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LINKING LOCAL KNOWLEDGE & COMMUNITY SCIENCE IN SUPPORT OF COASTAL MARINE STEWARDSHIP

By

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B.A. Skidmore College, 2013

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Marine Biology & Marine Policy)

The Graduate School

The University of Maine

May 2022

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Thesis Advisors: Dr. Heather Leslie & Dr. Joshua Stoll

An Abstract of the Thesis Presented
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In the last two decades, there has been a shift towards more integrated, ecosystem-based approaches to marine management, including fisheries. At the same time, there have been calls for greater inclusion of diverse perspectives in conservation science and practice. For these reasons, there is renewed interest in the integration of indigenous and local knowledge into science, management, and environmental decision making. Despite these developments, local knowledge often is poorly integrated or treated as something of lesser value than knowledge generated or curated by professional researchers. Novel methods that integrate social and ecological data and prioritize local knowledge and community-based approaches are needed to meet this challenge. This thesis explores how linking local knowledge and community science approaches can bolster ecosystem-based management and coastal stewardship. Here I define community science as inquiry that is community-led, place-based, and aimed at improving governance processes with the goals of stewardship and social-ecological sustainability (after Charles *et al.*, 2020). Together, local knowledge and community science can generate robust social and ecological data. I highlight the connections among these approaches and model how they can be applied to small-scale coastal fisheries.

Using participatory mapping and interviews, I demonstrate how local knowledge can complement scientific knowledge by generating ecosystem hypotheses that can inform scientific inquiry and long-term monitoring. Local knowledge is critical because this holistic information is uniquely able to support actionable and responsive research and management by: (1) characterizing the social-ecological system at a fine spatial scale; (2) highlighting stakeholders' priorities and observations; and (3) generating hypotheses about how and why the system is changing, and what drivers may be influencing these changes. I explore how local knowledge can inform the development of community science initiatives and examine the community science process through a case study in the Damariscotta River estuary, Maine, USA. I use a typology to assess the conditions for community science and how it can generate ecosystem-level information. The assessment revealed two primary conclusions: (1) community science can be an effective approach to studying co-managed fisheries and (2) community science is, by its nature, an ecosystem-scale approach to research.

Integrating diverse knowledges and community partners can contribute to holistic understandings of dynamic marine coastal systems. These approaches can be applied to fisheries locally and regionally and have the potential to support ecosystem-based approaches to stewardship and management in marine coastal environments in Maine and beyond.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS……………………………………………………………………iii

LIST OF TABLES………………………………………………………………………..ix

LIST OF FIGURES………………………………………………………………………. x

CHAPTERS

1. THESIS INTRODUCTION…………………………………………………………..1

1.1. Background……………………………………………………………………. 1

1.2. Purpose of research……………………………………………………………2

2. ILLUMINATING COASTAL ECOSYSTEM COMPLEXITY AND CHANGE THROUGH LOCAL KNOWLEDGE MAPPING………………………………………..5

2.1. Introduction……………………………………………………………………5

2.2. Methods………………………………………………………………………...7

2.2.1. Study system……………………………………………………..7

2.2.2. Participatory mapping…………………………………………….. 10

2.2.3. Semi-structured interviews………………………………………..13

2.3. Results & Discussion…………………………………………………………15

2.3.1. Local knowledge guides investigations of change in shellfish populations and harvester behavior…..……………………………………..15

2.3.1.1 Shellfish habitats and distributions are shifting…..……………………16

2.3.1.2 Shellfish species compositions and abundances vary spatially and temporally……………..19

2.3.1.3 Harvesters adapt to stochastic shellfish populations……………………26

2.3.2. Local knowledge characterizes change and generates hypotheses about drivers of change……………………………………………………………………...29

2.3.2.1 Magnitude and direction of change and hypothesized drivers of change…………………….. 29

2.3.3. Connections among shellfish aquaculture and the wild shellfish fishery…....37

2.3.3.1 Larval dynamics and population connections ………..………………...37

2.3.3.2 Diverse observations of aquaculture & wild shellfish interactions…….41

2.4. Conclusion……………………………………………………………………....45

2.4.1. Linking local and scientific knowledges……………………………………..46

2.4.2. Outstanding questions…………………………………………………….48

2.4.3. Concluding thoughts……………………………………………………..... 49

3. COMMUNITY SCIENCE IN SUPPORT OF SHELLFISH MANAGEMENT: A CASE STUDY FROM THE DAMARISCOTTA RIVER ESTUARY, MAINE, USA…………...50

3.1. Introduction……………………………………………………….………..50

3.2. Materials & methods…………………………………………………………….55

3.2.1. Study system…………………………………………………………………55

3.2.2. Case study analysis……………………………………………………….. 58

3.2.3 Motivation for community science………………………………………...59

3.3. Results & Discussion…………………………………………………………....63

3.3.1. Case study: The wild shellfish fishery in the Damariscotta River estuary, Maine, USA……………...………………………………………………...63

3.3.1.1 Model of community science ……………………………………………..63

3.3.1.2 Concrete results of community science………………………………...64

3.3.2 Application of community science typologies……………………………….70

3.3.3 Application of community science principles & conditions……..…………..70

3.3.3.1 Connection to place & local knowledge……………………………..71

3.3.3.2 Community-driven & community-controlled………………………….. 72

3.3.3.3 Leadership and links to governance……………………………………73

3.3.3.4 Availability of capacity & resources……………………………………73

3.3.3.5 Credible trust & empowerment……………….…………………….....75

3.3.3.6 A framework addition: Data quality & communication……………….. 77

3.4. Conclusions……………………………………………………………………...78

3.4.1. Community science can be an effective approach to studying co-managed fisheries……………………………………………………………79

3.4.2. Community science is, by its nature, an ecosystem-level approach to research………………………………………………………………………. 79

4. CONCLUSIONS……………………………………………………………………...81

BIBLIOGRAPHY……………………………………………………………………………..85

APPENDIX A: STUDY SYSTEM INFORMATION……………………………………...98

APPENDIX B: LOCAL KNOWLEDGE MAPPING STUDY METHODS…………………..103

APPENDIX C: INTERVIEW GUIDE FROM LOCAL KNOWLEDGE MAPPING STUDY………………………………………………………………………….112

APPENDIX D: CODING SCHEMA & DEFINITIONS…………………………………… 116

APPENDIX E: 2021 STATE OF THE DAMARISCOTTA RIVER ESTUARY REPORT…..125

APPENDIX F: 2021 STATE OF THE MEDOMAK RIVER ESTUARY REPORT…………. 147

APPENDIX G: LONG-TERM MONITORING SITE INFORMATION……………………...169

APPENDIX H: DAMARISCOTTA COMMUNITY SCIENCE HANDBOOK………………173

APPENDIX I: COMMUNITY SCIENCE ANALYSIS TABLES……………………………. 198

BIOGRAPHY OF THE AUTHOR…………………………………………………………..200

LIST OF TABLES

Table 2.1. Demographic information for participants in the participatory mapping study……………………………………………………………….14

