Spring 5-3-2024

Boundaries, Learning, and Collective Action: a Socio-Ecological Analysis of Fisheries in the Gulf of Maine and the North Atlantic

Anne CJ Hayden
University of Maine, anne.hayden@maine.edu

BOUNDARIES, LEARNING, AND COLLECTIVE ACTION: A SOCIO-ECOLOGICAL ANALYSIS OF FISHERIES IN THE GULF OF MAINE AND THE NORTH ATLANTIC

By

Anne Hayden

B.A. Harvard College, 1977

M.S. Duke University, 1985

A DISSERTATION

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

(in Interdisciplinary Studies)

The Graduate School

The University of Maine

May 2024

Advisory Committee:

James Wilson, Emeritus Professor of Marine Policy

Joshua Stoll, Associate Professor of Marine Policy

Keith Evans, Associate Professor of Economics

Christine Beitl, Associate professor of Anthropology

Michelle Staudinger, Associate Professor of Marine Sciences

UNIVERSITY OF MAINE GRADUATE SCHOOL LAND ACKNOWLEDGMENT

The University of Maine recognizes that it is located on Marsh Island in the homeland of Penobscot people, where issues of water and territorial rights, and encroachment upon sacred sites, are ongoing. Penobscot homeland is connected to the other Wabanaki Tribal Nations— the Passamaquoddy, Maliseet, and Micmac—through kinship, alliances, and diplomacy. The University also recognizes that the Penobscot Nation and the other Wabanaki Tribal Nations are distinct, sovereign, legal and political entities with their own powers of self-governance and self-determination.

BOUNDARIES, LEARNING, AND COLLECTIVE ACTION: A SOCIO-ECOLOGICAL ANALYSIS OF FISHERIES IN THE GULF OF MAINE AND THE NORTH ATLANTIC

By Anne Hayden

Dissertation Advisor: Dr. James Wilson

An Abstract of the Dissertation Presented
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy
(in Interdisciplinary Studies)
May 2024

Atlantic Cod *Gadus morhua* has been subject to commercial exploitation since the thirteenth century. An analysis of cod fisheries over space and time reveals a pattern of serial depletion that reflects the cross-scale interaction of fish population structure, economic incentives, developments in fishing technology, and government efforts to limit access to fishing areas. The meta-population structure of cod populations allows overharvesting, even when strict but broadscale controls are in place. Three case studies illustrate a pattern of fish population depletion followed by expansion of fishing activity that repeats at a range of scales.

Sustainable use of a commons, rare among fisheries, is attributed to conditions that constrain users to a defined territory, limit the number of users, and align such a territory with local conditions. Constrained by boundaries, fishermen's incentives shift from maximizing harvests in the short term to ensuring sustained harvests over the long term. Fishermen learn

from others where to fish when they find it less costly to do so than than to search for fish themselves. When a fishing territory is congruent with local components of a metapopulation, sharing information, a form of social learning, allows fishermen to develop a refined, collective understanding of subpopulation dynamics and can lead to group formation and the capacity to address unsustainable harvests and other collective action dilemmas.

Co-management, the sharing of responsibility for management between fisheries agencies and fishermen, allows for local information to be incorporated into the management process and for fishermen to test management strategies based on their understanding of population dynamics. It reduces the costs for fisheries agencies of monitoring and understanding fine scale conditions and allows for local action that they cannot manage. Analysis of comanaged fisheries in Maine, for lobster, clams, river herring, and scallops, indicates that comanagement improves fisheries productivity and is more effective than standard, top-down, broad-scale fisheries management

ACKNOWLEDGEMENTS

Chapter 1 was published in Conservation and Society in 2015 (Hayden, Acheson et al. 2015). In addition to their involvement in development of the paper, my co-authors, James Acheson, Michael Kersula, and James Wilson, contributed sections on the role of technology, markets and administrative boundaries.

Chapter 2 has been submitted to Ecology and Society. My co-author, James Wilson, oversaw the development of the paper and provided critical insights as well as editorial improvements.

Chapter 3 was recently published in the Maine Policy Review (Hayden 2023).

I am indebted to my advisor, James Wilson, for his guidance, mentorship, perseverance and good humor in seeing me through the long process of finishing this work. Thanks, also, to my family and friends who have supported me along the way.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii

LIST OF TABLES vi

LIST OF FIGURES vii

INTRODUCTION 1

CHAPTER 1 SPATIAL AND TEMPORAL PATTERNS IN THE COD FISHERIES OF THE NORTH ATLANTIC 4

- Overview 4
- Incentives for Exploitation 11
- Role of technology 13
- Role of Administrative Boundaries 16
- Serial depletion at multiple scales: three case studies 18
  - Labrador 18
  - Larger Northwest Atlantic 21
  - New England 25
- Conclusion 29

CHAPTER 2 PRECURSORS OF SOCIAL LEARNING IN FISHERIES AND THEIR ROLE IN COLLECTIVE ACTION 36

Introduction 36

Background 38

Social learning and collective knowledge 40

Case Study 43

Findings 52

CHAPTER 3 CO-MANAGEMENT IN MAINE: INTEGRATING FISHERMEN'S KNOWLEDGE INTO GOVERNMENT OVERSIGHT OF FISHERIES 58

Introduction 58

Case Studies 62

Lobster fishery 63

Soft-shell clam fishery 67

River herring fishery 70

Scallop fishery 72

Summary of findings 74

Conclusion 78

CONCLUSION 80

BIBLIOGRAPHY 83

BIOGRAPHY OF THE AUTHOR 97

LIST OF TABLES

Table 1. Four comanaged fisheries in Maine and conditions necessary for emergence of local adaptive capacity.. 64

Table 2. Comparison of local actions to restrain harvests and improve productivity................... 75

LIST OF FIGURES

Figure 1. Number of vessels fishing in ICNAF area, 1953-1977, by vessel size class. 22

Figure 2. Cod landings in New England, 1960-2005 (NMFS 2006).. 28

Figure 3. Cod landings for Northeast and Northwest Atlantic (Fisheries and Agriculture Organization 2013). 29

INTRODUCTION

With a handful of notable exceptions, scientific fisheries management has generally failed to sustain harvests in commercial fisheries. The purpose of this research is to identify factors that affect harvests over time and identify changes in policy and management that may improve outcomes. Scientific fisheries management, developed in the late twentieth century, is based on deterministic models of fisheries production and simple profit seeking by fishermen. In contrast, fisheries are here described as socio-ecological systems, incorporating the ecological dynamics of fish populations and the complexly motivated behavior of fishermen and managers, at a range of organizational scales.

The research includes three studies. The first, described in Chapter 1, analyzes the causes of the decline in the north Atlantic cod fishery. Over the past several hundred years, expanding market demand and developments in fishing technology have put growing pressure on cod stocks in the north Atlantic. The implementation of scientific fisheries management in response to the dramatic escalation of fishing effort after World War II failed to rebuild declining stocks or prevent the collapse of several cod fisheries. More recently, research into the structure of fish populations has shown that most are not panmictic, as assumed by traditional fisheries management, but comprised of hierarchies of subpopulations, known as metapopulations. With productivity driven by reproduction at the finest scale of such hierarchies, management at the scale of metapopulations leads to the serial depletion of its subpopulations, a decline in harvests, and often the collapse of metapopulations. Three case studies, at a range of spatial scales, document the serial depletion of cod subpopulations in the northwest Atlantic, from the beginning of the nineteenth century through the dawn of the 21st century. Such results are not inevitable, however, as demonstrated by the work of Ostrom and others, who analyzed successfully managed commons, including fisheries, and identified now well-known factors underlying their success, including limits on fishing boundaries and group membership, rules that match local conditions, a role for fishermen in making such rules that is respected by authorities, a system for enforcing rules, and building governance in nested tiers.

The second study, described in Chapter 2, focuses on how two of Ostrom's factors, limits on fishing boundaries and group membership and rules that match local conditions, contribute to sustainable management. Removing the option to expand the search for fish, by limiting where fishermen can fish, shifts their incentives from maximizing harvests in the short term to sustaining harvests over the long term. Aligning fishing areas with local conditions is interpreted here to mean fishing at a scale at or near the base of metapopulation hierarchies. To find fish, fishermen have two non-exclusive choices; to search for fish themselves or to learn from others where to fish. Learning from others, a form of social learning, occurs when fishermen find that it is less costly to acquire information from other fishermen than to search for fish autonomously. In a bounded fisheries system, ongoing engagement with a complex system and continued information sharing among a limited group of users refines the collective understanding of the structure and dynamics of such systems. As information is shared among sets of individuals, such social learning may, under certain circumstances, lead to group formation, cooperation, and the development of strategies for sustaining harvests. Policies that incorporate the factors identified by Ostrom as conducive to sustainable management increase the likelihood, but do not guarantee, that groups of fishermen will develop mutual restraint.

Such policies establish a shared responsibility for management between fishermen and government agencies that is referred to as co-management. It allows for local information to be incorporated into the management process and for fishermen to test management strategies based on their understanding of population dynamics. Private information collected by fishermen is moved into the public realm. It reduces the costs for fisheries agencies of monitoring and understanding fine scale conditions and allows for local action that they cannot manage.

The third study, described in Chapter 3, is an analysis of four co-managed fisheries in Maine. These fisheries, for lobster, clams, river herring, and scallops, are compared regarding the degree to which they incorporate Ostrom's factors and their relative effectiveness in sustaining harvests. The analysis suggests that these fisheries benefit from co-management even when they incorporate only some of Ostrom's factors.

Taken together, the studies indicate that taking the complexity of fish populations and human behavior into account in fisheries management generates benefits not provided by the standard, top-down, broad-scale approach.

CHAPTER 1

SPATIAL AND TEMPORAL PATTERNS IN THE COD FISHERIES OF THE NORTH ATLANTIC

Overview

Atlantic Cod *Gadus morhua* has been subject to commercial exploitation since the thirteenth century. An analysis of cod fisheries over space and time reveals a pattern of serial depletion that reflects the cross-scale interaction of fish population structure, economic incentives, developments in fishing technology, and government efforts to limit access to fishing areas. Three case studies from Newfoundland and Labrador, the larger Northwest Atlantic, and the Gulf of Maine illustrate a pattern of fish population depletion followed by expansion of fishing activity that repeats at a range of scales. The meta-population structure of cod populations allows overharvesting, even when strict but broadscale controls are in place. The results argue for the reform of fisheries management to incorporate governance that more closely reflects the scale of the local components of metapopulations.

Atlantic Cod Gadus morhua, once supporting one of the world's most prolific fisheries, occurs at a fraction of its former abundance. Cod is not an isolated example, marine fisheries globally have declined dramatically (Garcia and Newton 1997, Srinivasan, Watson et al. 2012, Worm and Branch 2012, Watson, Cheung et al. 2013). Even though most marine fisheries have been under scientific management for decades, efforts to manage them have not met with notable success. This lack of success implies that the various theories developed to understand the factors influencing the size of fish populations and management are flawed (Keith and Hutchings 2012, Vert-pre, Amoroso et al. 2013). Stock/recruitment models in biology, rational choice theory in the social sciences, and adaptive management from ecology have all been applied to understand problems in marine resource management, but unless combined with insights gained from history, they are insufficient to explain the current state of depletion of cod fisheries or the rest of the North Atlantic groundfishery.

In this article we describe the history of the cod fishery in the North Atlantic, with a view toward describing factors and patterns of events leading up to its decline. Our goal is to develop another view of why fisheries fail based on the idea of fisheries as a complex, coupled, natural and human system; and to suggest an alternative, coupled natural and human systems strategy for sustaining fish populations and their associated fisheries.

The history of Atlantic Cod and its fisheries is largely one of serial depletion of subpopulations, resulting in the loss of ecological memory of locations appropriate to the species' life history, e.g., spawning areas, nursery grounds and other useful habitat, and to population collapse. Given sufficient demand, fishing effort on a local subpopulation increases, the subpopulation becomes depleted and patchier, and fishermen's search more expensive and less successful. Economic incentives lead some fishermen to expand their fishing range beyond the local subpopulation, using a roving-bandit strategy to fish among several local subpopulations (Berkes 2006, Wilson 2006). The depletion of subpopulations continues, resulting in broadscale collapse. Fishing activity expands to target less exploited populations, and it leads to the development of vessels and gear capable of harvesting populations further from port. As depletion proceeds and conflicts between fleets from different regions emerge, authorities establish boundaries to privilege local fishing interests, a process that results in new rounds of depletion at a finer scale and pushes roving bandits to find new places to fish. Across the range of Atlantic Cod, patterns of serial depletion have emerged that reflect the cross-scale interaction of fish population structure, economic incentives, developments in fishing technology, and government efforts to limit access to fishing areas. The current study represents a socioecological analysis of the Atlantic Cod and its fisheries over the past several hundred years. Consideration of both social and ecological factors provides insights into understanding the depletion of cod populations that are not clear from the analysis of either factor alone.

Fishermen first began hunting cod for the purposes of trade in Europe as early as the thirteenth century (Barrett, Orton et al. 2011). Different fishing communities pursued cod locally in many areas; some expanded their fishing activity regionally, reaching the Northwest Atlantic in the fifteenth century (Rose 2007). Though global populations are much diminished from historic levels, commercial harvesting continues today. Several factors explain the long-standing popularity of cod as a commercial target. First, throughout much of the history of its fishery, cod were extremely abundant. Unlike warmer waters of the mid-latitudes, which, as a rule, support greater diversity of species but lower abundance of any one species, the colder waters of the North Atlantic support fewer species, many exhibiting tremendous abundance (Rose 2007). Second, cod is relatively easy to preserve, a characteristic critical to its value as a commodity.

Demand for cod over the past several hundred years, a function of population growth, religious dictates and cultural preference, has led to exploitation throughout its range in the North Atlantic—from the Bay of Biscay in the east to the mid-Atlantic bight in the west. The story of the cod fishery presents an unusual opportunity for socioecological analysis of the interaction of exploitation and species dynamics at a series of temporal and spatial scales.

Management theory

The dominant contemporary paradigm of fisheries management is based on bioeconomic theory articulated in the 1950s. As exemplified by the Gordon-Schaefer curve (Gordon 1954), this theory is based on deterministic models of fisheries production and simple profit seeking by fishers. Such models describe a relationship between population size and recruitment of juveniles into the population; over time, however, these models have grown increasingly complicated as factors such as the age structure of the population and assumptions regarding fishing mortality were incorporated in the hopes of finding a functional relationship. In practice, it has proved difficult to document such relationships empirically (Beverton 1998, Longhurst 2010). Nevertheless, we have managed fish populations as if stock-recruitment relationships exist, and as if such relationships are the critical determinant of sustainability.

Generally, management has assumed that the demographically relevant range of cod and other fish populations is broad, encompassing large areas, such as the entire Gulf of Maine. However, a growing body of scientific evidence shows that cod (and probably most other fish populations) occur in loosely connected hierarchies of populations known as metapopulations (Smedbol and Wroblewski 2002, Kritzer and Sale 2004, Kritzer and Sale 2006, Wright, Neat et al. 2006). A metapopulation consists of a number of subpopulations that tend to be reproductively isolated, especially in the short run. In evolutionary time, this kind of population structure allows a species to adapt to local oceanographic and ecological circumstances, reducing its vulnerability to drastic, broadscale change, at the same time, giving it the ability to repopulate local areas, in which the species has been extirpated. The metapopulation structure of cod, most likely, consists of weakly connected local demographic units arranged in a multi-scale hierarchy of subpopulations that reflect, at the largest scale, nearly geographically isolated areas, such as the Newfoundland Banks, Barents Sea and North Sea, and at a much smaller scale, local regions and embayments (Ruzzante, Taggart et al. 1999, Ames 2004). Patchiness also occurs within the range of subpopulations although these patches may have little demographic relevance. Recent advances in genetic analyses reveal divisions within populations of cod once considered panmictic; such differences are evident among subpopulations at a large-scale across the range of the species, but also at much finer scales, e.g., within an area 300 km in length (Hauser and Carvalho 2008). Areas once thought to support homogeneous cod populations, such as the Gulf of Maine and the banks off Newfoundland and Labrador, are now recognized to have more complex population structures. From a scientific perspective, this population structure calls into question the fundamental logic of broadscale management based on the idea that sustainability is driven principally by a stock-recruitment dynamic. From the fisher’s perspective, a metapopulation structure represents a series of patches, or search targets, going from a very broad to a very fine scale. As we discuss later in this paper, this multi-scale patchiness creates strong incentives for overfishing, even with stringent broadscale controls.

Implementation of fisheries management programmes across the North Atlantic in the second half of the twentieth century reflected the understanding of fish population structure at the time. Fish populations were thought to be panmictic across broad geographic areas. Management programmes focused then, and continue to focus now, on reductions in fishing effort as averaged across a large area. Reductions in harvests are sought through input controls—limits on fishing effort, or output controls—limits on landings. Such programmes do not take into account that fishing exploits the tendency of fish to form dense aggregations that reduce search costs and make fishing gear such as trawls economically feasible (Ames 1997, Wilson, Hayden et al. 2012). Actual effort and catch, of course, is not averaged across a management area, but is concentrated on aggregations of fish. Broad controls on harvesting do not protect local populations and consequently, do not prevent the sequential overfishing of local populations. As subpopulations have been extirpated, the viability of the metapopulations, of which they are a part, become compromised, a process that has resulted in the crash of one cod population after another. The persistent, depleted state of most cod populations throughout the North Atlantic is evidence that the current fisheries management paradigm has not worked to protect either fish populations or the economic activity derived from fishing.

This paper describes a different theoretical approach to the understanding of human-ecological interactions, one that could lead to a more effective approach to fisheries management (Wilson 2006). We view the natural system as one which is patchy in space and time, and at multiple scales. This patchiness creates regularities that reflect the adaptive behaviour of the many species of fish and the essential self-organized structure of the system. Its regularities make it possible for fishermen to learn about the natural system and, at the same time, makes it economical to search for fish and harvest fish. Especially important, it makes it possible for humans to hunt down and deplete local, demographically relevant components of broadscale populations. In short, fishing tends to unravel the natural order of the ocean system, patch by patch, leading to overharvesting and a tragic social dilemma. The cod fisheries are a particularly clear and important example of the problem.

According to (Ostrom 1990), establishing the boundaries of common pool resources, such as fish populations, and specifying those who are allowed access to such resources, is a prerequisite for collective action that results in effective management. Boundaries and associated rules regarding participation in resource use are most effective when designed such that resource users live near each other, are interested in the long-term sustainability of the resource, are willing to enforce harvesting rules, and are trustworthy. Consequently, the analysis of the interaction of social systems (human aggregations) with groups of cod (fish aggregations) involves an understanding of self-organization, in both, social and ecological systems. Key to this analysis is knowledge of the scale at which the fish aggregate, and the scale at which fishing occurs. When fishing activity is limited by available technology or administrative boundaries to a scale that matches the scale of cod subpopulations, fishing generates feedback that can give a relatively accurate picture of the effects of fishing. This feedback does not assure, but certainly increases, the chances for successfully collective action that can restrain overharvesting (Wilson, Acheson et al. 2013). Absent such spatial and technological limitations, and given a growing market for fish, fishers generally expand the spatial extent of their fishing without regard to the demographically relevant scale of the affected populations. As the scale of fishing expands, feedback regarding its effects upon smaller-scale fish aggregations is attenuated or lost, and the serial extirpation of aggregations results. As is evident in the long history of the cod fisheries, the expansion of fishing is repeated until local aggregations of fish over a broad range are decimated, cumulating with the broadscale collapses whose recent history is so vivid. We argue that this coupled, multi-scale, natural and human system approach to understanding the effect of fishing presents opportunities for developing newer models of fisheries management that incorporate social phenomena, in particular learning and adaptation, and emphasize the importance of matching the scale of restraints on fishing with the demographically relevant scale of targeted populations.

Analysis of the history of cod fishing in the North Atlantic has revealed three major drivers in the dynamics of cod fisheries over space and time: 1) persistent and increasing market demand for cod; 2) development of harvesting and product storage technologies that allowed for exploitation of virtually every cod population; and 3) the imposition of territorial boundaries as constraints on fishers' mobility. Given the metapopulation structure of cod populations, the impact of these drivers on the behaviour of fishers has resulted in a consistent pattern of serial depletion that occurs in a similar pattern at both broad and finer scales—what might be called a socioecological fractal.

