Scheibling, 2001; Steneck et al., 2013). When urchins are in low abundance, kelp beds thrive. As urchins feed on the kelp, they grow and their numbers are augmented by new settlement. As their density increases, large urchins aggregate into “grazing fronts” that feed extensively on the kelp along what is known as “the feedline.” In these circumstances, their growth and reproduction remains high. Eventually, with a reduction in kelp and an increase in the local urchin population, the nutritional state of urchins declines leading to reductions in growth and reproduction, a state called an urchin barren (Botsford et al., 2004). These barrens persist until wave action, ice scouring, or harvesting removes all, or at least a large proportion, of the urchins. Once urchins are eliminated, diatoms and then macroalgae grow rapidly; kelp beds can become reestablished within 2 to 3 years if there are no adult urchins present.

Even though larval distribution is extensive, repopulation of newly kelp-dominated sites through larval settlement appears to be limited. Steneck et al. (2013) describe local urchin extirpations, or local system flips, that occur as a result of urchin removal via intensive harvesting. Extirpation of urchins allows for increased growth of kelp forests providing favorable habitat for crabs that eat small urchins (Scheibling, 1996; Steneck et al., 2013). This kelp-dominated state appears to be relatively long-lived and stable; urchin fishermen report no known departures from this state once it is achieved (Johnson et al., 2012). In short, the mechanism leading to the observed broad-scale overfishing has been the long-term extirpation of one local site after another not, as one might suppose from the state-wide data, a uniform and gradual reduction of urchins along the entire coast.

3.1.2. The Social Domain

Formal institutions for managing this fishery have not prevented broad-scale depletion. Management did not begin until 1992, when an urchin license was first required. Soon after, in 1994, the state created a co-management system, consisting of an advisory council of industry members and independent scientists charged with providing management advice to state managers. The fishery has been managed primarily through input controls: limited entry, seasons, two large zones, and minimum and maximum size limits (the minimum size was set to conform to the requirements of the market and is well above the size of first maturity). Season length, is the most actively used control, and as in most fisheries managed this way, the length of the season has declined as the fishery has become more depleted. Currently, the fishery operates for 10 days in one zone and 45 days in the other. The scale at which these management measures are applied leaves individual sites in an open-access condition, and therefore, susceptible to overharvesting. As noted above, the usual outcome from overharvesting of any site is a local, and apparently long-term, system flip in which the site moves from a state with urchins and kelp to a kelp-dominated system with no urchins present.

Sea urchin harvesters are mobile and heterogeneous when compared to lobster fishermen, but less so than groundfish fishermen. Two gear groups, divers and draggers, target the resource mostly in shallow water sites that are accessed from numerous ports up and down the coast. Urchin harvesters move their operations easily from port to port and live in widely scattered coastal and inland communities. The lack of technological or institutional barriers to entry in 1987 resulted in a large, mobile, and heterogeneous fleet of small boats (6 to 12 m) characterized by skippers with diverse experience and knowledge.

Harvesting by divers occurs primarily on the feedline, where urchin roe is of the highest quality, and hence, highest market value. Some harvesters practice “straight raking,” where they take all urchins, while others take only the legal-sized urchins at the feedline. Usually the choice of harvesting technique depends upon the time of the year, prices, and the buyer's ability to easily detect differences in roe quality. Dragging, the least selective technique, is more important in eastern Maine where high tides, strong currents, and turbidity make diving more difficult.

The sedentary nature of adult urchins would appear to indicate a simple search problem. However, the complex interactions of urchins, kelp, and harvesters mean that the location of economically viable patches can change rapidly, creating a peculiar search problem with definite antisocial implications. At the time the fishery began, urchins were so abundant that little knowledge or experience was needed for success. This meant that there were few incentives for either sharing or withholding information about the location of urchins (Johnson et al., 2012). A completely autonomous diver could leave an area and return the next month, or year, with only a small learning cost. As a result, harvesters formed few associations that might make their searches more efficient.

The rapid depletion of the fishery led to different biological circumstances, but little apparent change in individual and social relationships among harvesters. Depletion is not a simple reduction in the average density of urchins. Rather it leads to increasing patchiness of economically viable urchin aggregations. In the current fishery, the remaining productive sites are in various intermediate states between the flipped state and an urchin barren. The quantity, quality, and age distribution of urchins and the density of fishable aggregations vary widely on these sites mostly due to harvesting. As one might suspect, this creates a difficult search problem for harvesters. A harvester might visit a site one day, leaving it in a nicely fishable state, only to return a day or a week later and find it has been stripped by another harvester. Simple observation of another harvester anchored and diving at a site might indicate a productive site or, just as likely, the end of a productive site. This kind of rapid and unpredictable change (from the perspective of the harvester) makes information sharing far less valuable than it would be in a more predictable environment. It means that harvesters acquire new knowledge about the resource almost exclusively through autonomous search and has led them to develop “quick search” techniques that allow them to assess sites with minimal expenditure of time. The technique also means smaller patches can be economically exploited. When divers find a site this way they immediately begin harvesting and, of course, do not broadcast the news of their find. Consequently, even though the fishery is depleted and patchy, the unpredictability of the resource created by the actions of the harvesters themselves means there are generally few opportunities that might lead to the growth of cooperative behavior and little basis for the growth of informal institutions (Johnson et al., 2012).