Table 2.2. Shellfish habitat and intertidal distribution information in the Damariscotta (n=11) and Medomak (n=7) River estuaries, based on interview data……………………………………………………………18

Table 2.3. Changes observed by participants in the Damariscotta and Medomak estuary systems (total n=44)…………………………………………………………35

Table 3.1. An adaptation of ‘Table 2: Key Principles and Conditions for Community Science from Charles et al. (2020)…………………………….. 54

Table B.1. Descriptions of potential participants for each study type…………………...103

Table B.2. Stickers for the two types of surveys for the participatory mapping study….105

Table D.1. Participatory mapping coding schema………………………………………116

Table I.1. Summary statistics for all species of interest (SS=soft-shell clam, Q=quahog, GC=green crab) at the study sites (n=3)……………………….198

Table I.2. Summary statistics for the soft-shell clam recruitment study (n=2 sites)…...199

Table I.3. Summary statistics for the shellfish ecological survey (n=3 sites)………….199

LIST OF FIGURES

Figure 2.1. Study site information…………………………………………………………..9

Figure 2.2. Medomak clam abundance……………………………………………………….22

Figure 2.3. Damariscotta clam abundance…………………………………………………23

Figure 2.4. Medomak shellfish species richness………………………………………...24

Figure 2.5. Damariscotta shellfish species richness……………………………………..25

Figure 2.6. Changes identified by study participants (Medomak n=22, Damariscotta n=28)…………………………………………………………31

Figure 2.7. Wild oyster distribution in the Damariscotta River estuary, as indicated by total sticker count by 10 participants……………………………………40

Figure 3.1. Damariscotta River estuary and surrounding towns……………………….. 57

Figure 3.2. Three community science models…………………………………………..58

Figure 3.3. Size frequency distribution for three commercially important shellfish species in the Damariscotta River estuary…………………………………..65

Figure 3.4. Shellfish abundance in the Damariscotta River estuary…………………….66

Figure 3.5. Soft-shell clam recruitment at three sites in the Damariscotta River Estuary………………………………………………………………… 100

Figure A.1. Upper and lower sections of the Damariscotta River estuary and Medomak River estuary ………………………………………………….102

Figure B.1. Guide map of the Damariscotta River estuary and Medomak River Estuary…………………………………………………………………...106

Figure B.2. Example of a page the Damariscotta River estuary and Medomak River estuary map packets………………………………………………….107

Figure B.3. Example of a filled in map page from a Damariscotta River estuary
"General user" study and a Medomak River estuary
"General user" study…………………………………………………………..108
Figure G.1. Long-term monitoring sites in the upper Damariscotta River estuary
selected using local knowledge data……………………………………… 169
Figure G.2. Day's Cove site map showing clam abundance (high, medium, and low)
based on local knowledge mapping data………………………………….170
Figure G.3. Westview site map showing clam abundance (high, medium, and low)
based on local knowledge mapping data………………………………….171
Figure G.4. Chadbourne site map showing clam abundance (high, medium, and low)
based on local knowledge mapping data………………………………….172

CHAPTER 1

INTRODUCTION

1.1 Background

Marine coastal areas are dynamic and highly variable social-ecological systems that present unique stewardship and conservation challenges (Stuchtey et al., 2020). Coastal regions throughout the world support diverse small-scale fisheries that provide income, food, and livelihoods to coastal residents (Berkes, 2001). They are also locations of deep cultural and historical significance, and today host growing industries, like tourism and aquaculture, that are increasingly important drivers in coastal economies (S. Hanna, 2000; Stoll et al., 2019). Management of marine coastal areas and their fisheries is confounded by patchy or incomplete data, largely due to the challenges of studying marine environments and the spatially and temporally variable human and non-human populations living within marine systems (Levin & Poe, 2017). These knowledge gaps create challenges for those who manage these social-ecological systems (SESs) at the local, regional, or national level (Young & Gasser, 2002).

Increasingly, researchers and managers are shifting towards ecosystem-based management approaches that integrate social and ecological data to address challenges in marine coastal SESs (Link & Marshak, 2019; McLeod & Leslie, 2009; USCOP, 2004). Ecosystem-based management (EBM) considers the entire scope of the ecosystem, including the range of human activities and uses that occur within the system. EBM recognizes the interconnectedness within systems, among species and habitats, and between the ecological, economic, and social dimensions of a system (McLeod et al., 2005) and in some instances overlaps with parallel concepts like co-management (Cucuzza, 2020). Many have sought novel methods to support EBM approaches in data limited marine systems (Botsford et al., 1997; Sherman, 2014) or in marine fisheries contexts (Hall & Mainprize, 2004; Pikitch et al., 2004; Pitcher, 2001). One approach is the inclusion of local knowledge through community science. Community science is one approach that engages local knowledge holders, managers, scientists, and students in collaborative research to document social and ecological data. Increasingly, community-based research programs are viewed as an effective and important approach to ecosystem-based fisheries management and environmental sustainability(Ebel et al., 2018; Johnson et al., 2012; Schroeter et al., 2009). Community science is a powerful tool for tackling local challenges related to stewardship, climate change, and resilience, and to inform resource management and enhance community engagement (Bonney et al., 2021; McKinley et al., 2017) because it provides a means for integrating local knowledge .