Incentives for Exploitation

Fishing behaviour is driven by economic and social incentives, and given shape by the social and natural environments, within which fishing occurs. As human populations and the scale of markets increase, demands for quantity, quality and stability of supply create incentives for increasing scales of fishing in the face of increasing patchiness in the resource. Greater mobility and fishing capacity also require greater investment, which leads to a split between (usually) company-owned vessels pursuing a broader scale mobile strategy, and smaller scale, less capital intensive, inshore vessels owned by captains or small companies. These smaller vessels may pursue different fisheries according to what is locally abundant by season. Differences arising from type of ownership, various traditions and other institutional factors, including the implementation of boundaries and regulations, result in more diverse patterns in fishing behaviour than might be expected if fishers were assumed to be homogeneous in capabilities and history.

Fishing was long carried out as a subsistence activity. The advent of methods for preserving fish allowed for their use in trade. Growing human populations and Catholic edicts against eating meat many days a year made for increasing demand for piscine flesh during the early Middle Ages (Fagan 2006, Roberts 2007, Barrett, Orton et al. 2011), and demand for cod has remained strong ever since. Demand created incentive for increased effort and adoption of more intensive fishing practices. Other important strategies for increasing harvests were to expand the area fished, to allow for fishing on several populations during one trip, fishing on unexploited populations, and fishing on larger populations, often found on offshore banks. The decline in abundance of local populations created further incentive for fishing at a larger scale but still nearby. As harvests in nearby stocks also declined, vessels were forced to go further afield in search of cod. By the fourteenth century, the legendary fishing grounds of the North Sea were in decline and the British, French, and the Dutch began to seek richer Patterns in North Atlantic Cod fisheries fishing grounds further afield, first in Norway and Iceland, and then on the Grand Banks (Roberts 2007, Bolster 2008, Bolster 2012).

In the Gulf of Maine and elsewhere, a dichotomy of fishing behaviours has prevailed throughout history—smaller vessels take advantage of seasonally abundant populations when they are present locally, while the vessels of larger commercial ventures seek the best return on capital, searching out higher abundance and/or higher value of populations further offshore, higher abundance offsetting the higher costs of travel (Goode 1887, Ackerman 1941, Alexander, Leavenworth et al. 2009). The pattern of inshore and offshore fishing is a reflection of an ideal free distribution of fishing effort, whereby fishers distribute themselves among patchy resources in a way that tends to equalize profits at the various scales, with a division of effort based principally on access to capital, the abundance, seasonality and patchiness of fish, and the availability of alternative economic opportunities. It is reinforced by the greater seasonal variability of inshore stocks. Inshore fishermen compensate by diversifying their fishing activity and balancing it with shoreside work. Offshore fishermen continue fishing by searching for other subpopulations on which to fish.

Changes in mobility and fishing capacity can also occur in response to economic incentives created by regulations. Many countries provided bounties to cod fishermen, in part, to ensure a source of able-bodied seamen. For example, from 1792 to 1866, the US Congress passed a nearly continuous series of bounty laws that provided boats in New England's cod fishery, with subsidies, if they could meet certain standards (O'Leary 1996). More than a century later, small boat fishermen in post-EEZ (Exclusive Economic Zone) New England increased their scale of fishing partly in response to what might be termed regulatory incentives. Investments in newer, larger vessels were encouraged by favourable government loan and tax programmes to promote increased fishing capacity; the yearly, then quarterly, race for quota created by initial efforts to manage populations of groundfish within the US EEZ further incentivised these investments (Acheson 1984, Apollonio and Dykstra 2008).

Role of technology

Vikings had migrated by ships to various parts of the coasts of Europe and Iceland by 870 CE, but the inadequacy of vessels confined most European maritime activities, including fishing, to inshore coastal waters until the fourteenth century (Lewis and Runyan 1985). By the fifteenth century, the seaworthiness of boats and the ability to navigate had improved to the point where fishermen were fishing in the waters of northern Europe and Iceland. Europeans began to fish in the Northwest Atlantic in the fifteenth century (Rose 2007). The ability to preserve cod allowed the distance between the source of the cod and its markets to greatly increase. The Vikings may have been the first to preserve cod by drying them in the cold, dry air of the Arctic. Once dried, cod could be kept for months. Further to the south, where salt was widely available, salting became the preferred method of preservation. By the 1840s, icing made possible the development of markets for fresh cod. In the twentieth century, the development of filleting machines and blast freezers added a final chapter to the market dominance of cod.

Two notable innovations changed fishing practices. The first, in the early eighteenth century, was the widespread use of a schooner with fore and aft sails, a type of sail configuration that proved to be especially adaptable to fishing because of its speed and manoeuvrability. The second was the introduction of dory fishing after the 1830s. That is, fishermen carried dories aboard their schooners and when they reached the fishing ground began to fish from them with one- or two-man crews, which, allowed them to exploit a wider area of ocean away from their mother ship. Dory fishing greatly increased catches (O'Leary 1996).

Over the course of the nineteenth century, the production of salt fish declined and the production of fresh fish expanded enormously. The marketing of fresh fish depended on a number of innovations. In England, the adoption of the boat well allowed live fish to be sold in all coastal areas of the country. The widespread sale of fresh fish in cities of the interior, however, had to await the development of the railroad (Roberts 2007). In the US, the switch to fresh fish was greatly facilitated by the spread of the use of ice on boats, which, had become common on Gloucester boats by 1845, and the use of domestic ice boxes, which, had become wide spread by the 1880s (O'Leary 1996).

At the end of the nineteenth century, the combined use of engines to power vessels and of trawls—large nets towed along the bottom—greatly increased fishing capacity. Steam trawlers began to appear in numbers late in the nineteenth century (Roberts 2007), and by 1900, the first schooners were being equipped with diesel and gas powered engines (McFarland 1911).

Fishing gear also changed. Although bottom trawls date from the fourteenth century (Roberts 2007), coupling them with engine-powered boats greatly increased their efficiency. In New England, groundfish were caught on hooks until 1900, but after that, an ever increasing proportion of boats were equipped with otter trawls, which, were more efficient, did not require bait, were safer than dory fishing, and could be used over more months of the year, alleviating the winter shortage of fish. This technology allowed fishermen to target spawning aggregations of cod, and other species, for the first time with devastating consequences for cod populations throughout the North Atlantic.

In the 1920s, at the same time that trawlers came on the scene in large numbers, the marketing of fish was revolutionised by the fish-filleting machine and freezing technology that allowed processors to turn out huge amounts of frozen fillets and minced fish, which, by the 1940s, came to dominate many markets (Ackerman 1941, Roberts 2007).

In 1954, the British launched the Fairtry; at 85 m and 2,642 tonnes, it had significantly more fishing capacity than the next largest vessel in the North Atlantic fleet at that time. The Fairtry, and the many others like it, that soon joined fleets from several countries, allowed large-scale commercial exploitation of the cod populations of the most northern reaches of the North Atlantic. The diversification of the industrial, distant water fleet into trawlers, factory processing vessels, transports and other support vessels ensured that fishing, and the search for abundant populations, occurred continuously (Warner 1983).

A revolution in electronics, that began at the outset of the twentieth century, reached fishing fleets in the late 1920s, when the radio-telephone, an easy to use device, had been perfected (Schroeder 1967). The development of Loran that came into widespread use in the fishing fleet in the early 1970s, and geographic positioning systems (GPS), widely adopted in the 1990s, permitted fishers to pinpoint exact locations of vessels, fishing gear, and fishing locations with ease. Other devices, based on sonar technology (i.e., white line recorders, side scanning sonar) greatly improved the ability of fishermen to find concentrations of fish in the water, particularly when combined with the increasing mobility of the fleet.

For several decades the use of otter trawls was limited to smooth bottom (i.e., sand, mud, gravel), allowing fish to use ledges and rocky bottom as a sanctuary. In the mid-twentieth century, the advent of monofilament gillnets allowed for fishing on rocky bottom. Later, the addition of rollers to the ground lines of otter trawls permitted them to pass over rocks. These innovations, allowed fishermen to exploit fish on all kinds of bottom, increased the area that could be searched for fish, and greatly reduced the amount of area that had served as de facto fish refuges.

Role of Administrative Boundaries

In 1609, the Dutch jurist Hugo Grotius wrote in Mare Liberum (=the freedom of the sea) that the seas are free to all, especially in terms of international rights to navigation and trade. This work intended to prove that Portuguese claims to sovereignty in the East Indies were null, and the Dutch could navigate and trade freely. In terms of fisheries, “the principle applicable in regard to navigation—namely, that the activity in question shall remain open to all—should also be applied in connection with fishing” (Grotius 1608 (2009)). Fish were res nullius (= the property of none), until caught (Grotius 1608 (2009)). The English juror John Selden produced the contrasting Mare Clausum (=closed sea) claiming the sovereign right of the King of England, especially to the waters south and east of England. Though finished in 1618, it was not immediately published, because King James I of England was in debt to the King of Denmark and feared displeasing him (Fletcher 1933). With tensions flaring over the Dutch monopolization of the herring fisheries in the North Sea, the Dutch republished Grotius' work, and, in response, King Charles ordered Selden's work published (Fletcher 1933). Nearly a century later, the concept of a three-mile limit to a state's waters was defined in Cornelius van Bynkershoek's De Dominio Maris Dissertatio (= dissertation on the ownership of the sea). Enforcement of marine law was then, as it is now, the key issue in creating meaningful edicts. In De Dominio Maris, Bynkershoek (1744 (1923)) states, "I should have to say in general terms that the control from the land ends where the power of men's weapons ends; it is this...that guarantees possession".

The power of human weapons has continuously increased, but relatively recently, the three-mile (approximately 4.83 km) coastal boundary has been expanded. The expansion of distant water fleets after World War II (WWII) led to an international effort to protect fisheries by expanding state sovereignty over adjacent marine waters. In 1958, when the first United Nations Convention on the Law of the Sea (UNCLOS) failed to produce an agreement, Iceland unilaterally established its own boundary, declaring a 12-mile exclusive fishing zone, which, they managed to enforce not with firepower, but by cutting the cables English trawlers used to tow their nets. They, then, extended this line out to 50 miles in 1972, and 200 miles in 1976 (Kurien 2000). Most nations in the North Atlantic followed suit within a year. The 1982 UNCLOS reached agreement on the EEZ, which, granted coastal states exclusive access to resources of the seabed and overlying waters from the shore out to 200 miles (Reed 2008).

The 200-mile limit is not the only line in the water that has affected cod fishing. Coastal states have developed a number of nested boundaries granting management rights within their EEZs, from the regional fishery management councils of the US to recognition of traditional institutions in the Lofoten island chain of Norway (Jentoft and Kristoffersen 1989). Locally defined and enforced boundaries have also been described, which, reflect varying degrees of recognition by state authority (Durrenberger and Palsson 1987).

When governments create boundaries, they often create rules that allow participation in resource-use by strangers, without a long-term commitment to the resource (Ostrom 1999). Such rules "may generate conflict and unwillingness to abide by any rules" (Ostrom 1999). The history of the northern cod fisheries is replete with examples of such consequences of government boundary setting. With establishment of the 200-mile limit, coastal states generally limited fishing to their citizens, but did little to develop effective methods of domestic governance. When management was attempted it was almost always top-down, command-and-control approaches that, over the last 35 years, have proved ineffective.

Serial depletion at multiple scales: three case studies

Analysis of cod fishing in the Northwest Atlantic reveals a pattern, occurring at multiple scales, of serial depletion of subpopulations, expansion of fishing effort, and subsequent collapse of entire populations. Three case studies, drawn from three time periods and three cod fishing regions, illustrate the cross-scale interaction of fish population structure, economic incentives, developments in fishing technology, and, in one case, government efforts to limit access to fishing areas. Each demonstrates a pattern of cod population decline that occurs as a result of the expansion of fishing activity in response to local depletion.

Labrador

In the nineteenth century, as cod subpopulations along the Newfoundland coast became increasingly depleted, fishermen turned to Labrador. As the century progressed, cod populations were sequentially depleted northward, eventually bringing the fishery to the very northern edge of Labrador.

The cod population of coastal Newfoundland and Labrador exhibits a metapopulation structure of fairly discrete, year-round, bay-scale populations, including both those, that winter within bays and in deep water nearby, migratory populations that overwinter offshore and migrate inshore seasonally to the same general areas, and populations that stay offshore (Lear 1984, Myers, Barrowman et al. 1997, Ruzzante, Taggart et al. 1999, Green and Wroblewski 2000, Robichaud and Rose 2004). Each component may form a more demographically closed component than had previously been assumed (Bradbury, Laurel et al. 2008, Hauser and Carvalho 2008).

The population of coastal Newfoundland increased during the Napoleonic era, circa 1810–1815, partially as a result of a temporary monopoly on the salt cod market. Local populations of cod could not support the growing pressure from increasing numbers of inshore fishermen (Cadigan and Hutchings 2001). As coastal cod populations were depleted, the Labrador cod fishery and the seal fishery became important alternative sources of income (Cadigan and Hutchings 2001).

From 1806 to 1820, cod landings, primarily from southern Labrador, increased from roughly 4,904–6,161 Mg live weight to 26,664–33,501 Mg live weight (as estimated using the method for converting quintal to live weight described by Alexander et al. (2009) (Cadigan and Hutchings 2001). As the century progressed, fishermen continued ever further northwards in search of better catches (Cadigan and Hutchings 2001). Throughout this period, the local populations targeted by the inshore fishery in Newfoundland regularly failed (Cadigan and

Hutchings 2001). Turning to Labrador, the fishery sequentially depleted cod subpopulations along the coast up to its northernmost reaches.

Much of the Labrador fishery was carried out by a new class of vessels, larger than those employed in the inshore cod fishery, but smaller than those used in the seal fishery. With local cod populations in decline, inshore Newfoundland fishermen took advantage of government subsidies for shipbuilding and constructed ‘jacks’, double-masted, schooner rigged vessels of around 20 tons that could make the journey to Labrador and back (Cadigan and Hutchings 2001). As Labrador cod populations became increasingly patchy, it was more advantageous to pursue a mobile strategy. Fishermen who pursued a mobile strategy were known as ‘floaters’, and were often well served by using the flexible jacks (Cadigan and Hutchings 2001).

As the nineteenth century began, fishing companies from New England pursued cod along the Labrador coast. Many schooners, small in size relative to those of the Grand Bank fleets, took advantage of the large supply of small cod, combined with the security of the coastal fishery. The Labrador fishery was an option for smaller Maine companies as the boats required less investment, while a mobile strategy in response to patchiness in cod populations was still possible. By the 1850s, even with some boats bringing in 92,000 cod in a season, the Labrador grounds were abandoned by Maine fishermen responding to the better market for larger Grand Banks cod (O'Leary 1996).

As local cod populations declined along the Newfoundland and Labrador coasts, catches were boosted temporarily by increases in the intensity of harvesting technology. Bultows (long lines) and seine nets were introduced in the 1840s, gillnets in the 1860s, and the cod trap in the 1870s (Cadigan and Hutchings 2001). Each new technology led to another round of serial depletions. By the turn of the century, the inshore Labrador fishery had dwindled to a few farranging floaters whose cod traps yielded many small fish (Cadigan and Hutchings 2001). Small cod cure poorly (Fagan 2006), and the added detriments of Labrador's damp weather and extended storage in salt bulk did not improve the quality of the final product. Markets for the good suffered accordingly.

The nineteenth-century Newfoundland and Labrador coastal cod fisheries provide an acute example of fisheries expansion propelled by the serial depletion of cod subpopulations. Increased harvesting activity led initially to a decrease in the stability of Newfoundland's inshore populations. Government subsidies and inshore cod population failures provided incentive to fishermen to acquire larger vessels and travel to Labrador to fish. As the subpopulations off Labrador were fished down, some fishermen pushed northward to exploit unfished subpopulations. Others continued to fish locally, an example of the dynamic balance between local and roving exploitation that characterizes cod fisheries throughout the North Atlantic.

Larger Northwest Atlantic

In the Northwest Atlantic, the last 70 years has seen groundfish catches go from all time highs to disastrously low levels. A new round of technological advances occurred in the twentieth century that allowed large and previously unfished populations in the deeper and colder waters of the North Atlantic to be exploited. After WWII, fishing fleets of countries exploiting the Northwest Atlantic expanded greatly, putting far more pressure on cod populations with highly mechanized and mobile fleets of vessels operating out of ports in northern Europe. Most notable was the appearance of fleets of Western rig stern trawlers that delivered product to huge factory ships capable of filleting and freezing catches of fish at sea (Acheson 1984, Lear 1998). This development of industrial-scale fishing first resulted in dramatic increases in catch as both existing and new fishing grounds in Labrador and Iceland and in the Norwegian and Barents seas were exploited. Cod landings on both sides of the Atlantic peaked in the late 1960s.

The International Convention for the Northwest Atlantic Fisheries came into force in 1951 for the purposes of "investigation, protection and conservation of the fishery" (Halliday and Pinhorn 1990). Data collected under the terms of the Convention reveal the dramatic increase in industrial scale fishing in the convention area (Figure 1), which, began with the launch of the Fairtry in 1954. In 1959, 37 vessels as large as or larger than the Fairtry were fishing in the Convention area; that number increased to 100 in 1962, before peaking at 236 in 1971. A primary focus for some of these vessels, at least initially, was herring or redfish, but cod were also an important target (Armstrong 1966).

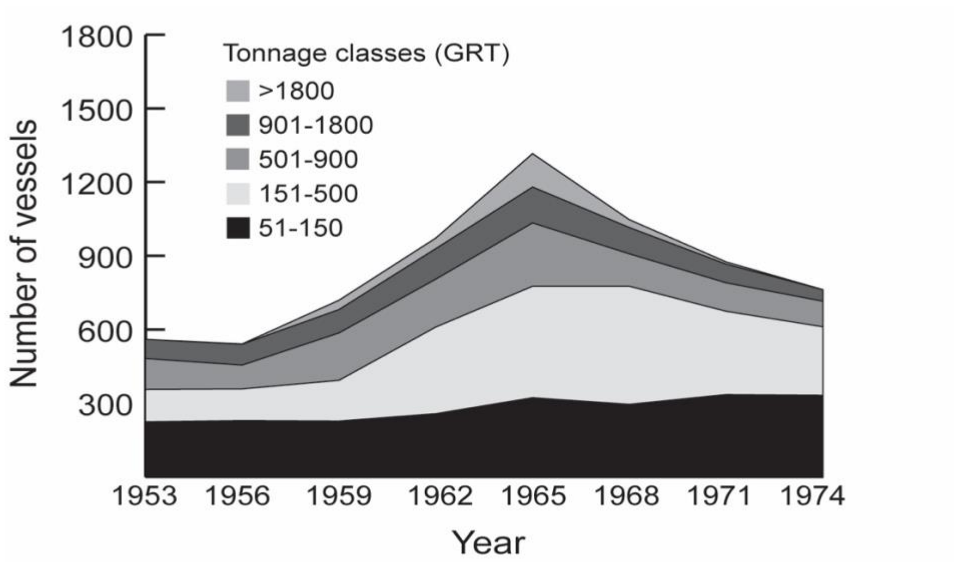

Figure 1. Number of vessels fishing in ICNAF area, 1953-1977, by vessel size class.

In regions with greater historical participation in fishing, such as Norway, Iceland, England, Spain and Portugal, the expansion of fishing activity to an industrial scale in the twentieth century was built on knowledge and experience accrued during countless generations' participation in fishing. The opportunity to fish at an industrial scale brought new entrants, with little fishing experience, into the cod fisheries of the North Atlantic, in particular the then Soviet Union, and its satellite states. The Soviet fishing industry was launched shortly after the revolution in 1917 as a collective enterprise designed to reverse food shortages in the new nation. Investments in industrial fish production were motivated by the value of fish products relative to other foodstuffs rather than by a potential return on investment. However, the protein requirements of the populace and resulting competitive rewards from the government for increased production provided incentive for the crews of Soviet fishing vessels to maximize production. The relative efficiency of fishing compared to agricultural production resulted in a rapid build up in the Soviet fishing fleet after WWII; by 1952, Murmansk was the leading fishing port in the World (Armstrong, Hoffman et al. 2011). By 1959, the Soviets had deployed 35 Pushkin-class vessels, modelled on the Fairtry, in the Convention area; by 1968, the number was 61 large vessels along with 354 smaller vessels.