3.2. Lobster

The American lobster (*Homarus americanus*) is found in the inshore waters off the Atlantic Coast of North America from Newfoundland to Virginia. The bulk of the lobster fishery is an inshore day fishery conducted from small boats, using traps. In Maine, where approximately 75% of US landings occur, the majority of boats are 10 to 15 m long and are operated by one to three person crews who fish up to 800 wire traps. They use hydraulic haulers to retrieve traps. The electronic gear for communications and locating traps is quite standard (Acheson, 2003). Currently there are about 6000 lobster boats in Maine. Total landings in the fishery have risen steadily since the late 1980s and are now approximately five to six times the average of the 42 years from 1947 to 1989 (Fig. 2).

3.2.1. Biophysical Domain

Although lobsters can be found at depths ranging to 1200 ft, (400 m) the vast majority live in waters within 3 miles of shore at depths of less than 150 ft (25 fathoms). Lobsters are relatively sedentary. Early work on migration in the 1950s found that the majority of lobsters were caught within 2 miles of where they were released. Other studies show that more extensive local movements occur (Krouse, 1977). Under some circumstances, lobster will move long distances (Cooper and Uzmann, 1971; Pezzack and Duggan, 1986); however, Cowan et al. (2007) report that younger lobsters, that are the bulk of the catch, are relatively sedentary whereas the ones that move longer distances are larger, older animals. Lobsters move into shallow water to molt in late spring and summer. At this time of year, fishermen place most of their traps in shallow water. Since there is relatively little of this “shedder bottom,” traps are crowded and placement is highly competitive. Fall is the most productive time of year. Catches are high, and fishermen concentrate their traps in areas between 20 and 30 fathoms, which can be a few miles from shore. As fall turns to winter and shallow water turns colder, lobsters are more often caught in deep, relatively warmer water on muddy bottom, so fishermen respond by moving traps to these areas. Since there is a good deal of this mud bottom and fishing is less productive, traps are further apart and less competitive. The location of concentrations of lobsters plays a major role in determining where fishermen place traps. They are also constrained by informal territorial rules and formal zone boundary lines.

3.2.2. The Social Domain

From 1947 to 1989, lobster catches averaged about 20 million lbs per year (Maine DMR, n.d.) (Fig. 2). Since the early 1990s catches have risen steadily and are now at 123 million lbs in 2012, a record high level. Although there is no consensus on the reasons for these record high catches, two factors are almost certainly involved: (1) environmental factors (e.g., favorable water temperature and low predation by large

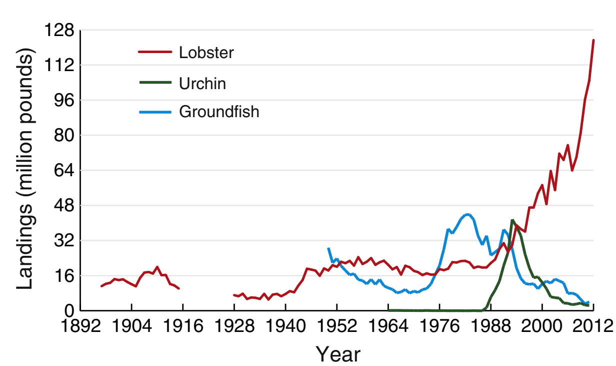

Fig. 2. Historical landings in millions of pounds for the State of Maine based on data from the Maine Department of Marine Resources. Landings for groundfish and urchins are only available from 1950 and 1960, respectively. The category groundfish combines landings for cod, haddock, hake, pollock, and cusk.

finfish, (Steneck et al., 2011) and (2) effective formal and informal rules that restrain fishing through an extensive set of input controls (Acheson and Steneck, 1997).

Yet, it was not always this way. In the late 1920s and early 1930s, catches dropped to between 5 and 7 million lbs. During this “bust,” low catches were matched by low prices. Incomes were so low that 40% of lobster fishermen went out of business between 1928 and 1930 (Maine Department of Marine Resources and Correspondence of the Commissioner, 1933). The bust was a searing experience for the industry — one that caused a major change in attitudes towards conservation (Acheson, 2003; Acheson and Gardner, 2010).