Maine is a useful case study for examining local knowledge and community science applications in marine coastal SESs and small-scale fisheries. Maine's intertidal shellfish fisheries, in particular, are a rich context to explore these questions due to the diverse challenges faced by the fishery, the scale and organization of its co-management structure, and its inherent connection to community and place (S. Hanna, 2000; McGreavy et al., 2018). Studying the application of local knowledge in these systems provides invaluable insights into the process, conditions, and outcomes of these approaches to community-based research that can be applied elsewhere to enhance capacity and support resilient management and stewardship.

1.2 Purpose of research

The goal of this research is to examine local knowledge and community science applications and approaches to EBM in coastal systems. In this thesis, I review how I have implemented these approaches in collaboration with many others, with a focus on Maine's intertidal shellfish fisheries. I evaluate how community-based research that prioritizes local knowledge in both research design and process can support ecosystem-based coastal management in Maine. This research has two central guiding questions:

(1) How do we use local and scientific knowledge to characterize social-ecological systems and identify hypotheses and drivers about how and why systems are changing?

(2) How can local knowledge and community science approaches support scientific inquiry and long-term monitoring in coastal social-ecological systems?

These questions are addressed in my thesis chapters using information documented throughout the course of a partnership between the University of Maine Darling Marine Center, the Joint Damariscotta-Newcastle Shellfish Committee, and local high school, Lincoln Academy. The partnership between the Darling Marine Center and the shellfish committee, and my role as the Darling Marine Center Education & Community Engagement Fellow working with Lincoln Academy teachers and students, guided the development and direction of this research. Chapter 2 synthesizes the results of a local knowledge mapping study with shellfish harvesters and other estuary user groups. Our team conducted the study to support decision-making by providing fine-scale spatial data on human uses and shellfish populations in the Damariscotta River estuary. The results also formed the basis of the community science project described in the following chapter. Chapter 3 assesses the development and conditions of the community science project with Lincoln Academy to study the Damariscotta River estuary. The analysis will inform future steps for the project, as well as aid in the application of community science projects in other coastal marine contexts. Both chapters employ integrated ecological and social science methods. Detailed information about the study system is provided in Appendix A, while Appendices B-D describe the methods and present supporting materials for the local knowledge mapping study.

Appendices E-F offer contextual information about the Damariscotta community science project and the tools used to support its implementation thus far.

Local knowledge was fundamental to the development of meaningful hypotheses and community-based understandings of the factors driving ecosystem-level change. It rooted the research in the needs and questions of the community, in a way that would not have been possible without its documentation and integration. This approach serves as a model that can be replicated elsewhere to support community-based, engaged approaches to research in coastal marine systems. It also emphasizes the importance of beginning first with local knowledge. Deeply understanding the perspectives, concerns, and priorities of community members from research inception to completion is essential to solutions-oriented research that addresses local stewardship and conservation challenges. Centering research on local knowledge prioritizes the interests and questions of community members and promotes the production of knowledge with local scale, scope, and specificity. This knowledge is tuned to the needs of the community and can be readily applied to specific management challenges and support ecosystem-level decision making.

CHAPTER 2

ILLUMINATING COASTAL ECOSYSTEM COMPLEXITY AND CHANGE THROUGH LOCAL KNOWLEDGE MAPPING

2.1 Introduction

In the last two decades, there has been a shift towards more integrated, ecosystem-based approaches to marine management, including fisheries(Link & Marshak, 2019; McLeod & Leslie, 2009; USCOP, 2004). EBM is more holistic than traditional approaches because it considers the ecosystem as a whole and emphasizes the interconnectedness between target and non-target species and the human and non-human dimensions of a system. EBM strives for place-based approaches that support ecosystem structure, functioning, and processes (McLeod et al., 2005). At the same time, there have been calls for greater inclusion of diverse perspectives in conservation science and practice (Tallis & Lubchenco, 2014, and many others). For these reasons, there is renewed interest in the integration of indigenous and local knowledge into science, management and environmental decision making (Hill et al., 2020). Despite these developments, local knowledge often is poorly integrated into environmental decision making or treated as something of lesser value than knowledge generated or curated by professional researchers (Agrawal, 2002; Berkes et al., 2006) .

Our focus in this paper is on local ecological knowledge. We follow Berkes and colleagues' definition, which describes local knowledge as place-based, experiential learning, and development of relevant knowledge by the people who live, work, and depend upon an ecosystem (Berkes et al., 2000). Local knowledge is unique in that it is not siloed into a single category, like many approaches to scientific monitoring, but rather communicates the connections in systems and spans social, economic, and environmental dimensions (Dey et al., 2020; Lertzman, 2010; Matsui, 2015). Local knowledge has played an essential role in assessing data-poor species in coastal ecosystems (Beaudreau & Levin, 2014; Dey et al., 2020), fisheries species population declines (Rehage et al., 2019), integrating fishers' behavior and knowledge in marine protected area design (Aswani & Lauer, 2006), and assessing how fisheries management influences local knowledge itself (Farr et al., 2018). Local knowledge and participation have been essential for filling knowledge gaps and providing social data to complement existing knowledge (Lima et al., 2017; Loerzel et al., 2017).

However, researchers and resource managers often have struggled to fully connect local and scientific knowledges, particularly in cases involving integration of social and biophysical data (Agrawal, 1995; Hill et al., 2020; Hind, 2015). Frequently, researchers have used local knowledge data to validate scientific observations or models (Stead & Gray, 2006; Tesfamichael et al., 2014). The validation, or 'ground truthing,' of local knowledge through scientific field studies or experiments also is common practice (Gratani et al., 2011; Wilson, 2006). Rarely, however, are local and scientific knowledges in dialogue and treated as equally legitimate sources of information (see, however, Hill et al. 2020 for examples of how this is changing).