Unlike fleets participating in international markets for cod, where companies, and captains within the same company, freely competed with each other to land the most fish, the Soviets applied a systematic approach to the harvest of fish in the Northwest Atlantic. First, the vessels in their distant water fleet were specialized according to the various tasks required to catch, process, and land fish products. Fishing activity within a fleet was coordinated by shore-based managers who provided a coordinated plan for fishing, in which, vessels towed their nets across a fishing ground in a staggered line. Very large areas were swept in this way, a process that both compensated for lack of information about unfamiliar fishing grounds, and ensured that any fish in the area would be harvested. The use of transport vessels to deliver fish products back to the erstwhile Soviet Union allowed continuous fishing (Warner 1983, Armstrong, Hoffman et al. 2011).

In the post–WWII period, effort expanded dramatically in the deeper, colder waters off Labrador, Greenland, Norway and Russia. Fishing in the Northwest Atlantic allowed fishing fleets from Europe and the then Soviet Union to offset a decline in landings in the Northeast Atlantic that began in 1956. As industrial-scale fishing took hold, cod landings in both regions increased dramatically, reaching a peak in 1968. The then Soviet Union and its satellite nations were a major driver of this expansion, accounting for approximately one-third of cod landings from both, the Northwest Atlantic and the North Atlantic. Landings from the Convention area and the North Atlantic declined after 1968.

The scale of exploitation by distant water fleets led to the erection of barriers to foreign fishing in the 1970s, and the initiation of UNCLOS. As a result, the largest fishing vessels had to become even more mobile to harvest from the disparate few patches that were not yet off limits. Distant water fleets turned either to the small pockets of continental shelf outside of the 200-mile limit (Rose 2007), harvested largely unmarketable species from the abyssal depths of the still mostly unregulated high seas (Roberts 2007), or made agreements with developing countries to 'help' them to achieve the maximum sustainable yield they are required to reach under UNCLOS (Van Dyke 2008).

After claiming jurisdiction over fisheries within 200 miles of the coast in 1977, Canadian fishing vessels continued to fish the cod populations in the area. In 1976, catches had fallen precipitously. They recovered somewhat for a few years, only to crash in 1989 (Lear 1998). The cause was overexploitation from a fleet of large trawlers built by the Government of Canada in response to overly optimistic population assessments by the Department of Fisheries and Oceans, Canada (Finlayson 1994). In 1992, a moratorium was declared on the Canadian cod fishery. However, by 2011, the population had still not recovered. Populations of cod remained very low except for two near shore populations, which, experienced moderate recovery (Lear 1998).

The development and expansion of industrial scale fishing in the North Atlantic resulted in the exploitation of a natural resource at a level that must rank among the most dramatic examples of wild harvest in the history of human civilization. The nearly continuous expansion of cod fishing activity over the previous several hundred years came to end. The devastation of cod populations in the Northwest Atlantic was nearly absolute, leaving only remnant populations. Technological developments had allowed cod fishing to reach a point, at which, further expansion was not possible; all available populations of any size had been exploited. Lack of new populations to exploit forced the industrial fleet to leave the fishery in search of other species.

New England

In the late twentieth century, after the imposition of administrative boundaries that prevented foreign fishing within the US EEZ, cod populations in New England were further depleted by expansion of coastal fishing activity.

Cod fishing was a mainstay of the economy of the earliest settlements in New England, and has been important throughout its history. Cod fishing in New England took two forms; a smaller-scale fishery pursued the relatively small populations of cod when seasonally available inshore, and a larger-scale fishery focused on the larger populations of the offshore waters. By the later part of the seventeenth century, fishing dwarfed all other maritime industries in New England. Shortly after, New England fishermen began fishing on the Grand Banks, in the Gulf of Saint Lawrence and in Labrador (McFarland 1911, O'Leary 1996, Lear 1998).

New England's cod fishery reached its peak between 1840 and 1865 (O'Leary 1996). At the end of the nineteenth century, cod catches increased with the advent of vessels with increased range and the beam trawls; populations soon declined again. Landings rose again in the twentieth century with the revolution in fishing technologies. In the 1960s, catch per unit effort declined in the offshore fisheries of the Northwest Atlantic, and the Gulf of Maine and Georges Bank were invaded by a large fleet of foreign trawlers and factory ships that quickly overexploited populations of cod and other species (Playfair 2003). By 1972, the groundfish populations in the Gulf of Maine and on Georges Bank were so depleted that the foreign fleets left the region (Acheson 1984).

The establishment of the American EEZ led to a third phase of cod population depletion due to the rapid expansion of the American fishing fleet during the late 1970s and early 1980s. There was an estimated 50% increase in vessel tonnage in the groundfishery between 1977 and 1978, as fishermen who had previously fished inshore traded up in vessel size to allow them to exploit what remained of the cod populations in the deeper waters of the Gulf of Maine (Apollonio and Dykstra 2008). In 1977, 1,200 licenses were issued; in 1979, the number had increased to 2,191—almost an 83% increase in two years (Acheson 1984). Moreover, the boats entering the fishery were substantially larger, better equipped, and more versatile than those they replaced. These changes in the fleet have been described in some detail by Acheson (1984).

The expansion of the fleet was stimulated by four different factors. First, the price of fish was high (Doeringer, Moss et al. 1986), and capital became available for new boats and equipment when the Government of the United States established two loan programmes (i.e., the Capital Construction Fund and the Fishing Vessel Loan Guarantee Program) (Apollonio and

Dykstra 2008). Second, the New England Fishery Management Council's (NEFMC) first management plan, in place from 1977 to 1979, created a quota race. The plan set a maximum sustainable yield for a three-month period. When that amount of fish was caught, fishing was halted. The largest and best-equipped vessels did best because they could get out in stormy winter weather when smaller vessels were confined to port. When this became apparent, many fishermen began to invest in larger, better-equipped boats. Third, changes in the international boundary also increased fishing pressure. When the US and Canada extended jurisdiction out to 322 km, the Gulf of Maine was claimed by both countries. In 1984, the International Court in The Hague drew a new international boundary that excluded American fishermen from parts of the Gulf of Maine, including the northeast peak of Georges Bank. This forced many large vessels to crowd into the inshore waters of the Gulf of Maine. Within two years, these boats and the small boats of the inshore fleet had considerably reduced the remaining populations of groundfish. After this, many of the largest vessels went to distant locations and never returned to New England waters. The remaining fleet reflected an inshore, small-vessel diverse fishery and an offshore larger-vessel fishery that hunted down aggregations of cod and other groundfish wherever they could be found within the US EEZ. Fourth, from the late 1970s to 1988, populations became increasingly patchy as overfishing increased. Vessels had to fish in waters further from their home harbours, and they had to fish for more hours and over a bigger area to get the same amount of fish. This necessitated using larger boats that could stay at sea for several days at a time. Many smaller boats simply left the fishery.

New England catches of cod varied considerably from 1960 to the present (Figure 2). Catches were high in the mid-1960s; then they fell as populations were overfished by the foreign fleets. Landings rebounded again in the late 1970s and early 1980s due to the entry of new and better-equipped vessels into the New England fleet and the return to New England of American vessels that had previously fished in Canadian waters. The high landings of the early 1980s were followed by a severe decline as populations became overfished; cod landings declined by 50% between 1982 and 1987. Landings improved slightly, perhaps related to the departure of the largest vessels in the mid-1980s, but declined again dramatically beginning in 1990. Cod landings reached the lowest in 1995, and have remained low despite a variety of attempts by NEFMC and the National Marine Fisheries Service (NMFS) (under pressure from the environmental community through law suits and amendments to the Magnuson Act) to revive them (Acheson and Gardner 2011).

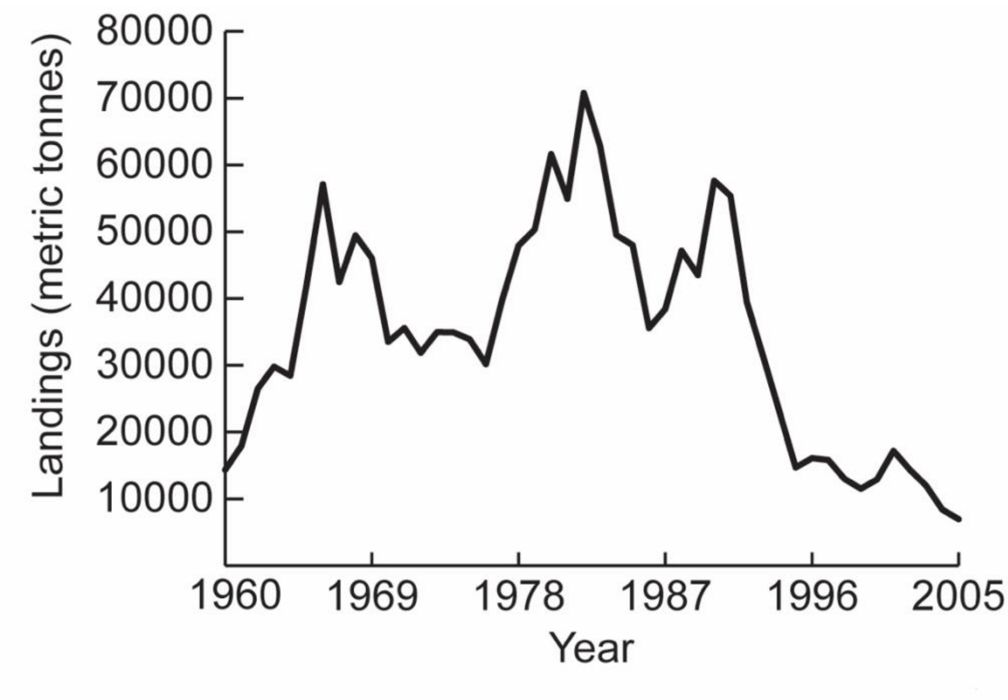

Figure 2. Cod landings in New England, 1960-2005 (NMFS 2006)

In 2005, the US portion of the Gulf of Maine (including the Georges Bank) produced far fewer commercial landings of cod than Frenchman's Bay, an area of a several hundred square kilometres in eastern Maine, produced in the 1860s (Alexander, Leavenworth et al. 2009). After a series of draconian measures were promulgated, in the 1990s and early 2000s, it appeared that cod populations were no longer declining. But in the fall of 2011, a stock assessment showed that cod populations have continued to decline. Spawning stock biomass is currently approximately 3-4% of peak levels since 1976 (NMFS 2006, Palmer 2014). In short, cod and groundfish populations in New England are in worse shape today than they were when management began in 1976 (Apollonio and Dykstra 2008, Acheson 2011).

Cod landings in the Northwest Atlantic remain very low. Those in the Northeast Atlantic are higher reflecting the fact that four of the five largest cod-producing grounds are in that region (Figure 3).

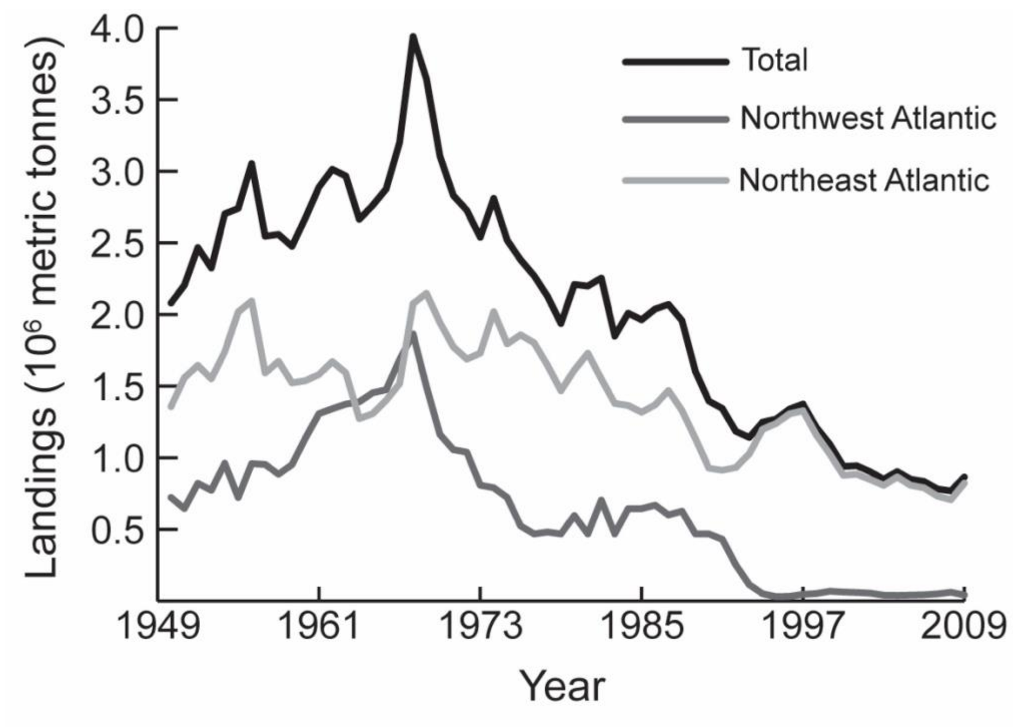

Figure 3. Cod landings for Northeast and Northwest Atlantic (Fisheries and Agriculture Organization 2013).

Imposition of EEZs drove the distant water fleet from New England's shores but put new pressure on the remaining populations of cod as American fishermen, banned from fishing in Canadian waters, focused their efforts in the Gulf of Maine and on Georges Bank. Many inshore fishermen bought bigger boats and expanded their fishing activity to take advantage of the vacuum left by the distant water fleet. The federalization of fisheries management has not prevented the continuing decline of New England's cod populations.

Conclusion

For the several hundred years of early commercial cod fishing, cod harvests were limited by the ability of fishermen to catch and preserve fish. Although there were local depletions, the largest populations, in northern waters, were untouched. With technological advancement in the early twentieth century, the huge populations of cod, once found off the coast of Canada, from the Grand Banks north towards Greenland, were overharvested. Implementation of very broad administrative boundaries in the late twentieth century did not prevent a second round of local- and regional-scale depletions. As illustrated by case studies in the Northwest Atlantic, the depletion of smaller-scale populations and expansion of fishing effort occurred at various spatial scales and over various periods of time from the outset of commercial cod fishing, and it can be described as a series of socioecological fractals.

The development of administrative boundaries reflects a continuing conversation between commercial interests in trade and natural resources, such as fisheries and the governments that serve them. From English claims of sovereignty in the North Sea in the early 1600s to Iceland's defence of its essential fisheries resource in the twentieth century, administrative boundaries have been used to limit access to coastal waters by foreign fleets and to ensure that the economic benefits of fisheries are captured by resident fishermen. Failure to address the complexity of cod population structure within EEZs, however, has decreased the benefits of limited access and resulted in the decline of cod populations. The New England case study is but one example where limits on foreign fishing failed to protect cod stocks.

Although the interaction of economic, technological, and administrative factors has driven patterns in the exploitation of cod populations in the North Atlantic over the past several centuries, other influences have also played a role. In the Middle Ages, religious edicts regarding diet drove the market for cod to a higher level than it might otherwise have reached (Roberts 2007). Climatic warming at the end of the Little Ice Age reduced the biological productivity of cod populations (Rose 2007). Initial exploitation of Newfoundland's abundant cod populations was hampered by lack of shore area, on which to place drying racks (Rose 2007). Until the end of the nineteenth century, some nations provided subsidies to fishing vessel owners, partly because, experienced fishermen provided a ready source of naval manpower (O'Leary 1996). In the mid-twentieth century the Soviet Union developed a state-sponsored, distant water fleet driven by non-market, economic goals (Helin 1964). Throughout history, wars and other geopolitical forces have interfered with fisheries trade. For example, the American civil war disrupted the shipment of dried cod from New England to New Orleans (O'Leary 1996). Such factors have influenced cod fisheries over the centuries to some degree, but they are secondary to the interaction of market incentives, the metapopulation structure of cod populations, the development of increasingly effective fishing technology, and the imposition of administrative boundaries–an interaction that has established a repeating pattern of exploitation and expansion.

Various approaches to fisheries management are currently being practised. The population dynamicists, who dominate management efforts, rely on stock-recruitment models, which assume recruitment into the fishery is a function of fishing effort. They are interested in modelling such variables as overfishing, egg production, growth, fishing mortality, and natural mortality in an effort to define total allowable catch for an entire population. Another approach has been taken by scholars interested in adaptive or ecosystem management (Axelrod 1997, Link, Bundy et al. 2011). This method involves developing explicit alternative strategies to reach management goals, using relative knowledge to reduce uncertainty and evaluate merits and limits of management strategies, and reducing management risks inherent in situations, in which, imperfect information is used. Neither of these approaches address our major concern—namely, changes in technology, fleet mobility, scale and the serial destruction of subpopulations. These factors, leading to the depletion of northern cod, are quite different from any of those considered by academics interested in fisheries management. Taking these factors into consideration requires a new approach to management.

Another approach has been taken by social scientists interested in describing the traits of communities that increase the probability that they will develop rules to constrain fishing effort and conserve fish populations. They have argued that small, homogenous communities, where people are highly dependent on the resource, with a good deal of interaction and social capital, are more likely to succeed in generating such rules (Ostrom 1990, Ostrom 2000). The case studies described in this paper demonstrate that the ability of fishing activity to expand as local populations are depleted results in serial depletion. Absent the authority and the ability to defend their fishing grounds from fishermen outside of the community, the effectiveness of communities in constraining harvests is limited.

It is our contention that overexploitation of cod populations is primarily a problem of governance, and then, one of management strategy, wherein governance includes the development of rules restraining fishing, and the science and local ecological knowledge required to formulate those rules. According to the principle of subsidiarity, devolving authority for decision-making increases emergent solutions to issues of governance, such as collective action dilemmas. As Ostrom (2010) has argued, polycentric governance can prevent overuse of common property resources, and must be developed on site-specific basis to be effective. As applied to fisheries, such governance must engage local users in decision making and match the scale of the ecological dynamics of fish populations. The finest scale of decision-making must occur at a scale, at which, participants are able to effectively assess the status of subpopulation abundance and test management strategies for sustaining harvest levels.

The case studies we describe, make clear that demand for cod provided incentive for fishing activity, which expanded more or less continuously for several hundred years, as facilitated by a series of technological developments. The vast range of cod populations, and in some cases their enormous size, allowed for increasing harvests even as spawning populations were targeted. Even as landings declined, fishing at a broadscale prevented fishermen from recognizing their efforts as the serial depletion of subpopulations. Current understanding of the metapopulation structure of cod stocks provides a basis for polycentric governance; management of cod populations will be more effective to the degree that communities are given authority over fishing activity on subpopulations, particularly their spawning aggregations.

Just as fish populations exhibit a complex structure, comprised of a multi-level hierarchy of interconnected subpopulations, so the governance must reflect a similar interaction: decision-making bodies at the finest scale must engage with each other and with bodies at higher levels in the governance hierarchy. Such a system cannot be designed or implemented from the top down, but can be fostered by policies that allow for the emergence and ongoing adaptation of multi-scale decision-making. Such decision-making will reflect the dynamics of the local subpopulations and the impact of such dynamics on the metapopulation. Lacking an understanding of the dynamics of the local subpopulations and the consequences of their extirpation, fishermen in each of our case studies focused on expanding fishing activity. As opportunities at a broader scale became limited, by either the collapse of offshore populations or the imposition of national boundaries, they turned again to local subpopulations.

The structure of fish populations (assuming they have not been extirpated) changes only on an evolutionary scale; however, social learning allows for the continual adaptation of governance to factors affecting fish populations and fishing behaviour, such as, changes in markets and the development of new technologies. Fishing at the scale of subpopulations allows fishermen to gauge the effect of both fishing activity and conservation measures.