The lobster industry is highly territorial. To lobster, a person must gain acceptance by a group of people fishing from one harbor, called by Acheson (1988) a “harbor gang.” Once admission is gained, the fisher can fish only in this group's territory, with territories averaging about 100 $mile^2$ (~250 km^2). This means that lobster harvesters spend their lives crisscrossing a small body of water, which they come to know intimately. This territory is jointly held by a group of people who know each other well. It is defended by keeping intruders at bay, in some cases by the surreptitious destruction of gear (Acheson, 1988, 2003; Wilson et al., 2007). Offshore, where skippers exploit far larger, nonterritorial areas, they tend to operate like a typical mobile fishing operation, taking concentrations of lobsters wherever they occur.

These gangs are also reference groups. One is a good or bad fisherman in comparison to others in the same harbor or from nearby harbors. In such harbor groups, a good deal of social capital has been built up. As a result, they are able to organize to defend fishing territories, they cooperate in getting bait, and many have organized cooperatives. None of this is to suggest that fishermen in the same harbor gang are always friendly. If they are useful to each other, they are also competitors. Within any gang, there is intense competition to become a “highliner,” a person who earns a lot and catches a lot of lobsters (Acheson, 1988). An important aspect of territoriality is that it restricts the movement of fishermen. Fishing outside one's territory can be costly because of the defenses raised in other territories and even if a fisher does move successfully to another area the cost of coming home can be high.

Fishing skills are important for success. Those who have learned where to place traps catch far more lobsters than others fishing in the same place using the same amount of effort. Learning trap placement skills is not easy. Lobsters move across the bottom and are rarely in the same place for more than a few weeks. The local places where they are found will almost certainly change from year to year. Learning how to find these concentrations of lobsters is a never-ending process and is a lesson that highly skilled fishermen have mastered, but which remains a mystery to the “dub” fishermen.

Many factors influence where traps should be placed and how they should be fished: season, type of bottom, bait type, number of traps in the area, depth, and working time of the bait (Acheson, 1988, 2003). To complicate matters, fishermen will try to obscure the degree of their success. Nevertheless, it is far easier to learn about lobster concentrations than it is to learn about locations of groundfish or urchins. One source of knowledge is communications among fishermen. Older kinsmen will often instruct novices about lobster movements. Moreover, fishermen will often exchange accurate information on their lobster operations and degree of success with others at the same level of skill expecting reciprocation. There is no reason to be secretive about lobster locations after concentrations of lobsters have moved out of the immediate area. Fishermen make little effort to conceal their activities and GPS and sonar have made it easier to learn about depths, locations, and types of bottom. And most important, one can see where others have traps and how they are moving them.

The Maine lobster industry is unusual in that it has had great success in solving its collective action problems with restraints that limit the inputs to fishing, i.e., the number of people, boats, traps. Like many traditional local fisheries there are no rules intended to control the number of lobsters caught (Wilson et al., 1994; Acheson and Wilson, 1996; Schlager and Ostrom, 1992). Over the course of the past 120 years, five important restraints have been enacted in the law:

1. Lobsters may only be caught by traps. Trawls are prohibited.
2. Lobsters must be 3.25 in. (82.5 mm) on the carapace, which protects juvenile lobsters, and less than 5 in. (127 mm) on the carapace, which creates a protected pool of large, long-lived, reproductive-sized lobsters (Cowan et al., 2007).
3. Traps must be equipped with biodegradable escape panels that allow small lobsters to escape and, if the trap is lost, keep it from fishing indefinitely.
4. A lobster with eggs attached to her belly may not be sold. Fishermen may voluntarily cut a notch in the tail of an egged lobster (a V-notch), preventing others from scrubbing the eggs in an attempt to sell the lobster. A lobster with a V-notch may not be sold as long as any mutilation from the V-notch is visible (Acheson, 2003).
5. In 1995, the state legislature passed the so-called zone management law, which not only changed many aspects of lobster management (e.g., apprenticeship program, statewide trap and license limit), but also formalized the importance of bottom-up rule-making. It established a co-management system making it possible for lobstermen in any one of seven zones to change several management practices in that zone by a two-thirds majority vote. In recent years, many of the most important lobster management rules have been passed within the framework of the new co-management system.

All of these laws were passed with strong support by the industry often after long negotiations between the industry and the state government. Compliance is high. Fishermen believe the rules are effective (and have considerable evidence to support that belief) and, because of the local nature of the fishery, they have strong assurances that all other fishermen are following the rules.