Here, we report on research from Maine, USA to illustrate how local knowledge can help to guide and catalyze interdisciplinary science and connect it to environmental decision making. Our research prioritized local knowledge from design to implementation, an approach that produced outcomes relevant to the unique problems faced by local communities, and centered knowledge that is congruent with ecosystem- and community-based approaches to management (St. Martin et al., 2007). Using participatory mapping and interviews, we demonstrate how local knowledge can help generate and validate hypotheses of interest to both community members and researchers. Specifically, we demonstrate how it can be used to generate ecosystem hypotheses that are not currently being studied and inform scientific inquiry and long-term monitoring. Leading research with local knowledge is critical because this holistic information is uniquely able to support actionable and responsive research and management by: (1) characterizing the social-ecological system at a fine spatial scale; (2) highlighting stakeholders' priorities and observations; and (3) generating hypotheses about how and why the system is changing, and what drivers may be influencing these changes.

2.2 Methods

We used participatory mapping and semi-structured interviews to document local experts' knowledge of two estuaries in midcoast Maine and how the shellfish resources in these systems are changing. The study provides fine-scale and spatiotemporally specific information about human activities and shellfish populations in these complex marine systems.

2.2.1 Study system

The study was conducted in two Maine estuaries, the Damariscotta River and the Medomak River (Figure 2.1). These estuaries are located in midcoast Maine, approximately 50 miles east of the state's largest city of Portland and are oriented north to south, with oceanic linkages to the Gulf of Maine and Northwest Atlantic Large Marine Ecosystem. These two estuaries were selected because of their proximity and because while they are ecologically quite similar, they differ in terms of the nature and magnitude of human activities that occur within them.

Both include a diversity of coastal marine habitats, including rocky shore and soft sediment intertidal areas, subtidal eelgrass beds, and kelp forests, and subtidal rocky and soft sediment benthic environments, they differ significantly in the type and magnitude of human activities that occur. The Damariscotta River estuary is home to more than a dozen marine aquaculture operations that total 0.93 km^2, where farmers grow American oysters, mussels, scallops, and kelp (Maine DMR, 2022). In contrast, the Medomak River estuary has only two active sea farms, which together occupy 0.03 km^2 (Maine DMR, 2022). In terms of wild fisheries, the Medomak has an active soft shell clam fishery involving more than 200 harvesters, as well as lobster, menhaden, marine worms, sea scallops and elver fisheries. The Damariscotta's wild shellfishery involves many fewer participants, perhaps less than 10 active shellfish harvesters and the area we focus on includes the territories of few lobstermen. Finally, the Damariscotta is a busier estuary not only in terms of aquaculture, but also recreation and navigation. For more details on the study system, see Appendix A.

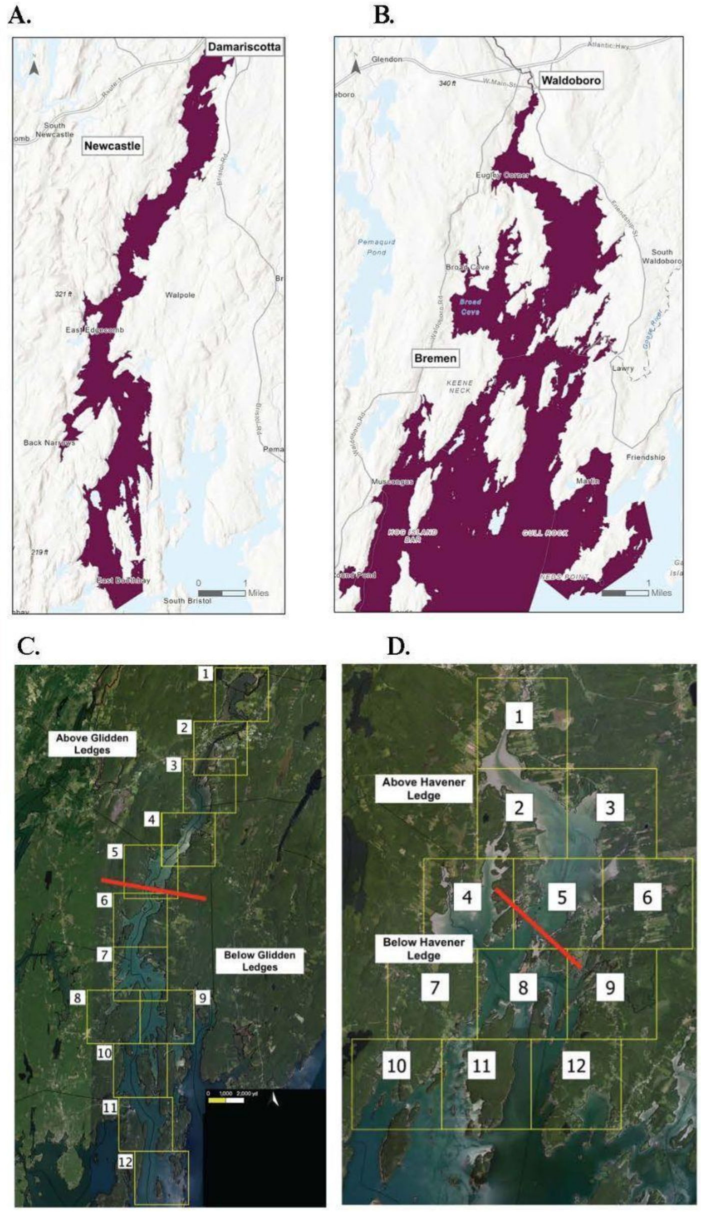


Figure 2.1 Study site information. The map above shows the study site locations (A and B) in midcoast Maine. **A.** The Damariscotta River estuary. **B.** The Medomak River estuary. **C.** Glidden Ledges divides the Damariscotta into two sections (as delineated by the red lines). **D.** Havener Ledge divides the Medomak into two sections (as delineated by the red lines) with distinct characteristics. The numbered squares (1-12) denote the sections of the river where participants were asked to share their knowledge.