Defining spatial boundaries of governance to match fish populations and subpopulations is not a trivial exercise; it is complicated by our incomplete understanding of ecological dynamics of fish populations, and the fact that subpopulations exhibit a range of life history strategies that often results in their overlap in space. It is possible that the pattern of both local and roving fishing found in each of our case studies could be sustained with local fishing rules designed to protect spawning populations and roving fishing activity confined to areas without spawning activity. It is unlikely that we will ever find clear, perfect boundaries. Fish move, ecosystems overlap. The connections between the subpopulations within the Gulf of Maine are far from clear, much less so for those among the Gulf of Maine, the Grand Banks, and Labrador. This makes governance all the more important because the understanding of the fishing restraints appropriate to the finer scale ecology of local places depends upon knowledge of those places, and the ability to negotiate meaningful ‘cross-boundary’ restraints (Steneck and Wilson 2010).

Two of our case studies occurred before the implementation of science-based fisheries management in the late twentieth century. Our third case study, in New England, demonstrates that such management is inadequate in preventing the serial depletion of cod populations that has characterized the first several hundred years of commercial cod fishing.

Management, that matches the scale of fishing to the scale of subpopulation dynamics, and that allows fishermen to participate in making rules about harvesting, creates incentives for conservation. Licensing vessels for areas of limited size would prevent the use of a roving-bandit strategy and create an incentive for conservation. Engaging fishermen in such areas in decision-making regarding the best means of sustaining the fish populations within these areas would increase the likelihood that the resulting rules would be both, effective and subject to compliance. Linking local management, at the scale of subpopulations, in polycentric, hierarchical governance generates better feedback about the effects of fishing, allows coordination of management strategies, and protection of populations.

Analysis of the interaction of economic incentives with the heterogeneity of ocean resources, within a hierarchical, socioecological framework, suggests solutions to overharvesting that are multi-scalar, and address both, population dynamics and incentives for harvesting. With administrative boundaries that reflect the scale of cod subpopulations and limit roving-bandit strategies, such approaches may prevent overharvesting of populations in the face of increased demand or improvements in technology.

CHAPTER 2

PRECURSORS OF SOCIAL LEARNING IN FISHERIES AND THEIR ROLE IN COLLECTIVE ACTION

Introduction

Fishing is foremost a costly search for information about the location and abundance of fish. Fishing is also an activity in which individuals engage in more or less cooperative and conservation-oriented behavior depending on the private costs and benefits of acquiring and sharing information. Those costs and benefits are a function of the scale and behavior of the target population, the technology in use, and the institutional structure that governs fishermen's behavior. We suggest that in a complex natural environment, the multilevel and collaborative features of co-management institutions strongly encourage social learning among fishermen and the movement of their private knowledge about the fine scale attributes of the resource into the public domain. This movement is due especially to the change in conservation incentives brought about by co-management. The private knowledge that moves into the public domain in this way can significantly reduce the costs of monitoring and understanding fine scale behavior. Co-management also facilitates collaborative research, builds a collective understanding among fishermen of local ecosystems, and validates a role for fishermen in management. We reach this perspective primarily based on experience in Maine's lobster, urchin, groundfish, and scallop fisheries.

We explore the circumstances that reduce the ambiguity of collective knowledge about the status and dynamics of fish stocks, the nature of social learning among fishermen, and the settings in which social learning contributes to effective fisheries governance and management. Our analysis focuses on 1) the circumstances in which fishermen find it less costly to acquire information about the location and behavior of fish from others rather than through their own search, 2) the circumstances in which social organization emerges as a result of such sharing, and 3) the implications for the health of species and ecosystems and the management of fisheries and other commons.

Our broad argument is that limiting fishermen to a territory that is spatially congruent with demographically relevant subpopulations of the fished population leads to social learning among fishermen and the evolution of a refined, collective understanding of local system dynamics; this understanding lays the foundation for self-regulation, collective action, and sustainable harvests. In other words, given the right conditions, fishermen contribute information essential for effective management.

In the absence of constraining boundaries, fishermen faced with declining harvests will usually adopt a roving bandit strategy, expanding their fishing area to exploit less depleted stocks. When territorial boundaries thwart this approach, an important change in incentives occurs. Fishermen's incentives shift from maximizing harvests in the short term to ensuring that harvests can be sustained over the long term. Because fishermen within a territory can't simply leave (if others also have territories) and because boundaries prevent outsiders from freeriding, fishermen's 'best' option is to learn how to act collectively to sustain a fishery. Colloquially, without boundaries, fishermen have to think about where to go next after they've fished out their current area. With boundaries, they have to think about what's going to happen in the years to come in their local area.

The Maine lobster fishery is an often-cited example of common property resource users working together to sustain their livelihoods e.g., Ostrom (2008), (Acheson and Gardner 2010, Barnett and Anderies 2014). In the Maine lobster fishery, information sharing among fishermen contributed to the emergence of social organization. The initial organization was focused on the collective defense of a group fishing territory. This organization allowed fishermen to solve a series of collective action dilemmas including controlling access to fishing territories and prohibiting the use of destructive fishing gear. Collective action by groups of lobster fishermen and agreement among the groups eventually led to the formalization of a role for fishermen in the management of the lobster fishery, a process known as co-management. Shared authority for management between fishermen and the State of Maine has contributed significantly to the success of the fishery. Building on lessons learned from the Maine lobster fishery, where fishers devised solutions to overharvesting, we argue that circumstances that incentivize information sharing among resource users are an essential driver of social organization and collective action. Other fisheries, in Nova Scotia, Japan, and the Lofoten Islands, have also benefited from information sharing and collective action, this trajectory is not typical, however, as private information about where to fish is tightly held because secrecy yields competitive advantage. As a result, the impact of management strategies on fish populations is often ambiguous, limiting the value of such information and its role in fostering emergent social organization.

Background

Ostrom described the principles that have allowed groups of users to successfully sustain a common resource (Ostrom 1990). We focus on the importance of defining clear territorial boundaries, limits on group membership, and matching rules governing the use of common goods to local needs and conditions. Ostrom (2008) described the importance of congruence (alignment of rules with local ecology and culture, both human and fish) including aligning territorial fishing boundaries with the local ecology. Fishing territories and local ecosystems can be considered components of a complex adaptive system. The flow of information among these components is affected by the alignment of the components, where alignment determines the clarity of information that relates changes in the natural system to fishermen's actions. The greater the alignment, the more meaningful the information emanating from the natural environment (Holland 2012), and the more likely are individuals and groups to understand their impact on the natural system.

Many, if not most, fish populations are now understood to occur as metapopulations of demographically semi-isolated subpopulations occupying fine-scale habitats that result from the interaction of oceanographic processes with geomorphological features (Smedbol and Wroblewski 2002; (Smedbol and Wroblewski 2002, Kritzer and Sale 2004, Kritzer and Sale 2006, Secor, Kerr et al. 2009, Johannessen, Skaret et al. 2014, Ouréns, Naya et al. 2015, Dean, Elzey et al. 2019, Schiesari, Matias et al. 2019). The productivity of a metapopulation is a cumulative function of the reproduction of the subpopulations at the base of the metapopulation hierarchy. Metapopulation structure confers benefits upon a species by allowing it to capitalize on the most suitable habitats and by buffering the species from the catastrophic loss of one, or a subset, of subpopulations. Among non-social species, adaptive capacity is genetically determined and the sustainability of local populations is facilitated by recruitment from nearby, surviving subpopulations. In contrast, among social animals, such as most teleost fish, adaptation to local conditions is a function of both genetics and socially acquired collective knowledge of behaviors appropriate to the local environment. Younger fish have to acquire this knowledge from older fish adapted to a particular local environment (Whiten, Biro et al. 2022, Wilson and Giske 2023). In these instances, the sustainability of local populations is dependent on the persistence of a learned body of collective knowledge adapted to a particular locality, i.e., local 'culture.' The implication is that local populations of social learners may be significantly less resilient than non-learners.

Social learning and collective knowledge

To find fish, fishermen have two non-exclusive choices; to search for fish themselves or to learn from others where to fish. Learning from others, a form of social learning, occurs when fishermen find that it is less costly to acquire information from other fishermen than to search for fish autonomously (Wilson, Hill et al. 2013). The iterative sharing of information is much more likely to occur among small populations of fishermen working in the same, restricted area. Individuals do not need to consciously participate in social learning to benefit from it (Holland 2014).

Subpopulations of fish tend to follow relatively regular patterns seasonally, e.g., in temperate climates they tend to move offshore to deeper water in the winter. Within seasons and at a fine scale, however, they tend to be less predictable and fishermen may find that sharing information results in lower information costs and greater economic benefits than autonomous search (e.g., those participating in Hawaii's longline fishery (Barnes, Arita et al. 2017)). Fishermen are not likely to share information that gives away their competitive advantage (e.g., where to find fish today) but will share somewhat broader observations, e.g., seasonal movements, changes in the abundance of juveniles, relevant oceanographic phenomena, the relative abundance of predators and prey, etc. Fishermen learn the complex patterns of the natural system through ongoing observation and sharing of information. However, if the information about the resource is ambiguous, it provides little basis for the growth of collective understanding and scant basis for cooperation. On the other hand, if fishing territories are aligned with the boundaries of subpopulations, the signals fishermen receive about the resource are likely to be less ambiguous and fishermen are more likely to communicate repeatedly with other fishermen fishing within the same boundaries. Game theory (Kleshnina, Hilbe et al. 2023) and computer science both argue that repeated communications are likely to lead to cooperation. Computer scientists elaborate the idea using the term ‘natural language’ (Holland 2012) to describe a structure of communications – a hierarchical arrangement of language and institutions – that reduces ambiguity and makes it possible for very imperfect agents to communicate and cooperate. The theory is relatively straightforward; a hierarchy of increasingly precise adjectives (e.g., “get the big, red, plastic ball”) emerges from repeated information sharing and makes agreement about what is happening more likely.

In a bounded fisheries system, ongoing engagement with a complex system and continued information sharing among a limited group of users reduces the ambiguity of signals about the effects of human activity and refines the collective understanding of the structure and dynamics of such systems. In other words, these circumstances are more likely to generate the information required to reveal a connection between fishing and the sustainability of the resource and, thus, a basis for cooperation.

As information is shared among sets of individuals, such social learning can lead to emergent self-organization of a group or a series of groups. Despite the ambiguity of signals from the natural system, such groups can assemble useful information about the dynamics of subpopulations and the effects of fishing pressure (Wilson, Hayden et al. 2012). According to Flack (2014), groups emerge when information aggregated by its members reduces ambiguity about the environment. Different types of environments have different costs for acquiring useful information and lead to the emergence of different types of social structures (Wilson, Hill et al. 2013, Wilson, Acheson et al. 2013). Faced with declining abundance, groups may devise solutions based on their collective understanding of the dynamics of the resource (Ostrom 1990). Characteristics of a species' natural history that apply at all levels of the metapopulation hierarchy, such as age or size at which individuals become reproductive, create incentives for information sharing and cooperation among groups. Individuals and groups tend to economize on the costs of sharing; as a result, information is not uniformly distributed, tending to reside where is it most useful.

Much of the social learning (among humans) literature focuses on the way social learning improves the outcomes of collaborative processes (e.g., Cundill and Rodela 2012, Emerson and Gerlak 2014, van der Molen, van der Windt et al. 2016). Our analysis is concerned with the social learning that emerges when fishing territories are bounded. In these circumstances, social learning among fishermen generates meaningful information regarding subpopulation dynamics. As such, social learning is a precursor of collective action; then, when collective action takes place, fishermen's private knowledge of the natural system effectively enters the public sphere. In short, social learning generates both inputs to the problem-solving process and outputs in the form of collective, adaptive behaviors.

Thus, the operation of social learning at a relatively fine scale is important because administrative necessity often forces government agencies to manage at a scale much larger than the scale of the effective, i.e., self-reproducing, population they seek to manage (Scott 1998). Fisheries agencies tend to rely on quantitative modeling based on assumptions (yet to be justified) regarding the relationship between spawning stock biomass and future stock abundance (Acheson and Wilson 1996). Assessment data collected at a metapopulation scale averages signals across subpopulations resulting in ambiguity regarding subpopulation dynamics and masking the impact of harvesting activities until the metapopulation collapses (Hayden, Acheson et al. 2015). In contrast, fishermen operate at a scale that is more closely aligned with that of an effective subpopulation and, as a result, they have detailed knowledge of the time and place patterns that complement broader scale measures of the subpopulation. This 'tangible' knowledge leads them to trust a qualitative, collective understanding of what contributes to a species' reproductive success.

The combination of natural system knowledge acquired at the top (by managers) and the bottom (by fishermen) of the system, can flesh out human understanding of complex natural circumstances and, as we argue below, can become the basis for ecosystem approaches. However, the usefulness of this knowledge depends critically on the flow of information within the institutions governing fishing. Combinations of top-down and bottom-up knowledge tend to partition information among groups at different scales, including fishermen and fisheries agencies. They affect the amount and flow of information between and are a pervasive attribute of complex systems (Holland 2014), including most forms of civil governance. Multi-scale governance and policies that facilitate the flow of information between fishermen and fisheries agencies allow otherwise unavailable information at both fine and broad scales to be brought to bear on fisheries decision-making.

Case Study

Three fisheries, for urchins and lobster in Maine waters and groundfish in the Gulf of Maine, provide a case study for understanding the role of fishermen's individual and social learning in fisheries outcomes. These fisheries illustrate how different life histories, habitat heterogeneity, and bounded fishing territories affect fishermen's search for costly information, the emergence of social organization and collective action, and shared management between fishermen and fisheries agencies.

A study by Wilson, Acheson, and Johnson (2013) analyzed the nature of the costly search problem addressed by fishermen in these three fisheries. The costly search problem differs from fishery to fishery and affects the willingness of fishermen to share information and learn from one another, which in turn affects their interest in cooperation and ability to solve the collective action dilemmas presented by declining harvests. The cost of search is affected by harvesting technologies, the way fishers are regulated, constraining boundaries, and the reproductive scale, mobility, and metapopulation structure of each species. The target species in each fishery have different reproductive strategies and mobility and are managed at different spatial scales relative to their metapopulation structure. Each has developed over different timeframes relative to the implementation of fisheries management regimes. And each is faced with very different regulatory and technological restraints. All these factors affect the conditions that facilitate or hinder social learning.

Each fishery is also affected by habitat diversity along the coast of Maine. Maine's island and bay-rich 4,500-mile coastline includes a range of geomorphological, oceanographic, and ecological features that interact to divide nearshore waters into a series of ecosystems with distinct characteristics. On a broad scale, the coast is affected by nearshore circulation in the Gulf of Maine with distinct coastal currents along the eastern and western coasts. The southwestern coast is distinguished by extensive beaches and exposure to the Gulf of Maine. Immediately to the northeast is an embayment with hundreds of islands affected by outflow from the Kennebec River. On the eastern side of the Kennebec, is a length of coastline that features a series of peninsulas and islands that divide coastal waters into small, narrow bays. Adjacent to the east is Penobscot Bay, the largest embayment along the coast; complex circulation patterns result from a mix of outflow from the river and inflow from the eastern Maine Coastal Current as these flows encounter a series of islands, large and small (Xue, Xu et al. 2000). Still further east is a region dominated by two large bays, with hundreds of coves and inlets created by still more islands. This easternmost part of the coast is characterized by extreme tides, strong tidal currents, and a mix of bold shore, islands, and smaller embayments. The distinct characteristics of each region create a range of habitat types for nearshore flora and fauna.

How this diverse geography affects urchin, groundfish, and lobster ecology is not entirely clear but broad patterns are suggested. Lobsters rely on a pelagic larval stage as part of their reproductive strategy. Lobster larvae remain in the water column for 15 to 20 days following hatching; studies demonstrate that while longshore transport does occur, recruitment is primarily from local sources and that accurate estimates of recruitment are scale-dependent (Xue, Incze et al. 2008, Incze, Xue et al. 2010, Chang, Chen et al. 2016). Urchins, groundfish, and many other marine species also rely on a pelagic larval stage; larval distribution may more generally be a function of the distinct features of Maine's coastline. The differing characteristics among regions of the coast also affect how the lobster and other fisheries are prosecuted. For example, strong tidal currents in eastern Maine present different fishing challenges than the protected waters of Casco Bay.

Maine's urchin roe fishery, which expanded dramatically in the 1980s in response to growth in demand from Japanese markets, shares characteristics of urchin fisheries in other regions (Ouréns, Naya et al. 2015). Fine-scale patterns of urchin abundance are apparent to harvesters, who harvest small-scale patches of urchins by diving or dragging. However, these patches are rapidly disrupted by harvesting activity. Regulations allow urchin fishermen to fish in one of two large zones that encompass the coast of Maine; as a result, urchin fishermen are highly mobile and rely on a roving bandit strategy, fishing at a scale much larger than the ecological scale of urchin patches or subpopulations (Johnson, Wilson et al. 2012). Broad patterns in urchin abundance are shared among fishermen; but, given the sedentary and locally patchy nature of the resource, such aggregate information has limited value when deciding where best to fish. Potentially valuable information about the specific locations of urchin abundance is not shared (Wilson, Acheson et al. 2013). As a result, the repetitive sharing of information on abundance or strategies for sustaining harvests is limited. Urchin landings peaked in 1994 at 17,371 mt and then rapidly declined; landings in 2021 were 378 mt, about 2% of the peak (MDMR n.d.).

Gulf of Maine groundfish, such as cod, hake, and haddock, are highly mobile, but apparently, each is characterized by multiple local - sub-panmictic – populations (Clucas, Kerr et al. 2019, O'Donnell and Sullivan 2021, Puncher, Wang et al. 2021). Groundfish subpopulations exhibit spawning site fidelity among many small spawning grounds along the coastal shelf of the Gulf of Maine (Ames 2004). Fishermen are also highly mobile; their effective boundary includes the entirety of the U.S. part of the Northwest Atlantic, effectively encompassing all the subpopulations of groundfish in that area. In contrast, information that is useful for fishing is fine-scale and very short-lived; it is not shared because it would result in a competitive disadvantage. A general understanding of annual seasonal migrations, which can vary in timing and geography, is broader scale, longer-term, and widely shared. Like urchin fishermen, fishermen targeting groundfish today have access to a broad fishing area, tend to be highly mobile, and originate from widely separated ports. The larger number of fishermen likely to be fishing a broad area limits the incentives and opportunity for sharing information. Pulse fishing on spawning aggregations and lack of social interaction limits information sharing. In addition, groundfish are targeted by a diverse fleet; fishing vessels specialize by gear type, such as trawling, gillnetting, longlining, and handlining and jigging, which results in different types of information about patterns in fish abundance, reducing the benefit of information sharing that may occur.

There is evidence from the mid-twentieth century of social learning among local groups of groundfishermen making day trips to nearshore fishing grounds, leading in turn to self-organization and the development of strategies to protect subpopulations. For example, fishermen in Ipswich Bay, Massachusetts developed informal rules to protect spawning fish (Dobbs 2000). Larger vessels fished multi-day trips offshore, including in Canadian waters, leaving smaller catches in nearshore waters to the day boat fleet. Passage of the Magnuson Act in 1976 and implementation of a 200-mile exclusive economic zone by Canada changed the dynamic in the fishery as the large boat fleet was forced to focus on the Gulf of Maine (or leave the region); in addition, new federal programs incentivized the construction of new and larger vessels. Consequently, after extended jurisdiction the large boat fleet, fishing at the scale of the Gulf of Maine, outcompeted smaller vessels in the day boat fishery, forcing many out of the fishery, resulting in the loss of a refined, collective understanding of subpopulation dynamics such as in Ipswich Bay. Fishing by fishermen with limited social connections and at a scale larger than that which would provide feedback on the effects of fishing on subpopulations forestalled collective restraint and resulted in the serial extirpation of spawning grounds and the eventual collapse of many, if not most, of the components of the Gulf of Maine cod metapopulation (Ames 2004, Hayden, Acheson et al. 2015). Landings of cod in New England peaked in 1980 at 53,000 mt and have since declined steadily; landings in 2022 were 491 mt, less than 1% of the peak (NMFS n.d.).

Like urchin fishermen, groundfishermen have little incentive to share the information that gives them a competitive advantage (Wilson, Acheson et al. 2013). The broad scale information they collect and share is of limited value in understanding population dynamics or promoting group learning. With decreasing harvests and few constraints on mobility, urchin and groundfish fishermen adopted roving bandit strategies and collective action did not occur.