If one considers the rules governing the lobster fishery the result of a costly collective search for biologically effective and enforceable restraints, then the substance of these rules is interesting because they strongly reflect fishermen's experiences and the immediately observable impact of fishing. They are based on the belief that the circumstances that ensure reproduction have to be protected, and to this end, multiple rules have been developed. The rule allowing fishing only with traps (prohibiting trawls) reflects first-hand experience with the effect of trawls on the benthic habitat favorable to lobsters (Acheson, 2003). Rules prohibiting the retention of egged lobsters and V-notching were justified in terms of common-sense protection of reproductive capabilities. The minimum size allows lobsters to reach the age of maturity and the maximum size rule aims to maintain an older population that is believed to make a disproportionately large contribution to egg production (Cowan et al., 2007). Biodegradable vents in traps minimize the predation exposure of young under-legal-size lobsters. If a trap is lost, the entire vent falls out, which stops the traps from “ghost fishing” indefinitely.

The knowledge required to verify the immediate effect of these rules was available to every fisher and for that reason their rationale was (and is) universally endorsed. Recent scientific work also affirms that the longer term effect of these rules is strongly positive (Zhang, 2010). This kind of knowledge contrasts strongly with the knowledge required to sustainably manage using output controls. The rational application of output controls requires quantitative knowledge of the long term relationship between current population size and future recruitment. Fishers do not have this knowledge and after decades of research there is little or no scientific evidence supporting the required knowledge (Incze et al., 2010).

3.3. Groundfish

The Gulf of Maine groundfishery pursues demersal fish such as cod (*Gadus morhua*), white hake (*Urophyscus tenuis*), pollock

(*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), flounders, and miscellaneous other finfish, 17 species in all. Since the beginning of extended jurisdiction in 1977, these species have been managed as if each was a single broad-ranging stock that inhabited the whole of the Gulf of Maine (and for some species all of Georges Bank and southern New England waters) (Apollonio and Dykstra, 2008). For nearly 20 years, almost all the species in the fishery have been severely depleted and abundance today is near or below the levels in 1977.

From the beginning of extended jurisdiction, there has been strong disagreement between fishers and scientists about the abundance of fish and the appropriate route to successful collective action (Acheson, 2011). The skippers of larger mobile boats, extrapolating from their experience, often reported greater abundance than scientists. Small "day" boat fishers who happened to be in localities where fish were abundant, e.g., the western Gulf of Maine, also thought the scientists were underestimating abundance. However, other small-boat fishers located in areas where stocks had been extirpated, such as Downeast Maine and the Massachusetts islands south of Cape Cod, argued that scientists were overstating the abundance of fish. Scientists, arguing from the results of their broad-scale randomly stratified surveys, claimed that on average the species in question were not nearly as abundant or were more abundant than fishers claimed (depending on which group of fishers they were talking to). The point is that the heterogeneous nature of the biological regime and the differing scale and location of the observation and analysis of the groups engaged with the fishery have not led to a shared sense of the current abundance of groundfish nor to a common mental model about the spatial structure of the stocks or the effects of fishing.

When scientists, managers and different groups of fishers have such different mental models of how the natural system reacts to fishing, the likelihood of a consensus leading to collective action is low. The more likely result is collective rules that reflect the interests of a dominant group or coalition of the interested parties (Acheson and Knight, 2000). Consequently, whether conservation or depletion results, it is the incidental outcome of a distribution fight. In the groundfishery, depletion has been the result.

Compared with the usual management assumption of broad-scale stocks, recent scientific evidence points to finer-scale population structure among groundfish species, i.e., multiple demographically distinct stocks of the same species contained within the area currently managed as if there was only a single stock (Ames, 1997, 2004). This evidence generates a picture of a patchy, complex ocean that is consistent with fishers' observations and what scientists know about both marine and terrestrial ecosystems.

In this kind of environment, searching for fish is a significant problem. No matter what kind or scale of gear (hooks or large trawls) they employ, fishers have to search for patches or schools of fish. Where they fish and what kinds of aggregations they can or prefer to target depends upon the scale of the gear they employ. Nevertheless, the behavior of the fish does not reflect the kind of gear that might catch them (so far as we know) and for this reason groundfishers working at all scales face a similar search problem,[5] but the feedback they get about the effect of their actions differs according to the kind of gear they use. This problem determines what knowledge fishers hold close and what they share. As we discuss, the social result of these competitive forces is another major reason why the basis for collective action in the fishery is so weak.

Adults of each of the groundfish species show variations on a common behavioral pattern over the course of the year. Spawning times for local stocks occur in either spring (most common) or fall. Before spawning, stocks tend to form fairly dense aggregations usually on the shoulder of the coastal shelf. They then move towards a spawning site on the shelf, spawn and afterwards disperse to follow a seasonal pattern of feeding opportunities. Generally, the broad direction of migratory movements is fairly reliable, but the timing and local deviations from the general route vary, often significantly, from year to year depending on water temperatures, storms, currents, the movements of prey species such as herring and alewives and, sometimes, competing species such as dogfish (which fish like cod tend to avoid).