2.2.2 Participatory mapping

We used participatory mapping to document local knowledge of spatial distributions of shellfish populations and human activities in the two estuaries (Schmitz Nunes et al., 2021). Participatory mapping is a community-based research methodology that solicits local knowledge to produce a collaborative cartographic output for geospatial data (Degraff & Ramlal, 2008). Researchers have used participatory methodologies in fisheries management as a tool to characterize marine habitats, harvesting behavior, and fishery species population dynamics (Aswani & Lauer, 2006; Schmitz Nunes et al., 2021; Selgrath et al., 2018). We chose to employ participatory mapping because it can document the biological and human system dynamics of the Damariscotta River and Medomak River estuaries by creating geospatial data on current shellfish populations and delineating human uses and areas of importance for different estuary user groups (Calamia, 1999; Klain & Chan, 2012; Moore et al., 2017; Selgrath et al., 2018). Participatory mapping is also an effective tool for integrating local knowledge data with biophysical data, generating a more comprehensive view of coastal SESs (Aswani & Lauer, 2006). Local knowledge maps function as spatial information translators between these two forms of knowledge, creating outputs that can support ecosystem-based management decisions (Close & Hall, 2006; De Freitas & Tagliani, 2009).

For the purposes of this paper, we use the term ‘observation’ to describe the knowledge shared with us by participants. We define an observation as knowledge acquired through firsthand experience with the ecosystem, often through multiple years of living and working in the estuary. The target population for the study was people with at least three years of experience who engage in commercial or recreational activities in one of the two estuaries. We stratified our target population into two subpopulations: commercial shellfish harvesters (which we refer to as “shellfish harvester”) and other users such as lobster fishers, aquaculture farmers, harbor masters, scientists, conservationists, and recreational anglers (which we refer to as “general user”).

We began the study design process with extensive conversations with municipal leaders, shellfish resource managers, academic researchers, and others knowledgeable about the shellfish resources and human uses within the focal systems. These conversations helped refine our methods regarding questions of study scale, focus, recruitment, and reciprocity. They also helped to inform a base map for the study and the types of information collected during the mapping process (Close & Hall, 2006). Six local experts tested the survey tool before the study design was finalized.

Two hundred and ten participants were contacted during the recruitment process between October and December 2020. Commercial harvester license information from local governmental organizations were used to identify study participants, in lieu of local associations (Davis & Wagner, 2003). Shellfish harvesters were identified using license information obtained from the towns of Damariscotta, Newcastle, and Bremen, as well as from the Maine Department of Marine Resources (DMR). Aquaculture farmers were identified from a publicly available list of farmers who have shellfish or seaweed farms in one of the two estuaries. Additional participants were identified through purposive sampling and subsequently by snowball sampling based on recommendations from other local resource users (Biernacki & Waldorf, 1981; Creswell, 2014).

Participants were recruited over the phone and by email. At minimum, three attempted contacts were made for each recruitment contact. Once participants agreed to participate, an interactive mapping packet (see Appendix B for full materials and methods) was mailed to the participant's home address. The study was administered by mail, rather than in-person, due to COVID-19 safety concerns. Using the mapping materials, participants were instructed to identify locations where different shellfish species can be found, where river activities occur, and where there are areas of significant change by placing a series of stickers on the maps. Stickers were placed on a base map of the estuary overlaid with a grid (de Oliveira Leis et al., 2019; Teixeira et al., 2013). Abundance (high, medium, low) stickers were provided only for the soft-shell clam because of its commercial significance and it being the primary species of interest for the shellfish committees. All other species of interest to the shellfish committees (razor clams, quahogs, wild oysters, and marine worm digging) and human use activities (sailing, kayaking, recreational fishing, aquaculture, and tourism & sightseeing) had stickers indicating presence. A final sticker category, 'Areas of Significant Change,' showed the locations that had recently experienced important change. Participants only completed the map sections with which they were most familiar. They also had the option to write notes with additional comments within the map booklet (de Oliveira Leis et al., 2019). Upon completing the mapping exercise, participants returned their maps in self-addressed envelopes that were included in the packet of materials.

Once received, we digitized the map booklets. We assigned a unique FID to each grid cell from the booklets. Our research team then manually entered the information from the booklets as binary data into a spreadsheet. For example, if a participant placed stickers for quahogs, oysters, and soft-shell clams within a grid FID-288, we placed a '1' in each of these three categories. We captured any handwritten comments as notes for the specified grid cells. All aggregated map data follow the fisheries rule of three to maintain confidentiality and be most representative of our participants' observations. For example, only shellfish species that were observed by three or more participants for a particular grid were included in the maps of shellfish species richness. As such, a shellfish species richness score of 3 means that three shellfish species were observed by three or more people in a particular area.

2.2.3 Semi-structured interviews

We scheduled a follow-up interview, the methods of which are described in detail below, with participants at the time of recruitment. Interviews were scheduled to occur within 2-3 weeks of mapping packet receipt and map booklet completion, although there were instances where interviews were rescheduled and occurred outside of this timeframe. Semi-structured interviews using an interview protocol allowed researchers to ask open-ended questions about history and change in the estuaries, providing additional qualitative context for the mapping data (see Appendix C for interview guide) (Creswell, 2014). The interviews provided an opportunity to ask questions extending beyond the single snapshot provided by the participants' maps and to explore how the focal systems were changing (Schmitz Nunes et al., 2021; Selgrath et al., 2018). The semi-structured interviews focused on the participants' place-based experiences in the estuaries and importantly their understandings of any social, economic, or environmental changes they had observed. Open-ended questions guided the interviews to allow participants to describe their experiences and observations in their own words (Creswell, 2014). We also asked participants to rank the top three most significant changes they had observed, what they thought caused these changes, and how the changes impacted how they and others used the estuaries.

We conducted 50 interviews between October 2020 and January 2021. Four participants completed the mapping packet, but declined to interview, while three participants interviewed, but did not complete the mapping packet. Participants possessed a wealth of knowledge, ranging from 25 to 35 years of experience, and included harbor masters, shellfish harvesters, aquaculture farmers, conservationists, lobster fishermen, other marine-dependent business owners, and coastal residents who live and recreate on the rivers. All individuals needed to have been active and have experience on the estuaries within the last three years to participate. Participants were frequent users of the focal systems, and typically engaged with the systems on a daily to weekly basis during their season of activity. Across the two focal systems, we had thirty-one general user participants and nineteen shellfish harvester participants. Eighteen out of the nineteen shellfish harvester participants were commercial harvesters, while the remaining one was a recreational harvester. The age of participants ranged from 25 to 88 and most study participants were male. See Table 2.1 for the detailed participant information. All interviews were approximately 30 to 90 minutes in length and occurred over the phone or via video conference due to COVID-19 health and safety concerns.