Lobsters along the Maine coast are less predictably patchy than urchins, creating a more costly search problem than for urchins. However, lobsters are more sedentary than groundfish and therefore present a less costly search problem as movement is somewhat predictable; due to the patchiness of the resource and the constraints of trap fishing an area with abundant lobsters is unlikely to be depleted in a day or week. While some information, such as indicated by the presence of trap buoys, is shared involuntarily, the higher cost of useful information regarding lobsters creates an incentive for fishermen to share additional, private information and over time build a hierarchy of increasingly precise descriptors regarding lobster dynamics and the risks of overharvesting, including from roving bandits. A two-tier system limits the mobility of lobster fishermen. They are restricted to fishing the majority of their traps within one of Maine's seven lobster zones. Within the zones, they are further restricted to very local, informal territories. Information about the dynamics of lobster populations and the characteristics of their catches are shared among fishermen who fish within the same territory; fishermen living and working in small communities have many opportunities for sharing information with others in their group. Some broader scale information, such as general abundance, or shedding time is also shared among neighboring groups. This ongoing flow of information helps maintain the boundaries and collective action in the fishery.

Cooperation at a broader than local scale first emerged following the collapse of the lobster fishery in the 1920s. Social learning expanded from among individuals to the group level as groups of fishermen tested strategies to sustain their harvests. The same information that helped fishermen understand local lobster population dynamics also helped them solve collective action dilemmas including threats presented by the actions of roving bandits. Fishermen banded together to protect their local fishing areas from nearby fishermen. At the same time, they cooperated with other groups, building on an emergent social structure to solve a series of broader-scale collective action dilemmas. Over several decades, they developed a series of both formal and informal input controls regarding who gets to fish and how (Acheson 2003).

A so-called "owner-operator" requirement ensures that fishing activity must be conducted by the license holder; the selling or transfer of licenses is also prohibited. Both policies, combined with fine-scale territorial boundaries, ensure that information is generated by those with a long-term interest in the fishery; they prevent consolidation of fishing activity into larger businesses with different incentives than owner-operators and ensure that local knowledge is retained in the fishery.

At least one of the solutions relied on by fishermen to sustain their harvests is based on a readily visible signal of reproductive capacity – the external attachment of eggs under the tail of the female lobster. "V-notching", i.e., cutting a notch in the right tail flipper of egg-bearing females, ensures that such individuals are protected even when they are not egg-bearing. Landings recovered by the mid-20th century and averaged roughly 10 mt per year until the late 1980s; then landings began to increase dramatically, reaching 60 mt in 2016; landings in 2021 were 50 mt (MDMR n.d.).

Informal organization and the capacity to solve collective action dilemmas emerged in Maine's lobster fishery before the establishment of government-defined administrative boundaries or effective regulatory regimes in the 1970s. The lobster fishery had sufficient political capital to resist the threatened federalization and likely broad scale, quota-driven management of the fishery in the late 20th century (Acheson 2003).

In Maine's lobster fishery, fishermen were able to solve a series of collective action dilemmas. Still, they were not able, without leadership from outside the fishery, to solve a collective action dilemma regarding trap limits that pitted "highliners" fishing hundreds of traps against small-scale fishermen (Acheson 2000, Acheson 2003); each region of the coast held to its understanding of how trap limits related to their local conditions. The solution was initiated by policymakers and negotiated by fishermen; it implemented formal co-management in the fishery by establishing lobster management zones. The process was aided by the fact that the value of costly information in the fishery remained high and the industry was experienced in working with policymakers at the state level. Implementation of co-management included formalizing the boundaries of fishing zones (within which informal territories still exist). Limited authority for management, subject to approval by the state, was delegated to the zones; including determination of the number of licenses and the ratio of new licenses granted to licenses retired, trap limits, the number of traps that can be fished on a single line, and fishing hours. The zone boundaries and delegated authority were largely determined by facilitated negotiation among fishermen. Co-management created a level of governance that reflected finer scale dynamics in the fishery than could be addressed by state-wide or Federal management.

While many of the input controls supported by the industry are formalized at the state level, a major benefit of finer scale boundaries and congruence in the fishery has been the ability of each zone to manage effort as the market value of lobster has remained strong and their relative abundance has increased fishing pressure. The ability of the lobster population to support fishing livelihoods varies from zone to zone as a function of the availability of lobster's preferred habitat and fishing conditions. Lobster licenses become available as older fishermen retire, in keeping with the prohibition on the sale of licenses. Most if not all zones have long waiting lists of fishermen awaiting licenses. Each zone has limited new entrants to a percentage of those exiting the fishery, reducing the number of commercial licenses held by fishermen between the ages of 18 and 70 by 28% between 1997 and 2018; the number of licenses per zone ranged from 291 to 853 in 2018 (MDMR n.d.).

Collective action dilemmas have been easier to solve in the lobster fishery than in the groundfish and urchin fisheries in part due to the nature of its search problem – which facilitated cooperation in the lobster fishery and discouraged it in the urchin and groundfisheries - but also due to other factors. For example, lobsters, unlike groundfish and urchins, don't aggregate to spawn, providing less of a target for fishing activity and limiting the impact of fishing activity on spawning stock biomass. Technological limitations in the lobster fleet in the early twentieth century constrained the ability of fishermen to adopt a roving bandit strategy. More recently, predator release due to the collapse of groundfish (and the concomitant decline of the trawler fleet and its destructive impact on lobsters), warming water temperatures, and other factors may have contributed to the increase in landings since the 1980s. However, the series of input control rules initiated by fishermen has certainly been a factor in preventing the type of collapse seen in the urchin and groundfisheries.

Findings

Maine's lobster and urchin fisheries and the federally managed groundfishery of the northeastern United States illustrate a range of ways that fisheries management and governance affect how fishermen acquire costly information, the type of feedback they get from their harvesting activities, the effect of territorial boundaries on their incentives, and the likelihood of collective action to sustain their harvests. Analysis of the three fisheries suggests that policies that foster opportunities for fishermen to establish territories based on their collective understanding of ecosystem dynamics, which will often be at a finer scale than management agencies have the capacity to oversee, may foster social learning that leads to cooperation and contributes to solving collective action dilemmas.

As described by Ostrom, the emergence of self-organization and self-restraint in fisheries requires spatial constraints that prevent fishermen from moving on from depleted areas as well as congruence between territories and local conditions.

While little is known about the nature of the lobster metapopulation in the Gulf of Maine, it is possible that the heterogenous nature of habitats along the coast sustains a series of subpopulations and that the lobster zones are sufficiently aligned with local conditions to provide less ambiguous signals to fishermen regarding the status of the local lobster population. Territorial boundaries in the fishery appear to align at least to some degree with subpopulations as fishermen appear to find less ambiguous information that is useful in conserving lobster productivity and abundance.

In practice, subpopulation boundaries are difficult to detect and likely to shift with changes in local conditions, exceeding both the capacity and capability of fisheries monitoring programs. Given the difficulty of accurately aligning fishing territories with subpopulation boundaries, creating territories that are likely to be smaller than subpopulations is a conservative strategy that retains fishermen's incentives to conserve and increases the likelihood of successful collective action. Larger territories are more likely to lead to roving bandit incentives.

Establishing co-management within territorial boundaries and sharing responsibility for management between fishermen and government agents, creates the opportunity to bring essential information regarding subpopulation dynamics into the formal management process. The lobster zone boundaries were negotiated with and among groups of fishermen who agreed with the idea of zones where boundaries made ecological sense and conformed with traditional fishing patterns. The allowance for fishing traps in neighboring zones recognized the reasonable likelihood that the negotiated boundaries were imperfect. The negotiation concerning zone boundaries is an example of the ways reliance on user knowledge of ecosystem dynamics and structure combined with historical use patterns led to acceptable boundaries that reinforce conservation incentives.

Co-management policies that embed such groups of fishermen within a hierarchy of governance align with Ostrom's condition regarding nested tiers of responsibility for governance from finer scale, rule-making bodies to those addressing an entire metapopulation or ecosystem. Co-management fosters social learning at a scale that generates information essential to effective management but largely beyond the capacity of fisheries agencies to collect. It also facilitates the flow of information up and down hierarchies of governance. Such hierarchies are defined as "an evolving mix of both designed and self-organizing activities" (Wilson, Hayden et al. 2012) that foster the flow of information among a variety of sources and at a range of scales (Berkes 2009), with the potential of increasing the resilience of fisheries social-ecological systems (Olsson, Folke et al. 2004). Such arrangements create forums for generating and sharing information that is beyond the capacity of fisheries agencies to collect. This is similar to most forms of civil governance in which effective governance and authority depend on information that resides at multiple locations and scales. For example, fine-scale features such as municipalities and usually even finer scale units are a persistent feature of such systems.

Traditional fisheries management relies on simple models of fisheries interactions, based on data collected at a broad scale, to generate quantitative limits on fishing activity; it has largely been unsuccessful (Wilson, Hayden et al. 2012). An attempt to apply traditional fisheries management to Maine's lobster fishery was rebuffed in the 1990s in favor of 'parametric' management (Acheson and Wilson 1996) which might be best defined as utilizing qualitative rules regarding "where fishing is allowed, when fishing can take place, and how fishing will be done" (Acheson, Apollonio et al. 2015).

Within a co-management context, parametric management allows fishermen to test different management strategies based on their understanding of subpopulation dynamics and generates rapid feedback on the effectiveness of such strategies. Such learning allows for the refinement of both the experimental process and adaptation of management rules and avoids the need "to predict potentially very complex ecological interactions" within a fisheries socioecological system (Wilson 2017).

Requiring fishermen to operate their vessels, through an "owner-operator" policy, tightly couples fishermen's knowledge of local conditions with the search for costly information. Vessel owners who do not operate their vessels rely on second-hand information, may consolidate information across multiple vessels and broader fishing territories, and have different incentives than owner-operators. In place in the lobster fishery for many years, an "owner-operator" requirement has recently been adopted by the Maine legislature for scallop and urchin draggers (Berleant 2017).

Learning by groups of fishermen can be fostered by engagement of group leaders with policy entrepreneurs, fisheries scientists, and bridging organizations (Olsson, Folke et al. 2004, Folke 2005, Beem 2007, Berkes 2009). A policy entrepreneur "connects political momentum to problem perception and a policy proposal" and bridging organizations have "the ability to strengthen social capital and the capacity for effective governance"; "the facilitation, leadership, and social incentives for collaboration provided by bridging organizations or key persons in the community appear to be essential for building the capacity to adapt to change" (Folke 2005). Bridging among groups with related interests can build momentum for new policies (Goldstein, Chase et al. 2016); such a process was important in the development of co-management in the lobster fishery. A similar process led to the development of informal, fine-scale co-management in Maine's scallop fishery (Hayden 2023, Maine Center for Coastal Fisheries n.d.).

More research is needed on how cooperation among fishermen and groups of fishermen can affect fisheries management, policy, and governance, including how learning at one level of organization affects learning at other levels (Siebenhüner, Rodela et al. 2016). To what degree must group leaders see the success of the group itself as important, in addition to, or instead of, considering the group as a means to pursue self-interest? Can the circumstances be identified that facilitate group-level learning? And can such circumstances be addressed in governance regimes and management strategies?

Finally, can momentum toward ecosystem-based fisheries management be aligned with policies designed to foster the emergence of self-organization as described above (Cucuzza, Stoll et al. 2021)? Such an approach has the potential to dramatically reduce the costs of research, implementation, and enforcement of an ecosystem approach to management. Fishermen are intimately in touch with the fine scale time and place regularities of the system. Engaging fishermen in data collection and analysis empowers their collective sense of ownership and, compared with a top-down approach, is likely to be far cheaper. In a similar vein, licensing fishermen based on an ecologically defined territory rather than by species would lay the foundation for coordinated, multispecies data collection at the local level. Effective management of cod in the Gulf of Maine has been hampered by the failure to recognize the metapopulation structure of the cod population and its reliance on Atlantic herring (Overholtz, Jacobson et al. 2008, Dean, Elzey et al. 2019). Ecologically defined fishing territories could help protect ecosystem-scale structure and function, limit fluctuations in target species abundance, and reduce gear and other inter-fishery conflicts.

Identifying opportunities for incorporating fine scale co-management within fisheries governance requires a willingness on the part of fishermen and fisheries agencies to work together, perhaps brought to the table by the need to address declining landings or other threats to fisheries livelihoods and with the support of nongovernmental actors.

Conclusion

The ecology of coastal ecosystems is characterized by fine-scale dynamics. Understanding such dynamics is costly, especially for fisheries agencies with limited resources and responsibility for management at a large-scale. Fishing at a fine scale generates among fishermen ecologically relevant information; when constrained by boundaries that align with the local ecology, fishermen are incentivized to share their private information with other fishermen. In co-management regimes embedded in complex systems, this private information transitions to the public domain and is essential for conservation. Policies that establish co-management with ecologically relevant boundaries reinforce incentives that encourage cooperation and the development of conservation practices.

Much of the social learning literature focuses on a role for collaboration in fostering social learning and improving outcomes. We argue that a reverse process, social learning leading to collaboration, is equally important. Creating the co-management circumstances in which fishermen are incentivized to participate in social learning has the potential to generate the information required for ecosystem management, strengthen conservation incentives, and improve fisheries outcomes.

CHAPTER 3

CO-MANAGEMENT IN MAINE: INTEGRATING FISHERMEN'S KNOWLEDGE INTO GOVERNMENT OVERSIGHT OF FISHERIES

Introduction

Maine is known for its high-quality seafood – and with good reason. Less well understood, and perhaps even more noteworthy, is the system of governance that has allowed several of Maine's fisheries to thrive. Known as co-management, it is characterized by the sharing of responsibility for management between fishermen and fisheries agencies Berkes, George et al. (1991). Co-management can resolve the challenges that arise when fisheries are managed at a spatial scale that is inconsistent with the scale at which fish[i] populations grow. By creating incentives among fishermen to sustain harvests, co-management generates the fine-scale information necessary for understanding the interaction of fishermen and fish populations and builds the capacity to adapt to threats such as climate change, use conflicts, and changing societal values.

Four fisheries in Maine – for lobster, soft-shell clams, river herring, and scallops – are co-managed, each has demonstrated success in enhancing fisheries productivity (Acheson 2000, Acheson, Stockwell et al. 2000, McClenachan, O'Connor et al. 2015, Cucuzza, Stoll et al. 2021, Jansujwicz, Calhoun et al. 2021). Each benefits from observation by fishermen, which generates ecologically relevant information regarding the status of fish populations. Traditional, top-down broad scale management in other fisheries, such as in New England's groundfishery, has obscured the local, fine-scale processes that drive fisheries productivity and have generally fared much less well. This paper analyzes the capacity of Maine's four co-managed fisheries to avoid overharvesting and to cope with other types of challenges, including climate change.

Wild fish in Maine constitute a commons, property managed by the state for the benefit of the people of Maine. Many commons, including many fisheries, have experienced the infamous "tragedy of the commons" (Hardin 1968). Maine's co-managed fisheries have avoided this fate. Elinor Ostrom's research revealed a series of conditions that can allow for successful commons management and are considered a framework for effective co-management (Ostrom 1990). They include defining boundaries that limit where groups of fishermen can fish; limiting group membership; matching rules governing harvesting to local needs and conditions; ensuring those affected by the rules can help modify the rules, and that the groups' rule-making rights are respected by outside authorities; developing a system for enforcing rules; and building responsibility for governing the common resource within nested tiers and from the lowest level up to the entire interconnected system (Ostrom 2008).

Ostrom also placed the use of commons within a broader setting that highlights the complex processes by which people (and their institutions) and organisms (and their ecosystems) interact (Ostrom 2009). This perspective expands the analysis of fisheries to incorporate their social drivers, such as fishermen's incentives and government policies, as well as their ecosystem context (Leslie, Basurto et al. 2015). It informs this analysis of Maine's co-managed fisheries which focuses on the importance of fine-scale information in understanding the interaction of humans and the natural system.[ii]

In a range of forms, co-management has a long history in fisheries (Berkes 2009); it is recognized as improving fisheries outcomes (Smallhorn-West, Cohen et al. 2022) and increasing fisheries' resilience (McCay, Micheli et al. 2014).

Co-management is not a panacea for sustaining fisheries. It is most effective where fishing territories do not exceed the scale at which recruitment[iii] and drivers of fisheries productivity occur. Fisheries for migratory species that do not spawn in the Gulf of Maine are unlikely to benefit from co-management in Maine. Co-management can also be subject to conflicts among rival factions leading to inequitable outcomes. Adoption of conservation practices do not resolve all disagreements about management, but does suggest that sufficient consensus exists to support chosen strategies.

Fish populations are composed of a series of subpopulations that form hierarchies[iv]. The growth of a fish population is driven by reproduction within individual subpopulations. The existence of subpopulations of shellfish is sustained by the local retention of a portion of the larvae they produced (Pineda, Reyns et al. 2009). This arrangement allows such species to take advantage of locally productive and protective habitats and guards against catastrophic population loss since locally extirpated subpopulations can be repopulated from nearby survivors through adult migration or larval dispersal. Because vertebrate fish are social animals, adaptation to local conditions is a function of younger fish observing and learning from the behavior of older fish (Wilson and Giske 2023). Anadromous fish, including river herring, spawn in freshwater lakes and ponds where their larvae are largely retained; the migration (or introduction through stocking) of some adults to non-natal spawning grounds allows for restoration of extirpated subpopulations if fish passage is not blocked.

The coast of Maine has a wide variety of habitats, at various scales, as tides and coastal currents swirl among its many islands, peninsulas, estuaries, and embayments. The overall result is fish populations that are patchy in both time and space. Boundaries that limit where fishermen can fish prevent them from leaving an area that is overfished to exploit less depleted stocks elsewhere. Such boundaries lead to an important change in fishermen's incentives. Without access to other fishing areas, incentives shift from maximizing harvests in the short term to maintaining harvests over the long term. Controlling access to a territory by limiting the number of fishermen who can fish there is a step in preventing the incentives for overharvesting within the territory. Aligning territories with the local ecology increases the likelihood that fishermen will be able to monitor subpopulation dynamics, develop new information about the local ecology, and generate conservation strategies to match local conditions (Ostrom 2008). Failure to monitor subpopulations masks loss due to overharvesting; the impact of overharvesting may not be evident until the population as a whole collapses (Hayden, Acheson et al. 2015).

Fishermen and fisheries managers also form groups and subgroups: informal groups of fishermen, various councils and committees in which fishermen have roles, and government agencies. Ideally, such groups are hierarchically arranged in nested tiers, aligning scales of management with those of ecological processes. Fishermen must learn where and when to fish, searching for patchy populations of fish in diverse environments. Acquiring useful information by interacting with or observing otherscan be more efficient than searching on one's own.

Information observed by fishermen is least ambiguous when the scale of the territory does not exceed the scale of a fish subpopulation or small group of subpopulations. The sharing of observations among a group fishing the same territory increases the likelihood of discerning meaningful signals and generates a progressively more precise understanding of the ecological and population dynamics within territories. This process contrasts to traditional science-based research that is most often conducted at a broad-scale and overlooks fine-scale information that is essential to accurately monitor the health of fish populations.

Working together to track the status of fish subpopulations within a fishing territory can lead to cooperation among group members and the capacity to address a range of threats to their fisheries, including declining harvests due to overharvesting and the negative impacts of climate change. As fishermen work together to address threats, social learning facilitates adaptation through an evolutionary process that reinforces those strategies that work and weeds out those that don't (Wilson 2017). Social learning at the group level requires a collective understanding of local conditions and the right to test a range of strategies. Group efforts are often limited to those allowed under existing governance regimes (which generally resist the establishment of new, finer-scale fishing territories) and tend to focus on those that might directly result in changes to local conditions.

Government oversight of fisheries often operates at a much broader scale than that at which fishermen can detect changes in abundance and productivity (Scott 1998). Government agencies often rely on broad-scale monitoring that obscures such changes (Hauser and Carvalho 2008). In contrast, fishermen trust a collective and qualitative understanding of what contributes to a species' reproductive success based on observation at a much finer scale (Wilson 2002). Co-management provides an opportunity for resolving this tension as it allows for more useful information on population dynamics to be incorporated into the management process. It also allows for local action that government agencies cannot manage.