The distances typically moved by each species differ, with haddock and flounders having a reputation for being the least likely to cover large distances and pollock the most. The population patterns of cod appear to be flexible; stocks appear to adapt to local residency and even to highly migratory life styles. This flexibility may extend even to fish within a single local stock (Robichaud and Rose, 2004; Rose, 2007). The finer-scale movements of flounders are less well known. The general opinion among fishers is that flounders are influenced less by mobile prey and more by relatively sedentary benthic food sources. As a result, fishers believe that flat fish move from deep to shallow water as the shallow waters become warm (relative to the deep waters) staying on preferred bottom types – mud or sand – in the process. As shallow waters cool, the movement reverses.

All fishers know these broad seasonal patterns of the species they fish and readily discuss them in public. This open discussion attests to the low competitive value accorded to knowledge of broad-scale fish movements; the industry generally does not object to the public reporting of catch locations, but only at a reporting resolution of 10′ of latitude and longitude, about 100 nautical mile^2. What is not discussed, but is much more important for successful fishing, is knowledge of the current location and direction of movement of fish aggregations. The scale of this knowledge occurs at a much finer resolution than a 10′. When it is current, this knowledge is valuable, but because fish move, its value is relatively short-lived. Fish can stay in roughly the same place for days or weeks, but currents, storms, changes in water temperature, and the movement of prey can cause the location of aggregations to change quickly. Understanding how these changes affect the movement of the fish is the key to efficient search and catching. By efficient search, we mean the ability to consistently search in places to which aggregations of fish have moved. Fishers call it "staying on the fish." In the usual broad-scale regulatory environment, these incentives for efficient search generate a spatial version of the race to fish and lead to the serial depletion of finer-scale subpopulations (Wilson, 2006; Wilson et al., 1999).

In environmentally complex areas with rough topography, strong currents, and a large tidal range, experience in a particular locality is important; knowledge about why fish might be in one rather than another place and why they might move this way rather than another is tailored to that particular environment. Such specific knowledge does not travel well to other locations because of the complexity of the local physical environment in which it was acquired. Nevertheless, a good fisher from a physically complex place might do well in a different equally complex environment because he knows what he has to learn. In the more commonly fished, deeper and less complex environments, knowledge of fish behavior is more easily generalized from place to place. Thus, in these deeper areas, a good fisher – i.e., one who understands the way fish respond to changes in water temperatures, currents, and other local conditions – can rapidly learn where the fish are even in an unfamiliar environment. Fish finders are helpful, but their range is very local, and they do not replace the fisher's understanding of the right localities to search. This understanding is what leads a good fisher to the fish; it generates specific knowledge of the immediate location of fish and when the feat is consistently repeated it defines a highliner. As might be expected, knowledge at this temporal and spatial scale is the source of competitive advantage and is held very tightly (Wilson, 1990).

[5] Except that draggers/trawlers have the ability to fish on much less dense aggregations and often, when coming to port for example, might tow for hours with little clue about the availability of fish.

The result of these search circumstances is that groundfishers have little reason to share valuable fine-scale information with one another, but they do share broader-scale information in private and public (Holland et al., 2010). Groundfishers range rather widely; even small boats cross local stock boundaries (Acheson, 2011). Trip boats often come from many different ports and go for long times without seeing one another. Although they do develop personal relationships, these relationships are based on alliances in the regulatory arena. Local day boat fishers have greater contact with one another, but they have very different experiences on the water compared to trip boats. As a result skippers of the two classes of boats have different mental models of the resource and small boat fishers tend to have different models depending on their local experience. This leads to a situation in which there is little industry-wide basis for self-organizing social structure that supports the kind of restraint necessary for successful collective action. Instead there is perpetual political conflict among the various segments of the industry.

4. Conclusions

We suggest the principal factor leading to informal relationships among individuals and the organization of groups is the costs individuals accrue while acquiring useful knowledge about the resources they use. Depending on the attributes of the environment, these informal relationships vary in ways that have a significant effect upon the likelihood of successful collective action.

In simple environments, such as occur when the spatial and temporal distribution of the resource (as perceived by the fisherman) is either predictably regular or predictably random, the cost of useful knowledge about the resource is low, and there is little or nothing that individuals gain by associating with one another. Consequently, there is likely to be no informal social structure supportive of collective action.

For example, even though the urchin resource is sedentary and patchy, its method of extraction injects a large element of randomness that makes it difficult for harvesters to predict the location of valuable patches. Because of this harvesters tend to treat found urchins as a windfall, do not interact frequently, do not develop close working relationships, and have only weak personal incentives encouraging restraint when a windfall is located. As a result, the prospects for collective action are very weak. In the groundfishery, even though the broad-scale patterns of the resource are well known, the importance of the very short-term and fine-scale deviations from these patterns and differences in the scale at which day boats and trip boats observe the fishery leads to scale-specific secrecy, infrequent encounters, and weak incentives for restraint. Here, also the social conditions supportive of collective action are not present.