Table 2.1 Participant demographics. Demographic information for participants in the participatory mapping study.

Estuary	Study type	Num. of participants	Male	Female	Average age	Average yrs. experience
Medomak	General user	14	8	6	56	31
Medomak	Shellfish harvester	8	8	0	54	25
Damariscotta	General user	17	14	3	59	31
Damariscotta	Shellfish harvester	11	10	1	55	35

Interviews were audio recorded with each participant's permission and then transcribed verbatim using a two-part process. First, interviews were automatically transcribed using an artificial intelligence software, Otter.ai. Next, we reviewed each transcript and revised any errors in the initial transcription. The transcripts were then analyzed using NVivo R1 in two cycles. We developed a coding thematic framework prior to analysis based on the literature and existing themes and questions raised by fisheries managers during the 2019 research (Creswell, 2014). In total, we coded for 21 upper-level themes ranging in topics from 'Access' to 'Water Quality' to 'Change' (see Appendix D for complete schema). Two coding rounds were completed in total, in which the first pass identified broader themes, while the second pass homed in on emergent themes and specific categories within upper-level themes. Observations, for example of shellfish habitat or distribution, were only included if three or more participants shared similar findings. Only 'Drivers' (see Table 2.4) presented observations of two or more participants, due to the heterogeneous nature of responses. 'Drivers' observations from fewer than two participants were aggregated, and the total n-value was recorded.

2.3 Results & Discussion

2.3.1 Local knowledge guides investigations of change in shellfish populations and harvester behavior

Local knowledge data analysis revealed compelling themes and potential applications for both the participatory mapping and interview results. One important theme was how local knowledge can guide investigations of change in shellfish populations and harvester behavior. Local knowledge provided detailed descriptions of the habitat and distribution of multiple commercially important shellfish species. It also identified shifts in shellfish population abundances and described how shellfish harvesters are adapting to these changes.

2.3.1.1 Shellfish habitats and distributions are shifting

Shellfish species are found throughout the intertidal zone, according to the interviews conducted in both estuaries (Table 2.2). However, shellfish habitat and species-specific distributions are not static. Participants observed how ecological patterns have shifted over the course of their fishing careers. For example, participants (total n=4) described how soft-shell clam habitat once encompassed the large area of soft, fine sediment mudflats stretching from the mid to the low intertidal zone. Over time, this band narrowed. In the past, "We could go way out in the mud, but there's no clams out in the mud, so all you got is just the shore…say 25 to 30 feet from the high-water mark down. Below that there's no clams," explained one Damariscotta participant. This was echoed in the Medomak:

> "And that's why I'm saying is why (sic) all of a sudden, all these clams that used to be all the way to the channel marker, now there's almost zero anywhere, they're all on the shore…I mean we got acres and acres and acres of flats, and there's not a clam there no more, where they used to be solid."

Harvesters linked this shift in the intertidal distribution of clams with observations of the distinct sediment types present within the different intertidal zones. Our results indicate that soft-shell clams are less abundant in the soft, fine-grained sediments (i.e., mud), and more abundant in the mid to high intertidal zones, where sand, gravel, rocks, and coarse-grained sediments predominate. One Medomak participant described this:

> “As far as where the clams are now…they're setting more than other places in the sand, where the sand and shell is…seemed that the clams seem to be setting there a lot more than they do out in pure mud that's got nothing in it…The harder the mud, there seem like the clams are setting in that versus the soft mud.”

It appears that soft-shell clam populations have shifted in both estuaries and are now more abundant in the high intertidal rather than the low intertidal zone. Participants proposed multiple explanations for this shift, including higher rates of predation in the fine vs. coarse sediments (n=2), harvesters preferring to dig the soft sediments and therefore depleting those populations first (n=1), or fewer toxins or lower levels of acidity in the shelly, coarse sediments (n=2). Overall, it appears that there is a decrease in suitable habitat area, at least for this species.

Knowing shellfish population distribution and habitat first is essential for guiding targeted field surveys. The intertidal zone is a vast habitat where exhaustive population surveys require extensive time and cost investment (Lewis et al., 2019). Acquiring local knowledge information on species-specific habitat is an essential first step in the research process to study shellfish fishery populations. Shellfish committees are seeking to acquire general estimates of shellfish abundance and distribution to support management decisions. Field methods that employ local knowledge to target specific habitats address core management questions–namely, “What is the status of shellfish populations, and how are populations changing?” (Gillespie & Bourne, 2000; Heritage et al., 1998). This is particularly useful in historically data-poor estuarine systems, like the Medomak and Damariscotta (Hillyer et al., 2021).

The habitat and distribution data generated by this study was used in ecosystem- and species-specific survey methods to study the Damariscotta’ commercially important shellfish species. The local knowledge information was central to refining survey methods so that researchers obtain information that is relevant and useful to the shellfish committee. Beyond informing methods, an analysis of how habitat and distribution has changed can also lead to further inquiry into why these changes have occurred. Observed phenomena, like the shift of soft-shell clam distribution from soft to coarse sediments, also raises questions that can be tested through targeted research efforts and experimentation to help explain how and why the system is changing. In this way, local knowledge guides research of variables affecting shellfish populations, allowing harvesters and managers to forecast how shellfish species, and the shellfish fishery, may change in the future.

Table 2.2 Shellfish habitat and intertidal distribution information in the Damariscotta (n=11) and Medomak (n=7) River estuaries, based on interview data. 'NA' refers to the cases where fewer than three participants shared habitat or distribution observations.