In summary, co-management can improve fisheries outcomes because it shifts fishermen's incentives to include longer term conservation goals, generates fine scale information for management that would not otherwise be available, and develops fishing strategies that are consistent with conservation.

Case Studies

Here, I examine Maine's four co-managed fisheries, lobsters, soft-shell clams, river herring, and scallops, to compare the degree to which they meet the conditions established by

Ostrom (Table 1.). I also examined each fishery regarding its capacity to address both internal and external threats.

Lobster fishery

The lobster fishery is the most valuable single-species fishery in the country (NMFS (National Marine Fisheries Service) 2022). In 2022, it accounted for 68% of the value of Maine's commercial fisheries landings. The fishery is managed by the Maine Department of Marine Resources (MDMR), subject to oversight by the Atlantic States Marine Fisheries Commission (ASMFC), a state-federal partnership with jurisdiction over coastal fisheries on the eastern seaboard.

Ostrom's conditions for the emergence of local adaptive capacity are largely met in the Maine lobster fishery. The fishery is divided into seven fishing zones. Fishermen are limited by fishing in their home zones (with an allowance for fishing in adjacent zones). Fishermen within each zone have the authority to manage certain aspects of the fishery within their zone, subject to approval by MMDMR. Each zone has the right to set 1) the number of licenses and the ratio of new licenses granted to licenses retired, 2) trap limits, 3) the number of traps on a trawl, and 4) fishing hours. Requests for rule changes within the zones are generally approved by MDMR and attest to the department's respect for the role of fishermen in the management of the fishery (Acheson 2013). Governance of the fishery forms a nested hierarchy with fishermen's participation in decision-making occurring at every level. Decision-making within zones is overseen by zone councils, comprised of fishermen elected from local districts within each zone. Zone councils, in turn, appoint a member to serve on the state-wide Lobster Advisory Council which advises MDMR on lobster policy.

Table 1: Four Comanaged Fisheries in Maine and Conditions Necessary for the Emergence of Local Adaptive Capacity

Ostrom Conditions	Lobster	Clams	River herring	Scallops
Territorial boundaries	Fishery is divided into seven zones. Fishermen must fish a majority of their traps in one zone.	Fishermen are limited to fishing within municipal boundaries (or, in two cases, within the boundaries of several municipalities).	Fishermen are limited to fishing a single river or stream within municipal boundaries.	Informally enforced exclusion of nonlocal fishermen from Zone 3.
Limits on group membership at local level	Each zone limits entry.	Slightly more than half of participating municipalities limit entry.	Fishing rights within a municipality are granted to individuals	No formal limits.
Rules fit local circumstances	Each zone limits entry, number of traps, number of traps on a trawl, and sets time of day for fishing.	Most municipalities adjust number of licenses to reflect changes in shellfish abundance. Municipalities also adopt a range of strategies to sustain harvests.	Fishing is primarily regulated at the state level. Fishermen often clear impediments to fish passage to improve productivity.	Management is based on local conditions within two of the three scallop fishing zones. In Zone 2, rules reflect circumstances with subzones.
Harvester participation in rulemaking	Formal and effective role in rulemaking at local, state and regional levels.	Formal and effective role in rulemaking at local level.	Very limited role, at local level.	Informal and effective role within Zones Two and Three.
Respect by authorities	High	Low	Low	Moderate
Enforcement	The advent of comanagement in each of these fisheries has reduced the role of fishermen in punishment and dispute resolution as responsibility for these activities was shifted to the Marine Patrol, Maine DMR's enforcement arm, when zone management was implemented. Monitoring of fishing activity by fishermen and others occurs in all four fisheries. Information regarding illegal activity is shared with the Marine Patrol, which lacks the capacity to adequately enforce fishing regulations on its own. As a result, enforcement is more effective and the costs of enforcement for, and the number of violent conflicts among, fishermen has been reduced. In the clam fishery, municipalities ensure compliance with state and local regulations by hiring clam wardens to monitor local flats, which reflects both the number of flats that need to be monitored and the importance of the fishery to municipalities.			
Participation by fishermen in nested tiers of governance	**Hyperlocal**: Election districts **Local:** Zone councils **State**: Lobster Advisory Council **Regional**: Atlantic States Marine Fisheries Commission	**Local**: Municipal shellfish management, **State**: Shellfish Advisory Council	**Local**: Municipal river herring management **Regional:** None	**Hyperlocal:** Informal cooperation between fishermen and state in subzones of Zones 2. **Local:** Informal cooperation between fishermen and state in Zones 2 and 3. **State:** Scallop Advisory Council **Federal:** Limited

ASMFC is comprised of an administrator, legislator, and gubernatorial appointee from each of the participating states; these individuals also sit on each of the boards that oversee individual fisheries. Reflecting the value of the lobster fishery to the state, a lobster fisherman is often appointed as Maine's gubernatorial appointee to the commission. As a member of ASMFC's American Lobster Board, this appointee has a direct role in lobster management decision-making at the highest scale of governance.

Challenges met

Unfettered harvesting of juvenile and adult lobsters in the early 20th century led to the collapse of the fishery in the 1920s, with a drop from 20 m pounds in 1910 to 5.5 m pounds in 1924 (MDMR n.d.). Fishermen worked together to test strategies for recovering and sustaining catches, laying the groundwork for emergent organization and the capacity for adapting fishing practices to local conditions. For several decades, industry leaders worked together to develop and implement state-wide regulations, including prohibitions on harvesting pre-reproductive and over-sized lobsters, the marking of reproductive females, escape vents (to prevent cannibalism of small lobsters), and strategies to limit ghost fishing (Acheson 2003). The effectiveness of industry-led strategies in sustaining and growing harvests is often attributed to a conservation ethic among lobster fishermen, and the scale at which their conservation practices are implemented is important.

In the 1980s, dramatic growth in the number of traps being fished created a problem that the industry was unable to solve on its own. Fishermen wanted to limit overall trap numbers but couldn't reach a consensus on an individual trap limit given the widely differing conditions faced by fishermen along the coast. The solution, developed by Robin Alden, commissioner of MDMR at the time, scientists at the University of Maine, and leaders in the lobster fishery, was to establish a regional level of governance that would allow fishermen in different areas to develop rules specific to local conditions. It was codified in 1995 by the passage of the Maine lobster co-management law (Acheson, Stockwell et al. 2000). The law established formal zones that have prevented coast-wide expansion of fishing effort as vessel range increased.

The major benefit of boundaries that do not exceed the scale of lobster subpopulations has been the ability of each zone to manage effort as the market value of lobster has remained strong and their relative abundance has led to increased fishing pressure. The ability of the lobster population to support fishing livelihoods varies from zone to zone as a function of fishing conditions, the availability of lobster's preferred habitat, and local retention of lobster larvae (Xue, Incze et al. 2008, Incze, Xue et al. 2010). Each zone limits new entrants to a percentage of those exiting the fishery, which reduced the number of commercial licenses held by fishermen between the ages of 18 and 70 by 28% between 1997 and 2018. The number of licenses varies by zone; in 2018 they ranged from 291 to 853 (MDMR n.d.).

MDMR and industry leaders have to some degree been able to develop co-management that generates fine-scale information and individual incentives that complement the top-down management mandated by the Magnuson Act and the Atlantic Coastal Fisheries Cooperative Management Act on Maine's fishery (Acheson 2003). In the early 2000s, MDMR and the industry also negotiated manageable changes to the fishery to lessen perceived threats to the federally endangered right whale population.

<u>Ongoing challenges</u>

Lobster landings rose dramatically beginning in the late 1980s peaking at 132 m pounds (live weight) in 2016. Increasing value has offset a decline in landings since 2016 but many in the industry are concerned about the future of the fishery. The industry is also facing several challenges that arise from outside the fishery, including 1) renewed regulatory pressure to limit the potential impact on the endangered right whale, 2) changing spatial dynamics in lobster populations as lobsters avoid warmer, shallow waters, 3) rising bait and fuel costs, and 4) potential use conflicts with offshore wind farms and aquaculture. Some members of the fishery recognize that the lobster population has benefited from the overharvesting of cod and worry that efforts to restore cod could affect lobster abundance; others are willing to see cod restored if they are allowed to fish for them.

Soft-shell clam fishery

The soft-shell clam fishery is the third most valuable in the state, representing 3% of the value of Maine's commercial fisheries landings. Oversight of the industry occurs at the state level, through MDMR, and at the municipal level. There is indirect federal oversight of the fishery through the National Shellfish Sanitation Program which permits interstate sales of shellfish by those states with effective public health monitoring programs. The soft-shell clam fishery takes place mainly in intertidal habitats and has been co-managed by the state and municipalities in some way since statehood. As of 2023, fifty-five out of 145 coastal towns exercise a right to local management subject to state oversight; an additional twelve towns, in two regional programs, manage shellfish resources collectively. The Passamaquoddy tribe manages the clam fishery in Sipayik and Washington County manages the clam fishery within unorganized territories within the county.

Ostrom's conditions for effective co-management are partially met in the soft-shell clam fishery. Municipal boundaries establish territorial limits on fishing activity. Licenses are limited to residents except for a ten percent allocation to non-residents required by the state. Approximately half of municipal shellfish management programs otherwise limit entry in the fishery. Harvesters participate in rulemaking through their roles on municipal shellfish management committees, which allows management strategies to be tailored to local conditions on a flat-by-flat basis. For example, shellfish management committees close flats when necessary to prevent overharvesting and seed flats to enhance productivity.

MDMR has had a mixed record in respecting local shellfish management programs. Harvesters share a perception that protecting consumers from the risks of shellfish-borne toxins and pathogens is a higher priority at MDMR than supporting co-management through collaborative research and monitoring. This contention is supported by MDMR’s statement that public health monitoring constitutes its support for the industry (Waller, Bartlett et al. 2023). It remains to be seen whether a recent MDMR effort to engage shellfish harvesters in improving Maine’s municipal shellfish management program shifts the dynamic between the department and the industry (Singer 2022).

Municipal management programs form the base of a two-tier system of governance. A statewide Shellfish Advisory Council advises MMDMR on the status of the soft-shell clam fisheries and to recommend updates to statewide shellfish regulations; four of its fourteen seats are reserved for commercial shellfish harvesters. The advisory Council has been subject to regulatory capture affecting fishermen’s participation in decision-making. It is actively engaged in MDMR’s current initiative regarding shellfish management and has developed its own set of recommendations, addressing improved access to flats for harvesters and increased support for conservation activities, management, technical assistance, data management, municipal committees, improved water quality, and enforcement (MDMR 2023).

Challenges met

The soft-shell clam fishery exhibits only a moderate degree of alignment with Ostrom's conditions and a relative inability to affect state policy and regulations. Despite a long-term decline in landings, the fishery remains the third most valuable in the state. Support for active management in many coastal communities remains high, an indication that shellfishermen value co-management and that the scale of local management aligns with drivers of recruitment which, in this case, are likely to be hyperlocal.

Municipal shellfish committees are also testing adaptations to external changes that affect the fishery. For example, several committees have worked with their boards of selectmen or town councils and MDMR 1) to eliminate sources of pollution causing closures, 2) to increase water quality monitoring to reduce the scale of rainfall closures, 3) to diversify their harvests to include other bivalves, such as quahogs, razor clams, and oysters, and 4) to allow harvesters to retain their licenses if they move to inland due to housing costs.

With rare exceptions, the industry has generally lacked the political capital to affect state-level shellfish policy and suffers from a strained relationship with MDMR managers.

Ongoing challenges

The greatest threat to the fishery is predation by the invasive green crab whose populations have expanded dramatically with climate-driven increases in water temperature (Beal, Coffin et al. 2018). Other external challenges facing the fishery include an increase in public health-related habitat closures, the loss of access to intertidal shellfish habitat (Genter 2022), restrictions on the use of airboats (O'Brien 2021), and rising housing costs in coastal communities.

River herring fishery

Commercial river herring fisheries are prosecuted in over twenty municipalities in Maine (MDMR 2020) but constitute less than 1% of the value of Maine's commercial fisheries landings. The river herring fishery is managed by MDMR subject to oversight by ASMFC. Highly productive in Maine's early history, these fisheries declined dramatically over time, primarily due to the construction of dams and other obstructions to fish passage (Hall, Jordaan et al. 2012). Maine's tribes are focused on restoring river herring as a means of re-establishing Wabanaki sustenance lifeways practices (Maine Indian Tribal-State Commission 2022). In partial alignment with this goal, commercial fishermen and environmental groups are engaged in river herring restoration for its ecological benefits, and for sustenance and commercial fishing. Recent restoration projects have led to dramatic increases in the abundance of adult and juvenile fish within restored runs; to date, such efforts have addressed a small number of the obstructions impacting river herring runs. Maine's river herring fisheries are co-managed by municipalities and MDMR. Municipalities are granted harvest rights if a sustainable fisheries management plan is submitted to MDMR that conforms with the state's river herring fisheries management plan. Municipalities may appoint a river herring management committee to oversee the fishery.

Maine's river herring fisheries meet Ostrom's conditions in only limited ways. Territorial and group boundaries and the alignment of fishing territories with subpopulations are clear: commercial fishing rights are sold annually to individual harvesters who often hold the rights for several years. A short fishing season and strict state control on harvests have left harvesters with little opportunity to adjust harvesting rules to local conditions. Some harvesters focus instead on clearing debris and notching beaver dams to enhance migration and productivity. If harvesters fish within a community with a river herring management committee, they may have a say in local management decisions. MDMR's respect for municipal river herring fisheries is mixed. Disputes have arisen between MDMR and municipalities seeking to re-establish commercial river herring fisheries over monitoring and sample collection methods as well as analysis and interpretation of resulting data.

While river herring management by state actors is comprised of a nested hierarchy from municipal to multi-state levels, there are few ways for fishermen to participate in decision-making at every level. Fishermen participation on municipal river herring management committees varies from community to community. At the state level, there is no advisory council. Because Maine's gubernatorial appointee to ASMFC is most often filled by a lobster fisherman, there is little prospect of a river herring fisherman participating in ASMFC's Shad and River Herring Management Board.

<u>Challenges met</u>

River herring fishermen have had little success in addressing threats to their fisheries. Because harvest rights are auctioned to an individual harvester, there is limited opportunity to share information with other harvesters or to collectively develop a more detailed understanding of run dynamics.

However, commercial harvesters, supported by the Maine Center for Coastal Fisheries, were successful in 2019 in petitioning MDMR and ASMFC to establish an experimental fishery program, an example of changing river herring fishery policy, which is a challenge in Maine's co-managed fisheries. Three provisional fisheries in Maine were approved, providing fishermen interested in restoring a river herring run an opportunity to harvest fish while collecting the ten-year data record required for full approval of a commercial fishery (ASMFC 2019).

Ongoing challenges

Changes in rainfall patterns related to climate change affect both the upstream migration of adults and the downstream migration of juveniles. Bycatch in Gulf of Maine pelagic fisheries affects to some degree the abundance of adult river herring. The restoration of additional river herring runs and expansion of commercial river herring fishing face challenges including resistance from dam owners and owners of shorefront property on impoundments. In addition, dam removal or installation of a fish ladder can be expensive.

Scallop fishery

The scallop fishery in Maine waters represents 1.5% of the value of Maine's commercial fisheries landings. Scallops are primarily harvested by towing a drag along the bottom; a small percentage of landings are from a dive fishery. MDMR provides oversight of the fishery within state waters and the New England Fisheries Management Council oversees scallop fishing in Federal waters.

Maine waters are divided into three scallop management zones, reflecting differences in scallop habitat and productivity. Zone 1, from the New Hampshire border to Penobscot Bay, is the least productive; Zone 2, from Penobscot Bay to Lubec, further subdivided into 24 subzones, is more productive; Zone 3 includes Cobscook Bay, the most productive scallop habitat in the state, which generates approximately half of Maine's total scallop landings. Informal co-management is evident in Zones 2 and 3. Management of Zone 2 is divided into a series of small subzones. Local larval retention is likely given genetic analysis that indicates distinct subpopulations of scallops (Owen 2008). The subzones are managed on a rotational basis; a subset of the subzones is open each year and divided between the drag and diver fisheries. Fishermen develop a collective, fine-scale understanding of the status of the scallop resource as they fish within each subzone. As the fishing season progresses, fishermen inform MDMR when they detect declining catch rates and request that the subzone be closed for the remainder of the fishing season, which MDMR implements in real time (Maine Center for Coastal Fisheries n.d.). Local harvesters in Zone 3 have informally limited access for nonlocal fishermen to their fishery.

Management of the state fishery meets Ostrom's conditions to a degree but it lacks formal territorial limits on where scallop fishermen can fish. Entry is limited in the fishery at the state level; lotteries are held for licenses that become available. Co-management in the fishery fits local circumstances. Cobscook Bay fishermen have indirectly limited nonlocal fishermen by lobbying for a low daily harvest limit and restricting the number of moorings available to fishermen from other parts of the coast (scallop value and abundance would otherwise make travel to and from Cobscook Bay worth the time and expense). The Zone 2 rotational management program curbs overharvesting within its subzones.

Scallop co-management forms a three-tier hierarchy; the most local level, in effect in Zones 2 and 3, is informal. The Scallop Advisory Council advises MDMR on scallop management, nine out of thirteen seats are reserved for scallop fishermen so it is an influential voice for fishermen. There is limited scallop habitat seaward of Maine waters, which is managed by the National Marine Fisheries Service and the New England Fishery Management Council. Maine fishermen struggle to compete with an industrial scallop fleet that operates out of southern New England. They have limited influence in federal scallop management but recently won a set aside of a portion of the northern Gulf of Maine scallop quota for the small boat fleet.

Challenges met

In 2009, the fishery in Zone 2 was closed, following a dramatic decline in landings. In cooperation with MMDMR, the Maine Center for Coastal Fisheries solicited management suggestions from fishermen that led to the implementation of the rotational management scheme in 2012. Landings recovered, and co-management has been effective; however, it is more vulnerable to change than if codified in law or regulation. Like the advent of the zone system in the lobster fishery and an experimental fisheries policy in the river herring fishery, the development of rotational management in Zone 2 is another example of outside groups working with fishermen to change fisheries policy at a higher level of governance.

Ongoing challenges

The ten-year rotational management plan is up for renewal, creating the potential for elimination or weakening of informal co-management. Some harvesters are concerned that the expansion of scallop aquaculture in Maine could negatively affect the market for wild-caught scallops and lead to the protection of wild stocks that are the source of seed for scallop farmers.[v]

Summary of findings

Analysis of the case studies suggests that co-management has contributed to improving fisheries productivity. The lobster, scallop, and river herring fisheries support increasing or sustained landings. Landings in the soft-shell clam fishery are declining, with predation by the invasive green crab a major factor. Anecdotal evidence of the overharvesting of clams in a community with no shellfish management program suggests that landings may have declined more sharply without co-management. Harvesting of other species of shellfish has helped compensate for losses due to green crab predation. The apparent effect of co-management on landings implies that territorial limits on fishing are no larger than naturally occurring boundaries in fish populations and that the opportunity to observe fine-scale ecological and fisheries phenomena has fostered the local adaptive capacity necessary to address threats to these fisheries.

Management strategies supported and adopted at the most local level of governance vary from fishery to fishery (Table 2.). In the lobster, shellfish, and scallop fisheries, strategies include constraint on local fishing activity, such as limits on local entry and trap limits. In the shellfish and river herring fisheries, strategies include improving local productivity; clam fishermen seed flats and river herring harvesters remove obstructions to stream flow to enhance migration. None of these fisheries rely on model-driven estimates of fisheries abundance or set limits on total catch. The right to make changes at the local level allows action that would be difficult to administer at the state level. That municipalities hire clam wardens indicates the challenge the state faces in managing local fisheries and demonstrates the value that towns place on local shellfish management.