In complex environments, on the other hand, the cost of useful knowledge is positive and individuals can gain by sharing information with one another. The extent of the gain and the resulting social context depends upon the particular learning problem individuals face in various environments. In some environments, such as the lobster fishery, the speed and patterns of movements of the resource and the harvesting technology creates a search and learning problem that brings lobster harvesters together on a near daily basis. These repeated communications and observations allow them to form relatively secure expectations about one another's behavior, to develop a continuing beneficial relationship and, because of an expectation about the value of continuing those relationships, an understanding of the value of restraint. This is the basis for the formation of persistent relationships and for the growth of those relationships into groups or, in the lobster fishery, 'harbor gangs.'

Whether one believes this social capital makes a difference, depends upon one's view of the ocean system. If one believes the typical single species representation of fisheries is an adequate description of the sustainability problem, then social capital is essentially irrelevant. All that should be necessary for sustainability is strict enforcement of a quota or other rules limiting catch. From this perspective the persistent success of the lobster fishery can only be explained as the lucky result of the depletion of predators. Although we are not aware of any evidence (except the correlation apparent in the latter years of Fig. 2) to support this often-stated argument, it is reasonable to assume, simply from basic ecology, that lobsters have benefitted from a decline in predators. Nevertheless, there is strong evidence from the period 1940 to the decline of groundfish in the mid-to-late 1980s that the rules governing the harvest of lobster had maintained a steady, sustainable fishery in spite of high levels of effort and the presence of groundfish. We also know that before the 1940s, when these rules were not in place, the lobster fishery had been thoroughly depleted (Fig. 2). In other words, the rules governing harvesting in the lobster fishery may not be the source of the current extraordinarily high levels of abundance, but since the 1940s they do seem to have protected the multiple determinants of reproductive success in the fishery, avoiding, thereby, the deep depletions experienced in other fisheries. Consequently, if one views fisheries as complex multiscale systems then the social capital that has been created in the lobster fishery is important because it has brought to the public table knowledge of the life history and fine-scale behavior of both lobsters and lobster harvesters and has resulted in a set of restraining rules that have sustained the fishery. Normally these kinds of input controls are shunned by managers because it is assumed harvesters can easily defeat their intent with changes in fishing strategies and 'capital stuffing' (Townsend, 1985). That kind of outcome appears to be avoided in the lobster fishery through careful choice of rules and a social structure that enforces their application.

In short, our argument is that the differences in the management outcome in these three fisheries can be traced back to the problem fishermen face when acquiring useful knowledge about the resource. In the lobster fishery this problem led to the formation of persistent, self-interested individual and group relationships. These relationships created a solid foundation for individual restraint and collective action. An important product of that collective action was an articulate, even if incomplete, understanding of the life history and behavior of lobsters and lobstermen. That knowledge was combined with scientists' knowledge and brought into the public arena where it resulted in a multiscale set of input rules that restrain fishing and have sustained the fishery. In the urchin and groundfisheries, on the other hand, the broad scale of formal regulations encouraged highly mobile harvesting strategies; these strategies did not lead to persistent informal social structure or to private incentives for mutual restraint.

Finally, since almost all the participants and managers of these fisheries were aware of the governance process in the lobster fishery, it is reasonable to ask why the management practices in the lobster fishery, especially matching the scale and other restraining rules to the local ecology, did not migrate to urchins and groundfish. This is an important question because our ability or willingness to learn from other people's experience is a critical mechanism for the evolution of sustainable management. In the instance of these three fisheries we would tentatively argue that the differences in fishing incentives were, indeed, so strong that the principal stakeholders did not see the fisheries as comparable. In the lobster fishery the restricted geographic scope of fishermen's activities, the apparently localized ecology and the history of the fishery were important factors in the perception of benefits of restraint. In the urchin fishery, on the other hand, fishermen quickly adapted to a mobile fishing strategy and in the groundfishery a highly mobile strategy was the norm for centuries. Any regulatory shift towards restricted mobility, which might have better aligned the scale of the ecology and governance of the fisheries and led to the creation of more social capital, would be immediately threatening to the economic viability of the fishing strategies and technologies that fishermen depended upon. While we might argue that these different incentives were important in this instance, we do not argue that they are the only factors that prevented the migration of good practices. Understanding the circumstances in which it is possible to learn from others experience is an important question for sustainability but not one that is resolved by the evidence we provide here.