Estuary	Species	Habitat	Distribution
Damariscotta	Soft-shell Clam	Soft mud to sandy, rocky areas.	Upper to low intertidal zone.
Medomak	Soft-shell Clam	Soft mud to hard mud, clay, sandy, shelly, rocky areas.	Mid to upper intertidal zone.
Damariscotta	Quahog	Sandy, rocky shore. Lives closer to the surface than soft shell clams.	Mid to low intertidal zone.
Medomak	Quahog	Harder mud, sand, or gravel areas.	NA
Damariscotta	Razor Clam	Sandy areas or softer mud.	Low intertidal, almost sub-tidal.
Medomak	Razor Clam	Soft mud to shelly, rocky mud.	NA
Damariscotta	American Oyster	Attached to rock or other substrates, often under seaweed or on rocky, shell, and gravel areas of shore.	Upper intertidal zone or low intertidal zone.
Medomak	American Oyster	NA	NA

2.3.1.2 Shellfish species compositions and abundances vary spatially and temporally

The local knowledge maps demonstrate that the Damariscotta and Medomak estuaries are distinct, with unique compositions and abundances of shellfish species. These locally specific characterizations highlight locations of importance, either for their economic significance as primary harvesting grounds (Figure 2.2 & Figure 2.3) or for their ecological significance as locations of high shellfish diversity (Figure 2.4 & Figure 2.5). The maps from our study are vital spatial tools that identify key locations for conservation and research and inspire inquiry by highlighting the spatial overlap among species and diverse human uses. In fact, the study maps were used to establish long-term monitoring sites for a new community science program to collect data on shellfish diversity, abundance, and distribution in the upper Damariscotta River estuary. Abundance, diversity, and distribution maps like those created by this study could be applied to other SESs seeking to spatially prioritize locations for long-term research or conservation. Interviews enriched the findings of our local knowledge maps and provided important contextual information to understand changes in shellfish populations.

According to participant interviews, commercial shellfish harvesters in the Medomak (n=7) primarily target soft-shell clams and razor clams, while harvesters in the Damariscotta (n=11) target wild American oysters (*Crassostrea virginica*), hereafter referred to as 'wild oysters', soft-shell clams (*Mya arenaria*), quahogs (*Mercenaria mercenaria*), and razor clams (*Ensis directus*). These findings are consistent with mapping data for shellfish species richness (i.e., the number of shellfish species found and/or harvestable in an area). Medomak shellfish harvester participants reported a shellfish richness of 1 for most harvesting areas (Figure 2.4), whereas the shellfish richness reported by Damariscotta participants ranged from 1-3 (Figure 2.5), indicating a greater diversity of harvested shellfish species in the Damariscotta.

Participants from both estuaries observed changes in the abundance and diversity of commercially important shellfish species through time. Medomak participants witnessed declines in razor clam populations – “There used to be razor clams in the Medomak" or “There's razor clams, I don't think there's many as it used to be”– and the rise of quahog populations – “But yeah, there's more quahogs I've ever seen since I was a kid.” or “There's some quahogs around now, littlenecks. I mean we get some guys that come in that are finding them down there on the big tides…harvesting 3,000 or 4,000 to a tide.” In the Damariscotta, participants observed a decline in soft-shell clams and razor clams, while quahogs (also known as littlenecks, cherrystones, or chowders depending on size) and wild oysters appeared to increase. Participants observed wild oysters in the Medomak, although mentions of their presence were far less prevalent than comments regarding wild oysters in the Damariscotta. For example, one Damariscotta participant noted:

> “...clam populations were going downhill [and] the wild oyster population took off…Most of the soft-shell clams and razor clams died out. But cherrystones and quahogs have increased in those areas. So, in last 40 years, we've had, seen a definite decrease in the species of razor clams and soft-shell clams and an increase in oysters and cherrystones.”

Damariscotta shellfish harvesters have observed a distinct shift in the fishery: from one previously dominated by soft-shell clams to the current one that includes wild oysters and quahogs. Wild oysters in the Damariscotta River estuary were not managed until recently and are a unique resource not commercially exploited in any other Maine estuary to our knowledge.

Local knowledge has made these trends in shellfish abundance and diversity visible, and enabled harvesters to share their observations and hypotheses about how shellfish populations are changing. Using local knowledge maps and interviews in tandem also enriches our understanding of the social and economic dimensions of these ecosystem changes. Harvesters are adapting to changes in the shellfish populations by harvesting different species in the Damariscotta than they did a generation ago.

Figure 2.2 Medomak River estuary soft-shell clam abundance. (a) Participants (n=7) identified areas with high, medium, and low soft-shell clam abundance in the Medomak River estuary through the participatory mapping. (b) Topographic map for reference. For detailed methods, see Appendix B.