Table 1. Comparison of local actions to restrain harvests and improve productivity

	Lobster	Clams	River Herring	Scallops
Constraints on fishing activity				
	Local limits on entry	Local limits on entry	Local limits on entry	*De facto* exclusion of at least some nonlocal fishermen from Zone 3
	Trap limits	Flat closures		Rotational management of subzones within Zone 2 Daily limit lower than state daily limit in Zone 3
Improving local productivity				
		Seeding	Maintenance of stream flows	

These fisheries also adjust rules to address issues unrelated to the population dynamics of the target species. The number of licenses within a fishery can be adjusted to ensure a meaningful level of income for license holders. Shellfish harvesters support closures that prevent harvesting until the summer months when market demand increases, and lobster zone councils can determine the time of day during which fishing can occur, most likely to prevent night fishing which is more difficult to monitor for noncompliance.

Each fishery is also subject to state level conservation rules. The lobster fishery is subject to conservation practices for which the industry is well known including prohibitions on harvesting large, reproductive, and juvenile lobsters. The softshell clam and scallop fisheries are subject to minimum size limits and the river herring fishery is limited to fishing four days per week. Each of the four fisheries includes an owner-operator requirement; fishing activity cannot be delegated and must be conducted by the license holder. In addition, the selling or transfer of licenses is prohibited. Both policies prevent consolidation of fishing activity into larger businesses with different incentives than owner-operators,[vi] and also help to ensure the retention of local knowledge in the fishery. Such state-wide measures likely contribute to the sustainability of these fisheries; a link between state-wide regulations and upper levels in the hierarchy of subpopulations can only be assumed.

While a range of factors may have contributed to the dramatic rise in lobster abundance and landings since the 1980s, the conservation strategies of the lobster industry have likely had a significant impact (Acheson and Gardner 2010). The restoration of fish passage has had a dramatic and clear impact on the productivity of river herring runs. In the soft-shell clam and scallop fisheries, the relationship between local management strategies and fisheries productivity is less obvious and has not been as closely studied; the support of harvesters in these fisheries, however, is indirect evidence of management effectiveness.

The layering of state and local strategies appears to mirror the hierarchies of interconnected subpopulations and may reflect a combination of local larval retention, affected by local strategies, and larval delivery from adjacent areas, affected by state-wide policies.

The lobster fishery meets all the conditions described by Ostrom as necessary for effective co-management. The soft-shell clam, river herring, and scallop fisheries appear to benefit from co-management even though they meet Ostrom's conditions only to varying degrees. The scallop fishery lacks the most basic of Ostrom's conditions: territorial boundaries. Long travel times from one zone to the next and barriers to fishing for nonlocals in Cobscook Bay may effectively confine scallop fishermen to one of the three zones. The management of stream flows by river herring fishermen may make up for their lack of a role in decision-making at state and regional levels. A greater degree of local larval retention may allow local shellfish conservation practices to be particularly effective. Despite the high value of both soft-shell clams and scallops, and with some exceptions in the soft-shell clam fishery, the river herring, soft-shell clam, and scallop fisheries contribute to but don't solely support full-time individual fishing livelihoods for fishermen. The growth of these fisheries to support larger numbers of fishermen could create more pressure to sustain harvests and lead to the further refinement of co-management practices.

The collapse of significant components of the lobster, scallop, and river herring fisheries created incentives to rebuild these fisheries, and the overharvesting of clam flats had a similar effect at the local level. Recovery in each case has led to the establishment or renewal of co-management and has reinforced its value. Fishermen support local and state-wide rules when they fit their understanding of stock dynamics because they perceive that such measures correlate with greater success in their fisheries.

Co-management facilitates cooperative research which plays an important role in resolving conflicts over the different ways that fishermen and scientists view fish population dynamics and ecosystem processes (Ebel, Beitl et al. 2018). MDMR recognizes the vital importance of cooperative research in improving fisheries outcomes and addressing climate impacts. The department has developed trusted partnerships with members of the fishing industry that support long-running programs such as lobster sea sampling and the Maine-New Hampshire Trawl Survey (Waller, Bartlett et al. 2023). Cooperative research has also been facilitated by the University of Maine and nongovernmental organizations, including Manomet and the Maine Center for Coastal Fisheries.

These and other organizations support fishermen's efforts to engage in management and often act as bridging organizations between MDMR and industry groups (e.g., Gulf of Maine River Herring Network and Maine Shellfish Learning Network).[vii] Such efforts support changes in fisheries policies at higher levels of governance and align co-management more closely with Ostrom's conditions.

Conclusion

Four fisheries in Maine suggest that co-management is an effective approach to conservation. Co-management helps integrate fine scale information on fisheries population dynamics with government responsibility for oversight of fisheries at a broader scale. Limits on fishermen's ability to expand their territories shift incentives from maximizing harvests in the short term (by moving to another place) to ensuring that local harvests can be sustained over the long term. The lack of boundaries on fishing territories has dominated overfishing in almost all cases around the world. Limits on group membership and other constraints on effort limit the risk of overharvesting. Sharing of information among fishermen results in a collective understanding of fish subpopulation dynamics and allows for testing the effectiveness of conservation strategies. Granting even limited authority for decision-making to the local level allows for local action, such as clam flat closures based on local knowledge, that would be difficult for the state to manage. The emergence of local adaptive capacity also allows groups of fishermen to respond to a range of external threats including climate change, use conflicts with offshore wind power projects, and efforts to protect endangered species. Collaboration with nonprofit organizations and other policy entrepreneurs facilitates changes to fisheries policy that enable the expansion of co-management practices. Co-management does two important things that top-down management does not: it creates incentives for conservation and sustainability and generates the required information.

Looking ahead, co-management could be explored as a tool for improving other Maine fisheries, such as for urchins (Ovitz and Johnson 2019); resolving tensions between the market-based approach of traditional fisheries management and Wabanaki sustenance lifeways practices (Maine Indian Tribal-State Commission 2022); incorporating an ecosystem-based approach to management (Cucuzza, Stoll et al. 2021); and transitioning from a single-species, broad scale management to a multi-species management approach within areas congruent with population and ecosystem structure (Nguyen Thi Quynh, Schilizzi et al. 2017).

While there is no guarantee that co-management will allow the lobster, soft-shell clam, river herring, and scallop fisheries to weather the challenges they face, such efforts to date make clear that this approach is more effective than the top-down, model-driven approach of standard broad-scale fisheries management.

CONCLUSION

Market incentives and the development of increasingly effective fishing technologies led to the overexploitation of a range of species at a range of scales in the north Atlantic. Fishermen respond to local depletions by moving on to underexploited areas in a process that results in the serial depletion of stocks, as evidenced by cod fisheries across the range of the species. In the northwest Atlantic, implementation in the 1970s of exclusive economic zones, designed to protect fishing grounds from foreign fishing fleets, and development of science-based fisheries management did little to slow the decline in some fisheries, such as for cod. Other fisheries, such as Maine's lobster fishery, have fared better.

The complex ecology of coastal ecosystems, inhabited by one or more life stages of most if not all commercially valuable marine fish populations, ensures that fish stocks exhibit complex stock structure and are not panmictic, as assumed by traditional approaches to fisheries management. Applying broad-scale approaches to management can result in the failure to detect the extirpation of subpopulations within the hierarchy of metapopulations until the latter collapse.

Understanding the fine-scale dynamics of coastal ecosystems is costly, especially for fisheries agencies with limited resources and responsibility for management at a large-scale. Limits on fishermen's ability to expand their territories shift incentives from maximizing harvests in the short term (by moving to another place) to ensuring that local harvests can be sustained over the long term. When constrained by boundaries that align with the local ecology, fishing generates ecologically relevant information and fishermen are incentivized to share their private information with other fishermen. Information sharing facilitates organization and the development of a refined, collective understanding of ecological and population dynamics. This understanding is essential for conservation and forms the basis for collective action.

Co-management, the sharing of responsibility for fisheries management between fishermen and government agencies, can resolve the challenges that arise when fisheries are managed at a spatial scale inconsistent with the scale at which fish populations grow. In complex systems, co-management allows for the transition to the public domain of fishermen's private information significantly reducing the costs of monitoring and understanding fine-scale behavior. By providing fishermen with the opportunity to test management strategies it allows for local action that government agencies cannot manage.

Analysis of Maine's four co-managed fisheries, for lobster, clams, river herring and scallops, suggests that co-management has been effective despite the fact that only the lobster fishery incorporates all Ostrom's factors. Harvests have dramatically increased in the river herring and scallop fisheries in recent years. Lobster harvests have declined slightly since reaching a peak in 2016 but remain at historically high levels. Clam harvests have declined over the past several decades despite being co-managed in many municipalities since statehood, a likely result of extensive predation by the invasive green crab which has benefited from warming waters. Historically, each fishery suffered a significant collapse of at least some subpopulations which may have incentivized protection of fishing territories as populations rebounded and the eventual adaptation of some form of co-management. Increasing market demand for clams, river herring and scallops may spur incorporation of Ostrom's factors not currently included in the policies and governance of these fisheries. Analysis of four co-managed fisheries in Maine suggests that co-management, embedded within ecologically relevant boundaries, reinforces incentives that encourage cooperation and the development of conservation practices.

Broadening analysis of fisheries to incorporate the complexity of fish populations and human behavior suggests that policies that incentivize learning at a local scale and ensure that the resulting understanding of fine-scale population dynamics informs management at every level are more effective than relying solely on standard scientific fisheries management.

---

[i] References to fish refer to both fish and shellfish

[ii] The use of a socio-ecological systems framework is now pervasive in the study of natural resources.

[iii] Recruitment is the process by which fish reproduce and mature.

[iv] Ecologists refer to such populations as metapopulations.

[v] Scallop co-management in Japan includes both a wild fishery and aquaculture (Kosaka, Y. (2016). Chapter 21 - Scallop Fisheries and Aquaculture in Japan. Developments in Aquaculture and Fisheries Science. S. E. Shumway and G. J. Parsons, Elsevier. 40**:** 891-936.)

[vi] For example, the captain of a fleet fishing vessel whose job and reimbursement depend on consistently generating profits for the owner has shorter term incentives than an owner-operator in a co-managed fishery.

[vii] https://www.gomriverherringnetwork.org/; https://themudflat.org/the-msln-team/

BIBLIOGRAPHY

Acheson, A. W., T. Stockwell, and J.A. Wilson (2000). "Evolution of the Maine Lobster Co-management Law." Maine Policy Review **9.2**: 10.

Acheson, J. (1984). "Government regulation and exploitive capacity: The case of the New England Groundfishery." Human Organization **43**(4): 319-329.

Acheson, J. (2003). Capturing the Commons: Devising Institutions to Manage Maine's Lobster Fishery. Lebanon, New Hampshire, University Press of New England.

Acheson, J. (2011). "Coming up empty: Management failure of the New England groundfishery." Maritime Studies **10**(1).

Acheson, J., S. Apollonio and J. Wilson (2015). "Individual transferable quotas and conservation: a critical assessment." Ecology and Society **20**(4).

Acheson, J., T. Stockwell and J. A. Wilson (2000). "Evolution of the Maine lobster co-management law." Maine Policy Review **9**(2): 52-62.

Acheson, J. and J. A. Wilson (1996). "Order out of chaos: The case for parametric fisheries management." American Anthropologist **98**(3): 579-594.

Acheson, J. M. (2013). "Co-management in the Maine Lobster Industry

A Study in Factional Politics." Conservation and Society **11**(1): 60-71.

Acheson, J. M. and R. Gardner (2010). "The evolution of conservation rules and norms in the Maine lobster industry." Ocean & Coastal Management **53**(9): 524-534.

Acheson, J. M. and R. Gardner (2011). "Modeling Disaster: The Failure of the Management of the New England Groundfish Industry." North American Journal of Fisheries Management **31**(6): 1005-1018.

Ackerman, E. (1941). New England's Fishing Industry. Chicago, University of Chicago Press.

Alexander, K. E., W. B. Leavenworth, J. Cournane, A. B. Cooper, S. Claesson, S. Brennan, G. Smith, L. Rains, K. Magness, R. Dunn, T. K. Law, R. Gee, W. Jeffrey Bolster and A. A.

Rosenberg (2009). "Gulf of Maine cod in 1861: historical analysis of fishery logbooks, with ecosystem implications." Fish and Fisheries **10**(4): 428-449.

Ames, E. P. (1997). Cod and haddock spawning grounds of the Gulf of Maine from Grand Manan to Ipswich Bay. The Implications of Localized Fishery Stocks. I. Hunt von Herbing, I. Kornfeld, M. Tupper and J. Wilson**:** 55-64.

Ames, E. P. (2004). "Atlantic cod stock structure in the Gulf of Maine." Fisheries **29**(1).

Apollonio, S. and J. Dykstra (2008). "An Enormously Complicated Intervention": Groundfish, The New England Fishery Management Council, and the World Fisheries Crisis. Montgomery, AL, E-Book Time, LLC.

Armstrong, M. P., W. Hoffman, M. Dean and D. Zemeckis (2011). The application of small scale fishery closures to protect Atlantic cod spawning aggregations. Reconciling Spatial Scales and Stock Structures for Fisheries Science and Management. Portsmouth, NH.

Armstrong, T. (1966). "Soviet sea fisheries since the Second World War." Polar Record **13**: 155-186.

ASMFC (Atlantic States Marine Fisheries Commission) (2019). Proceedings of the Shad and River Herring Management Board Meeting

October 2019, Atlantic States Marine Fisheries Commission,**:** 14-19.

Axelrod, R. (1997). The Complexity of Cooperation: Agent-based Models of Competition and Collaboration. Princeton, Princeton University Press.

Barnes, M. L., S. Arita, K. Kalberg and P. Leung (2017). "When does it pay to cooperate? Strategic information exchange in the harvest of common-pool fishery resources." Ecological Economics **131**: 1-11.

Barnett, A. J. and J. M. Anderies (2014). "Weak feedbacks, governance mismatches, and the robustness of social-ecological systems an analysis of the Southwest Nova Scotia lobster fishery with comparison to Maine." Ecology and Society **19**(4).

Barrett, J. H., D. Orton, C. Johnstone, J. Harland, W. Van Neer, A. Ervynck, C. Roberts, A. Locker, C. Amundsen, I. B. d. Enghoff, S. Hamilton-Dyer, D. Heinrich, A. K. Hufthammer, A. K. G. Jones, L. Jonsson, D. Makowiecki, P. Pope, T. C. O‚ÄôConnell, T. de Roo and M.

Richards (2011). "Interpreting the expansion of sea fishing in medieval Europe using stable isotope analysis of archaeological cod bones." Journal of Archaeological Science **38**(7): 1516-1524.

Beal, B. F., C. R. Coffin, S. F. Randall, C. A. Goodenow, Jr., K. E. Pepperman, B. W. Ellis, C. B. Jourdet and G. C. Protopopescu (2018). "Spatial variability in recruitment of an infaunal bivalve: experimental effects of predator exclusion on the softshell clam (Maya Arenaria) along three tidal estuaries in southern Maine, USA " Journal of Shellfish Research **37**: 1+.

Beem, B. (2007). "Co-management from the top? The roles of policy entrepreneurs and distributive conflict in developing co-management arrangements." Marine Policy **31**: 540-549.

Berkes, F. (2006). "From community-based resource management to complex systems: The scale issue and marine commons." Ecology and Society **11**(1).

Berkes, F. (2009). "Evolution of co-management: Role of knowledge generation, bridging organizations and social learning." Journal of Environmental Management **90**(5): 1692-1702.

Berkes, F., P. George and R. J. Preston (1991). "Co-management: The Evolution in Theory and Practice of the Joint Administration of Living Resources." Alternatives **18**(2): 12-18.

Berleant, A. (2017). Scallop fishery to open through lottery, new legislation. Island Ad-Vantages. Stonington, Maine, US, Penobscot Bay Press.

Beverton, R. J. H. (1998). "Fish, fact and fantasy: a long view." Reviews in Fish Biology and Fisheries **8**(3): 229-249.

Bolster, J. W. (2008). "Putting the ocean in Atlantic history: Maritime communities and marine ecology in the Northwest Atlantic, 1500-1800." American Historical Review **113**(1): 19-47.

Bolster, J. W. (2012). The mortal sea: fishing the Atlantic in the age of sail. Cambridge, Belknap Press of Harvard University Press.

Bradbury, I. R., B. J. Laurel, D. Robichaud, G. A. Rose, P. V. R. Snelgrove, R. S. Gregory, D. Cote and M. J. S. Windle (2008). "Discrete spatial dynamics in a marine broadcast spawner: Re-evaluating scales of connectivity and habitat associations in Atlantic cod (Gadus morhua L.) in coastal Newfoundland." Fisheries Research **91**(2,Äì3): 299-309.

Cadigan, S. and J. A. Hutchings (2001). "Nineteenth Century Exapnsion of the Newfoundland Fishery for Atlantic Cod: An Exploration of Underlying Causes." Research in Maritime History **21**: 31-65.

Chang, J.-H., Y. Chen, W. Halteman and C. Wilson (2016). "Roles of spatial scale in quantifying stock–recruitment relationships for American lobsters in the inshore Gulf of Maine." Canadian Journal of Fisheries and Aquatic Sciences **73**(6): 885-909.

Clucas, G. V., L. A. Kerr, S. X. Cadrin, D. R. Zemeckis, G. D. Sherwood, D. Goethel, Z. Whitener and A. I. Kovach (2019). "Adaptive genetic variation underlies biocomplexity of Atlantic Cod in the Gulf of Maine and on Georges Bank." PLOS ONE **14**(5): e0216992.

Cucuzza, M., J. S. Stoll and H. M. Leslie (2021). "Evaluating the theoretical and practical linkages between ecosystem-based fisheries management and fisheries co-management." Marine Policy **126**: 104390.

Cundill, G. and R. Rodela (2012). "A review of assertions about the processes and outcomes of social learning in natural resource management." Journal of Environmental Management **113**: 7-14.

Dean, M. J., S. P. Elzey, W. S. Hoffman, N. C. Buchan and J. H. Grabowski (2019). "The relative importance of sub-populations to the Gulf of Maine stock of Atlantic cod." ICES Journal of Marine Science **76**(6): 1626-1640.

Dobbs, D. (2000). The Great Gulf: Fishermen, Scientists, and the Struggle to Revive the World's Greatest Fishery. Washington, DC, Island Press.

Doeringer, P. B., P. L. Moss and D. G. Terkla (1986). The New England Fishing economy: jobs, income and kinship. Amherst, MA, The University of Massachusetts Press.

Durrenberger, E. P. and G. Palsson (1987). "Ownership at Sea: Fishing Territories and Access to Sea Resources." American Ethnologist **14**(3): 508-522.

Ebel, S. A., C. M. Beitl, J. Runnebaum, R. Alden and T. R. Johnson (2018). "The power of participation: Challenges and opportunities for facilitating trust in cooperative fisheries research in the Maine lobster fishery." Marine Policy **90**: 47-54.

Emerson, K. and A. Gerlak (2014). "Adaptation in Collaborative Governance Regimes." Environmental Management **54**(4): 768-781.

Fagan, B. (2006). Fish on Friday: Feasting, Fasting, and the Discovery of the New World. New York, Perseus Books.

Finlayson, A. C. (1994). Fishing for Truth: A Sociological Analysis of Northern Cod Stock Assessments from 1977-1990. St. John's, Newfoundland, Canada, Memorial University.

Fisheries and Agriculture Organization (2013). Global capture production - quantity (1950-2011).

Fletcher, E. G. M. (1933). "John Selden (author of Mare Clausum) and his contribution to international law." Transactions of the Grotius Society **19**: 1-12.

Folke, C. H., T.; Olsson, P.; Norberg, J. (2005). "Adaptive governance of social-ecological systems." Annual Review of Environment and Resources **30**: 441-473.

Garcia, S. M. and C. Newton (1997). Current situation, trends and prospects in world capture fisheries. Global trends: fisheries management.

Genter, E. (2022). Maine's real estate boom is making it harder for clammers to get to mudflats. Bangor Daily News. Bangor, Maine, Bangor Publishing Company.

Goldstein, B. E., C. Chase, L. Frankel-Goldwater, J. Osborne-Gowey, J. Risien and J. Schweizer (2016). "Transformative Learning Networks." Proceedings of the 60th Annual Meeting of the International Society of the Systems Sciences **1**(1).

Goode, G. B. (1887). The fisheries and fishing industries of the United States. Washington, D.C., GPO.

Gordon, H. S. (1954). "The economic theory of a common-property resource: the fishery." Journal of Political Economy **62**(2): 124-142.