Acknowledgments

We want to acknowledge the help of the many Maine fishermen, especially Ted Ames, who have given their time to talk with us about the problems addressed here. The support of the NSF program on the Dynamics of Coupled Natural and Human Systems [project 0909449] and Maine Sea Grant was invaluable. Along the way, our colleagues Yong Chen, Robert Vadas, Lew Incze, Huijie Xue, and Rick Wahle, and Robin Alden at Penobscot East Resource Center, and Carl Wilson, Maggie Hunter and Robert Russell at the Maine Department of Marine Resources and students Caitlin Cleaver, Mike Kersula, Julia Beaty, Pete Hayes, Jack Hill, Chris Wilson, Larry Whitsel, and Graham Morehead raised helpful questions and sometimes objections which we have tried to answer in the text.

References

Acheson, J.M., 1988. The Lobster Gangs of Maine. University Press of New England, Hanover, NH.
Acheson, J.M., Wilson, J.A., 1996. Order out of chaos: The case for parametric fisheries management. American Anthropologist 8 (3), 579–594.
Acheson, J.M., 2003. Capturing the Commons: Devising Institutions to Manage the Maine Lobster Industry. University Press of New England, Hanover, NH.
Acheson, J.M., 2011. Coming up empty: management failure of the New England groundfishery. Marit. Stud. 10, 57–85.
Acheson, J.M., Gardner, R., 2010. The evolution of conservation rules and norms in the Maine lobster industry. Ocean Coast. Manag. 53, 524–534.
Acheson, J.M., Knight, J., 2000. Distribution fights, coordination games and lobster management. Comp. Stud. Soc. Hist. 42, 209–239.
Acheson, J.M., Steneck, R.S., 1997. Bust and then boom in the Maine lobster industry: perspectives of fishers and biologists. N. Am. J. Fish. Manag. 17, 826–847.
Agrawal, A., 2002. Common resources and institutional sustainability. In: Ostrom, E., Dietz, T., Dolsak, N., Stern, P., Stonich, S., Weber, E. (Eds.), The Drama of the Commons. National Academy Press, Washington, DC, pp. 41–85.
Ames, E.P., 1997. Cod and haddock spawning grounds of the Gulf of Maine from Grand Manan to Ipswich Bay. In: Hunt von Herbing, I., Kornfeld, I., Tupper, M., Wilson, J. (Eds.), The Implications of Localized Fishery Stocks. PALS Publishing, Ithaca, NY.
Ames, E.P., 2004. Atlantic cod stock structure in the Gulf of Maine. Fisheries 29, 10–28.
Apollonio, S., Dykstra, J., 2008. An Enormously Complicated Intervention, in: Groundfish, The New England Fishery Management Council, and the World Fisheries Crisis. E-Book Time, LLC, Montgomery, AL.
Berkes, F., Hughes, T.P., Steneck, R.S., Wilson, J.A., Bellwood, D.R., Crona, B., Folke, C., Gunderson, L.H., Leslie, H.M., Norberg, J., Olsson, P., Nyström, M., Österblom, H., Scheffer, M., Worm, B., 2006. Globalization, roving bandits, and marine resources. Science 311, 1557–1558.
Botsford, L.W., Campbell, A., Miller, R., 2004. Biological reference points in the management of North American sea urchin fisheries. Can. J. Fish. Aquat. Sci. 61, 1325–1337.
Cooper, R., Uzmann, J., 1971. Migration and growth of deep sea lobsters. Science 171, 288–290.
Cowan, D., Watson III, W.H., Solow, A.R., Mountcastle, A.M., 2007. Thermal histories of brooding lobsters, *Homarus americanus*, in the Gulf of Maine. Mar. Biol. 150, 463–470.
Crona, B., Bodin, Ö., 2006. What you know is who you know? Communication patterns among resource users as a prerequisite for co-management. Ecol. Soc. 11 (2), 7 (www.ecologyandsociety.org/vol11/iss2/art7/).
Harris, L.G., Tyrrell, M.C., 2001. Changing community states in the Gulf of Maine: synergism between invaders, overfishing and climate change. Biol. Invasions 3, 9–21.
Holland, D., Pinto da Silva, P., Weirsma, J., 2010. A survey of social capital and attitudes towards management in the New England groundfishery. U.S. Department of Commerce, Northeast Fisheries Science Center Ref Doc 10-12, p. 13.
Incze, L., Xue, H., Wolff, N., Xu, D., Wilson, C., Steneck, R., Wahle, R., Lawton, P., Pettigrew, N., Chen, Y., 2010. Connectivity of lobster (*Homarus americanus*) populations in the coastal Gulf of Maine: part II. Coupled biophysical dynamics. Fish. Oceanogr. 19, 1–20.
Johnson, T., Wilson, J., Cleaver, C., Vadas, R., 2012. Social–ecological scale mismatches and the collapse of the Maine sea urchin fishery. Ecol. Soc. 17, 259–271.
Krouse, J., 1977. Lobster tagging study. Lobster Information Leaflet, no. 5. Maine Department of Marine Resources, Augusta.
Maine Department of Marine Resources (DMR), d. Historical Maine Fisheries Landing Data http://www.maine.gov/dmr/commercialfishing/historicaldata.htm.
Maine Department of Marine Resources, Correspondence of the Commissioner, 1933. Horatio Crie to Russell Turner, Sept 23, 1933.
McNaught, D., 1999. The indirect effects of macro algae and micropredation on the post-settlement success of the green sea urchin in Maine. Unpublished doctoral thesis, University of Maine, Orono.
Meidel, S.K., Scheibling, R.E., 2001. Variation in egg spawning among subpopulations of sea urchins *Strongylocentrotus droebachiensis*: a theoretical approach. Mar. Ecol. Prog. Ser. 213, 97–110.
North, D., 1990. Institutions, Institutional Change and Economic Performance. Cambridge University Press, New York.
North, D., 2007. Understanding the Process of Economic Change, Princeton Economic History of the Western World. Princeton University Press, Princeton, NJ.
Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, New York.
Ostrom, E., 2000. Collective action and the evolution of social norms. J. Econ. Perspect. 14, 137–158.
Pezzack, D., Duggan, R., 1986. Evidence of migration and homing of lobsters (*Homarus americanus*) on the Scotia Shelf. Can. J. Fish. Aquat. Sci. 41, 2206–2211.
Robichaud, D., Rose, G.A., 2004. Migratory behaviour and range in Atlantic cod: inference from a century of tagging. Fish Fish. 5, 185–214.
Rose, G.A., 2007. The Cod: Ecological History of the North Atlantic Fisheries. Breakwater Books, St. John's, Newfoundland.
Scheibling, R.E., 1996. The role of predation in regulating sea urchin populations in eastern Canada. Oceanol. Acta 19, 421–430.
Scheibling, R.E., Hatcher, B.G., 2007. Chapter 18: ecology of *Strongylocentrotus droebachiensis*. In: Lawrence, J.M. (Ed.), Developments in Aquaculture and Fisheries Science. Elsevier, Cambridge, MA.
Schlager, E., Ostrom, E., Aug., 1992. Property-rights regimes and natural resources. Land Econ. 68 (3), 249–262.
Steneck, R., Hughes, T.P., Cinner, J.E., Adger, W.N., Arnold, S.N., Berkes, F., Boudreau, A., Brown, K., Folke, C., Gunderson, L., Olsson, P., Scheffer, M., Stephenson, E., Walker, B., Wilson, J., Worm, B., 2011. Creation of a gilded trap by the high economic value of the Maine lobster fishery. Conserv. Biol. 1, 9.
Steneck, R., Leland, A., McNaught, D.C., Vavrinec, J., 2013. Ecosystem flips, locks, and feedbacks: the lasting effects of fisheries on Maine's kelp forest ecosystem. Bull. Mar. Sci. http://dx.doi.org/10.5343/bms.2011.1148.
Townsend, R., 1985. On capital stuffing in regulated fisheries. Land Econ. 61, 195–197.
Vadas, R.L., Beal, B.F., 1999. Relationships between adult size, maturity and fecundity in green sea urchins: the potential use of a roe-yield standard as a conservation tool. Report to the Maine Department of Marine Resources. Boothbay Harbor, ME.
Valiant, L., 2013. Probably Approximately Correct. Basic Books, New York.
Wade, R., 1994. Village Republics: Economic Conditions for Collective Action in South India. ICS Press, San Francisco.
Weaver, W., 1948. Science and complexity. Am. Sci. 36 (4), 536–544.
Williamson, O., 1985. The Economic Institutions of Capitalism: Firms, Markets, Relational Contracting. Free Press, New York.
Wilson, J.A., 1990. Fishing for knowledge. Land Econ. 66, 12–29.
Wilson, J.A., 2006. Matching social and ecological systems in complex ocean fisheries. Ecol. Soc. 11 (1), 9.
Wilson, J.A., Acheson, J., Kleban, P., Metcalfe, M., Metcalfe, M., Chaos, 1994. Complexity and Community Management of Fisheries, in Marine Policy. 18 (4), 291–305.
Wilson, J.A., Low, B., Costanza, R., Ostrom, E., 1999. Scale misperceptions and the spatial dynamics of a socio-ecological system. Ecol. Econ. 31, 243–257.
Wilson, J.A., Yan, L., Wilson, C., 2007. The precursors of governance in the Maine lobster fishery. Proc. Natl. Acad. Sci. U. S. A. 104 (39), 15212–15217.
Wilson, J.A., et al., 2013. Costly information and the evolution of self-organization in a small, complex economy. J. Econ. Behav. Organ. http://dx.doi.org/10.1016/j.jebo.2012.12.019.
Zhang, Y., 2010. Stock Assessment and Harvest Control Rule Evaluation for American Lobster in the Gulf of Maine. (PhD thesis) University of Maine, Orono.