Green, J. M. and J. S. Wroblewski (2000). "Movement patterns of Atlantic cod in Gilbert Bay, Labrador: evidence for bay residency and spawning site fidelity." Journal of the Marine Biological Association of the United Kingdom **80**(06): 1077-1085.

Grotius, H. (1608 (2009)). Mare Liberum. Leiden, NLD, Brill Academic Publishers.

Hall, C. J., A. Jordaan and M. G. Frisk (2012). "Centuries of Anadromous Forage Fish Loss: Consequences for Ecosystem Connectivity and Productivity." BioScience **62**(8): 723-731.

Halliday, R. G. and A. T. Pinhorn (1990). "The delimitation of fishing areas in the Northwest Atlantic." Journal of Northwest Atlantic Fisheries Science **10**: 1-30.

Hardin, G. (1968). "The tragedy of the commons." Science **162**: 1243-1148.

Hauser, L. and G. R. Carvalho (2008). "Paradigm shifts in marine fisheries genetics: ugly hypotheses slain by beautiful facts." Fish and Fisheries **9**: 333-362.

Hayden, A. (2023). "Comanagement in Maine: Integrating fishermen’s ecological knowledge into government oversight of fisheries." Maine Policy Review **32**(2).

Hayden, A., J. Acheson, M. Kersula and J. Wilson (2015). "Spatial and Temporal Patterns in the Cod Fisheries of the North Atlantic." Conservation and Society **13**(4): 414-425.

Helin, R. A. (1964). "Soviet Fishing in the Barents Sea and the North Atlantic." Geographical Review **54**(3): 386-408.

Holland, J. H. (2012). Signals and Boundaries: Building Blocks for Complex Adaptive Systems. Cambridge, Massachusetts, MIT Press.

Holland, J. H. (2014). Complexity: A Very Short Introduction, Oxford University of Press.

Incze, L., H. Xue, N. Wolff, D. Xu, C. Wilson, R. Steneck, R. Wahle, P. Lawton, N. Pettigrew and Y. Chen (2010). "Connectivity of lobster (Homarus americanus) populations in the coastal Gulf of Maine: part II. Coupled biophysical dynamics." Fisheries Oceanography **19**(1): 1-20.

Jansujwicz, J. S., A. J. K. Calhoun, K. H. Bieluch, B. McGreavy, L. Silka and C. Sponarski (2021). "Localism “Reimagined”: Building a Robust Localist Paradigm for Overcoming Emerging Conservation Challenges." Environmental Management **67**(1): 91-108.

Jentoft, S. and T. Kristoffersen (1989). "Fishermen's co-management: The case of the Lofoten fishery." Human Organization **48**(4): 355-365.

Johannessen, A., G. Skaret, L. Langård, A. Slotte, Å. Husebø and A. Fernö (2014). "The dynamics of a metapopulation: changes in life-history traits in resident herring that co-occur with oceanic herring during spawning." PloS one **9**(7): e102462-e102462.

Johnson, T. R., J. Wilson, C. Cleaver and R. Vadas (2012). "Social-Ecological Scale Mismatches and the Collapse of the Sea Urchin Fishery in Maine, USA." Ecology and Society **17**(2).

Keith, D. M. and J. A. Hutchings (2012). "Population dynamics of marine fishes at low abundance." Canadian Journal of Fisheries and Aquatic Sciences **69**(7): 1150-1163.

Kleshnina, M., C. Hilbe, Š. Šimsa, K. Chatterjee and M. A. Nowak (2023). "The effect of environmental information on evolution of cooperation in stochastic games." Nature Communications **14**(1): 4153.

Kosaka, Y. (2016). Chapter 21 - Scallop Fisheries and Aquaculture in Japan. Developments in Aquaculture and Fisheries Science. S. E. Shumway and G. J. Parsons, Elsevier. **40:** 891-936.

Kritzer, J. P. and P. F. Sale (2004). "Metapopulation ecology in the sea: from Levins' model to marine ecology and fisheries science." Fish and Fisheries **5**: 131-140.

Kritzer, J. P. and P. F. Sale (2006). The Future of Metapopulation Theory in Marine Ecology. Marine Metapopulations. J. P. Kritzer and P. F. Sale. London, Elsevier Academic Press**:** 517-530.

Kurien, J. (2000). "Icelandic Fisheries Governance: A Third World Understanding." Economic and Political Weekly **35**(34): 3061-3066.

Lear, W. H. (1984). "Discrimination of the stock complex of Atlantic cod (*Gadus morhua*) off southern Labrador and eastern Newfoundland Canada, as inferred from tagging studies." Journal of Northwest Atlantic Fisheries Science **5**: 143-160.

Lear, W. H. (1998). "History of Fisheries in the Northwest Atlantic: The 500-Year Perspective." Journal of Northwest Atlantic Fisheries Science **23**: 41-73.

Leslie, H. M., X. Basurto, M. Nenadovic, L. Sievanen, K. C. Cavanaugh, J. J. Cota-Nieto, B. E. Erisman, E. Finkbeiner, G. Hinojosa-Arango, M. Moreno-Báez, S. Nagavarapu, S. M. W. Reddy, A. Sánchez-Rodríguez, K. Siegel, J. J. Ulibarria-Valenzuela, A. H. Weaver and O. Aburto-Oropeza (2015). "Operationalizing the social-ecological systems framework to assess sustainability." Proceedings of the National Academy of Sciences **112**(19): 5979-5984.

Lewis, A. and T. Runyan (1985). European Naval and Maritime History, 300-1500. Bloomington, Indiana University Press.

Link, J. S., A. Bundy, W. J. Overholtz, N. Shackell, J. Manderson, D. Duplisea, J. Hare, M. Koen-Alonso and K. D. Friedland (2011). "Ecosystem-based fisheries management in the Northwest Atlantic." Fish and Fisheries **12**(2): 152-170.

Longhurst, A. R. (2010). Mismanagement of Marine Fisheries. Cambridge, Cambridge University Press.

Maine Center for Coastal Fisheries. (n.d.). "Scallop Fisheries Co-Management." Retrieved January 6, 2023, 2023, from https://coastalfisheries.org/collaborative-management/scallops/.

Maine Indian Tribal-State Commission (2022). Sea Run: A Study regarding the Impact of Maine policies on the Quality and Quantity of Traditional Tribal Fish Stocks and Sustenance Practices.

McCay, B. J., F. Micheli, G. Ponce-Díaz, G. Murray, G. Shester, S. Ramirez-Sanchez and W. Weisman (2014). "Cooperatives, concessions, and co-management on the Pacific coast of Mexico." Marine Policy **44**: 49-59.

McClenachan, L., G. O'Connor and T. Reynolds (2015). "Adaptive capacity of co-management systems in the face of environmental change: The soft-shell clam fishery and invasive green crabs in Maine." Marine Policy **52**: 26-32.

McFarland, R. (1911). A History of the New England Fisheries. New York, University of Pennsylvania Press.

MDMR (Maine Department of Marine Resources) (2020). 2015 Maine Herring Sustainable Fishing Plan Update Augusta, Maine, Maine Department of Marine Resources.

MDMR (Maine Department of Marine Resources). (n.d.). "Historical Maine Lobster Landings." Retrieved November 11, 2023, 2023, from https://www.maine.gov/dmr/sites/maine.gov.dmr/files/inline-files/lobster.table_.pdf.

MDMR (Maine Department of Marine Resources). (n.d.). "Historical Maine Sea Urchin Landings." Historical Maine Fisheries Landing Data Retrieved November 11, 2023, 2023, from https://www.maine.gov/dmr/sites/maine.gov.dmr/files/inline-files/urchin.table_.pdf.

MDMR (Maine Department of Marine Resources). (n.d.). "Maine Lobster Fishing and Trap Tag Counts." Retrieved November 11, 2023, 2023, from https://www.maine.gov/dmr/fisheries/commercial/fisheries-by-species/lobsters/maine-lobster-fishing-license-and-trap-tag-counts.

MDMR (Maine Department of Marine Resources) Shellfish Advisory Council. (2023). "List of recommendations from regional shellfish workshops." Retrieved November 19, 2023, 2023, from https://www.maine.gov/dmr/sites/maine.gov.dmr/files/2023-09/ShAC_Town_letter_shellfish_recommendations_092623.pdf.

Myers, R. A., N. J. Barrowman and J. A. Hutchings (1997). "Inshore exploitation of Newfoundland Atlantic cod (Gadus morhua) since 1948 as estimated from mark¬ñrecapture data." Canadian Journal of Fisheries and Aquatic Sciences **54**(S1): 224-235.

Nguyen Thi Quynh, C., S. Schilizzi, A. Hailu and S. Iftekhar (2017). "Territorial Use Rights for Fisheries (TURFs): State of the art and the road ahead." Marine Policy **75**: 41-52.

NMFS (National Marine Fisheries Service) (2006). Status of the fishery resources off of the northeastern US: Cod.

NMFS (National Marine Fisheries Service) (2022). Fisheries of the United States, 2020., U.S. Department of Commerce. **NOAA Current Fishery Statistics No. 2020**.

NMFS (National Marine Fisheries Service). (n.d.). "Annual Commercial Landing Statistics." Retrieved November 12, 2023, 2023, from https://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html.

O'Brien, K. (2021). Maine coastal residents want law to curb airboat noise. Times Record, Masthead Maine.

O'Donnell, T. P. and T. J. Sullivan (2021). "Low-coverage whole-genome sequencing reveals molecular markers for spawning season and sex identification in Gulf of Maine Atlantic cod (Gadus morhua, Linnaeus 1758)." Ecology and Evolution **11**(15): 10659-10671.

O'Leary, W. (1996). Maine Sea Fisheries: The Rise and Fall of a Native Industry 1830-1890. Boston, MA, Northeastern University Press.

Olsson, P., C. Folke and F. Berkes (2004). "Adaptive comanagement for building resilience in social-ecological systems." Environmental Management **34**(1): 75-90.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action, Cambridge University Press.

Ostrom, E. (1999). "Coping with tragedies of the commons." Annual Review of Political Science **2**: 493-535.

Ostrom, E. (2000). "Collective Action and the Evolution of Social Norms." The Journal of Economic Perspectives **14**(3): 137-158.

Ostrom, E. (2008). "The Challenge of Common-Pool Resources." Environment: Science and Policy for Sustainable Development **50**(4): 8-21.

Ostrom, E. (2008). Design Principles of Robust Property Rights Institutions: What Have We Learned? Land Policy Conference, Lincoln Institute of Land Policy.

Ostrom, E. (2009). "A general framework for analyzing sustainability of social-ecological systems." Science **325**: 419-422.

Ostrom, E. (2010). "Beyond markets and states: Polycentric governance of complex economic systems." American Economic Review **100**: 1-33.

Ouréns, R., I. Naya and J. Freire (2015). "Mismatch between biological, exploitation, and governance scales and ineffective management of sea urchin (Paracentrotus lividus) fisheries in Galicia." Marine Policy **51**: 13-20.

Overholtz, W. J., L. D. Jacobson and J. S. Link (2008). "An Ecosystem Approach for Assessment Advice and Biological Reference Points for the Gulf of Maine–Georges Bank Atlantic Herring Complex." North American Journal of Fisheries Management **28**(1): 247-257.

Ovitz, K. L. and T. R. Johnson (2019). "Seeking sustainability: Employing Ostrom's SESF to explore spatial fit in Maine’s sea urchin fishery." International Journal of the Commons.

Owen, E. F. (2008). Population Structure of the Sea Scallop, Placopecten magellanicus, in Coastal Maine. PhD, University of Maine.

Palmer, M. C. (2014). 2014 Assessment update report of the Gulf of Maine Atlantic cod stock. U. S. D. o. Commerce**:** 119.

Pineda, J., N. B. Reyns and V. R. Starczak (2009). "Complexity and simplification in understanding recruitment in benthic populations." Population Ecology **51**(1): 17-32.

Playfair, S. R. (2003). Vanishing Species: Saving the Fish, Sacrificing the Fisherman. Lebanon, NH, University Press of New England.

Puncher, G. N., Y. Wang, R. Martin, G. DeCelles, S. X. Cadrin, D. Zemeckis, S. Rowe, N. M. Leblanc, G. J. Parent and S. A. Pavey (2021). "Transborder Gene Flow between Canada and the USA and Fine-Scale Population Structure of Atlantic Cod in the Broader Gulf of Maine Region." Transactions of the American Fisheries Society **150**(5): 560-577.

Reed, M. W. (2008). National and International Jurisdictions and Boundaries. Ocean and Coastal Law and Policy. D. C. Baur, T. Eichenberg and M. Sutton. Chicago, American Bar Association**:** 1-37.

Roberts, C. (2007). The Unnatural History of the Sea. Washington, DC, Island Press.

Robichaud, D. and G. A. Rose (2004). "Migratory behaviour and range in Atlantic cod: inference from a century of tagging." Fish and Fisheries **5**(3): 185-214.

Rose, G. A. (2007). Cod: The Ecological History of the North Atlantic Fisheries. St. John's, Newfoundland, Breakwater Books.

Ruzzante, D. E., C. T. Taggart and D. Cook (1999). "A review of the evidence for genetic structure of cod (Gadus morhua) populations in the NW Atlantic and population affinities of larval cod off Newfoundland and the Gulf of St. Lawrence." Fisheries Research **43**(1,Äì3): 79-97.

Schiesari, L., M. G. Matias, P. I. Prado, M. A. Leibold, C. H. Albert, J. G. Howeth, S. J. Leroux, R. Pardini, T. Siqueira, P. H. S. Brancalion, M. Cabeza, R. M. Coutinho, J. A. F. Diniz-Filho, B. Fournier, D. J. G. Lahr, T. M. Lewinsohn, A. Martins, C. Morsello, P. R. Peres-Neto, V. D. Pillar and D. P. Vázquez (2019). "Towards an applied metaecology." Perspectives in Ecology and Conservation **17**(4): 172-181.

Schroeder, P. (1967). Contact at Sea. Ridgewood, NJ, Gregg Press.

Scott, J. C. (1998). Seeing Like A State: How Certain Schemes to Improve the Human Condition Have Failed. New Haven, Connecticut, Yale University Press.

Secor, D. H., L. A. Kerr and S. X. Cadrin (2009). "Connectivity effects on productivity, stability, and persistence in a herring metapopulation model." ICES Journal of Marine Science **66**(8): 1726-1732.

Siebenhüner, B., R. Rodela and F. Ecker (2016). "Social learning research in ecological economics: A survey." Environmental Science and Policy **55**: 116-126.

Singer, L. T. (2022). "Exploring Successful Program Elements abd Potential Improvements to Maine's Municipal Shellfish Management Program." Retrieved November 19, 2023, 2023, from https://www.maine.gov/dmr/sites/maine.gov.dmr/files/2022-09/MSM%20Workshop%20Summary%20Report_Final_081922.pdf.

Smallhorn-West, P., P. J. Cohen, M. Phillips, S. D. Jupiter, H. Govan and R. L. Pressey (2022). "Linking small-scale fisheries co-management to U.N. Sustainable Development Goals." Conservation Biology **36**(6): e13977.

Smedbol, R. K. and J. S. Wroblewski (2002). "Metapopulation theory and northern cod population structure: interdependency of subpopulations in recovery of a groundfish population." Fisheries Research **55**(1-3): 161-174.

Srinivasan, U. T., R. Watson and U. Rashid Sumaila (2012). "Global fisheries losses at the exclusive economic zone level, 1950 to present." Marine Policy **36**(2): 544-549.

Steneck, R. and J. A. Wilson (2010). "A fisheries play in an ecosystem theatre: challenges of managing social and ecological drivers of marine fisheries at multiple spatial scales." Bulletin of Marine Science **86**: 387-411.

Van Bynkershoek, C. (1744 (1923)). DeDominio Maris Dissertatio. New York, Oxford University Press.

van der Molen, F., H. J. van der Windt and J. A. A. Swart (2016). "The interplay between knowledge and governance: Insights from the governance of recreational boating in the Dutch Wadden Sea area, 1981–2014." Environmental Science & Policy **55, Part 3**: 436-448.

Van Dyke, J. M. (2008). The 1982 United Nations Convention on the Law of the Sea. Ocean and Coastal Law and Policy. D. C. Baur, T. Eichenberg and M. Sutton. Chicago, American Bar Assciation.

Vert-pre, K. A., R. O. Amoroso, O. P. Jensen and R. Hilborn (2013). "Frequency and intensity of productivity regime shifts in marine fish stocks." Proceedings of the National Academy of Sciences.

Waller, J., J. Bartlett, E. Bates, H. Bray, M. Brown, M. Cieri, C. Clark, W. DeVoe, B. Donahue, D. Frechette, H. Glon, M. Hunter, C. Huntsberger, K. Kanwit, S. Ledwin, B. Lewis, R. Peters, K. Reardon, R. Russell, M. Smith, C. Uraneck, R. Watts and C. Wilson (2023). "Reflecting on the recent history of coastal Maine fisheries and marine resource monitoring: the value of collaborative research, changing ecosystems, and thoughts on preparing for the future." ICES Journal of Marine Science **80**(8): 2074-2086.

Warner, W. (1983). Distant Water: The Fate of the North Atlantic Fisherman. Boston, Little, Brown and Company.

Watson, R. A., W. W. I. Cheung, J. A. Anticamara, U. R. Sumaila, D. Zeller and D. Pauly (2013). "Global marine yeild halved as fishing intensity doubles." Fish and Fisheries **14**(4): 493-503.

Whiten, A., D. Biro, N. Bredeche, E. C. Garland and S. Kirby (2022). "The emergence of collective knowledge and cumulative culture in animals, humans and machines." Philosophical Transactions of the Royal Society B: Biological Sciences **377**(1843): 20200306.

Wilson, J. (2002). Scientific uncertainty, complex systems, and the design of common-pool institutions. The Drama of the Commons. E. Ostrom, T. Dietz, N. Dolsak et al., National Academy Press.

Wilson, J. (2017). "Learning, adaptation, and the complexity of human and natural interactions in the ocean." Ecology and Society **22**(2).

Wilson, J. and J. Giske (2023). "Does fishing dismantle fish culture and ecosystem structure? Questions about the implications of social learning among fish and fishers." Fish and Fisheries.

Wilson, J., A. Hayden and M. Kersula (2012). "The governance of diverse, multi-scale fisheries in which there is a lot to learn." Fisheries Research **141**(0): 24-30.

Wilson, J., J. Hill, M. Kersula, C. L. Wilson, L. Whitsel, L. Yan, J. Acheson, Y. Chen, C. Cleaver, C. Congdon, A. Hayden, P. Hayes, T. Johnson, G. Morehead, R. Steneck, R. Turner, R. Vadas and C. J. Wilson (2013). "Costly information and the evolution of self-organization in a small, complex economy." Journal of Economic Behavior & Organization **90, Supplement**: S76-S93.

Wilson, J. A. (2006). "Matching social and ecological systems in complex ocean fisheries." Ecology and Society **11**(1).

Wilson, J. A., J. M. Acheson and T. R. Johnson (2013). "The cost of useful knowledge and collective action in three fisheries." Ecological Economics **96**: 165-172.

Worm, B. and T. A. Branch (2012). "The future of fish." Trends in Ecology & Evolution **27**(11): 594-599.

Wright, P. J., F. C. Neat, F. M. Gibb, I. M. Gibb and H. Thordarson (2006). "Evidence for metapopulation structuring in cod from the west of Scotland and North Sea." Journal of Fish Biology **69**: 181-199.

Xue, H., L. Incze, D. Xu, N. Wolff and N. Pettigrew (2008). "Connectivity of lobster populations in the coastal Gulf of Maine: Part I: Circulation and larval transport potential." Ecological Modelling **210**(1): 193-211.

Xue, H., Y. Xu, D. Brooks, N. Pettigrew and J. Wallinga (2000). Modeling the circulation in Penobscot Bay, Maine. Estuarine and coastal modeling: proceedings of the 6th international conference on estuarine and coastal modeling. American Society of Civil Engineers, Reston, Virginia.

BIOGRAPHY OF THE AUTHOR

Anne is a candidate for the Doctor of Philosophy degree in Interdisciplinary Studies from the University of Maine in May 2024.