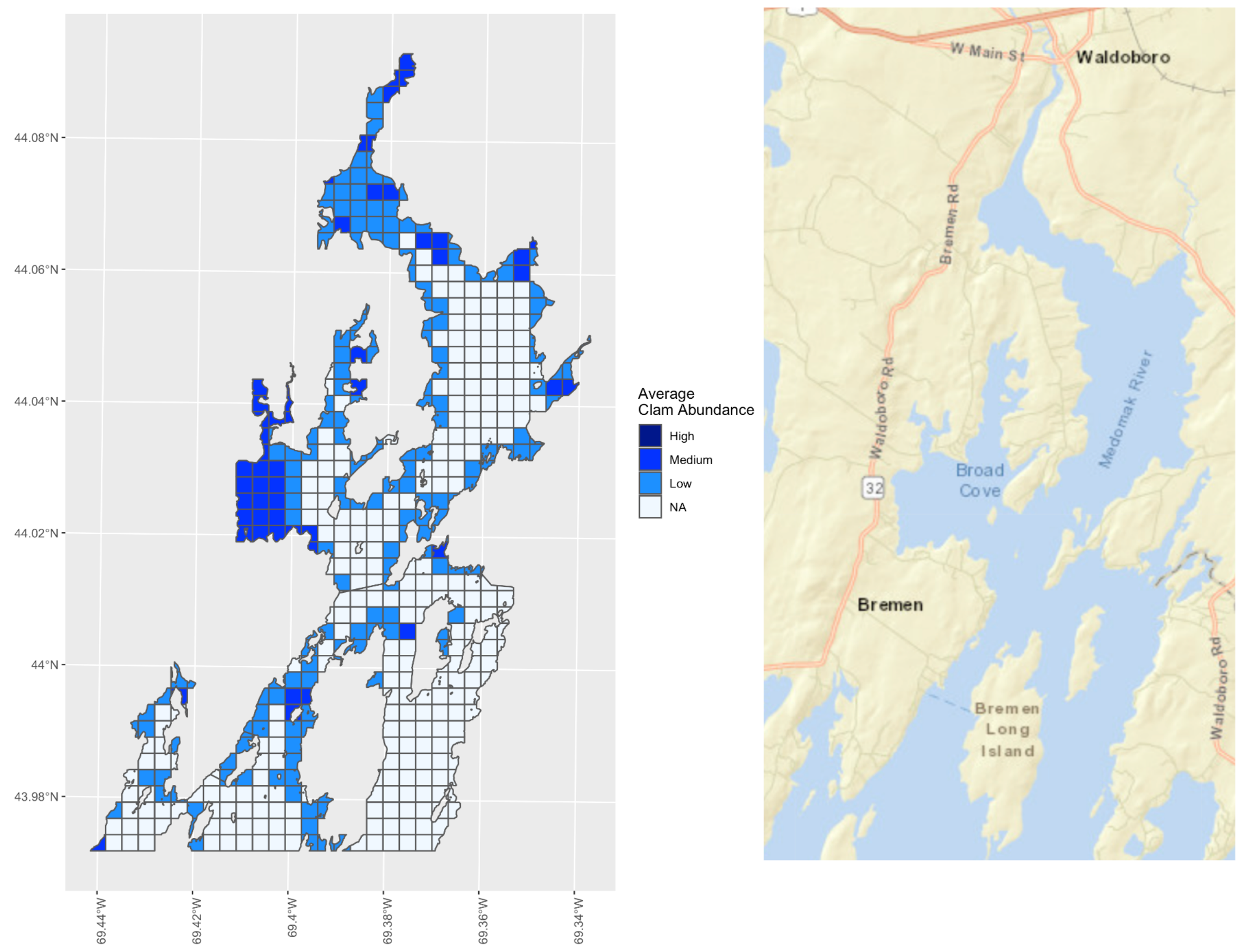


Figure 2.3 Damariscotta River estuary soft-shell clam abundance. (a) Participants (n=11) identified areas with high, medium, and low soft-shell clam abundance in the Damariscotta River estuary. (b) Topographic map for reference. For detailed methods, see Appendix B.

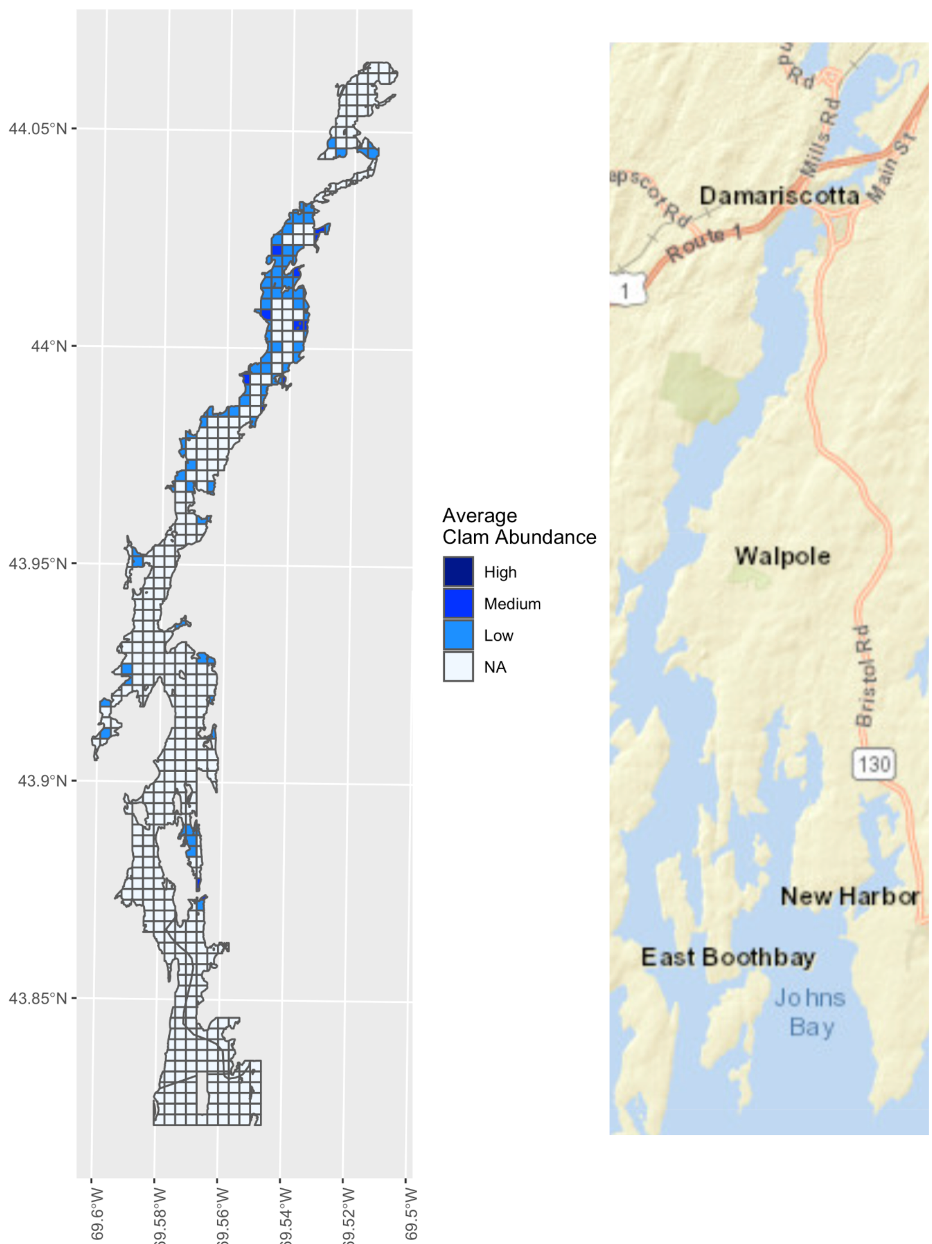


Figure 2.4 Medomak River estuary shellfish species richness. (a) The number of shellfish species observed by Medomak study participants, including soft-shell clams, wild oysters, razor clams, and quahogs. (b) Topographic map for reference. For detailed methods, see Appendix B.

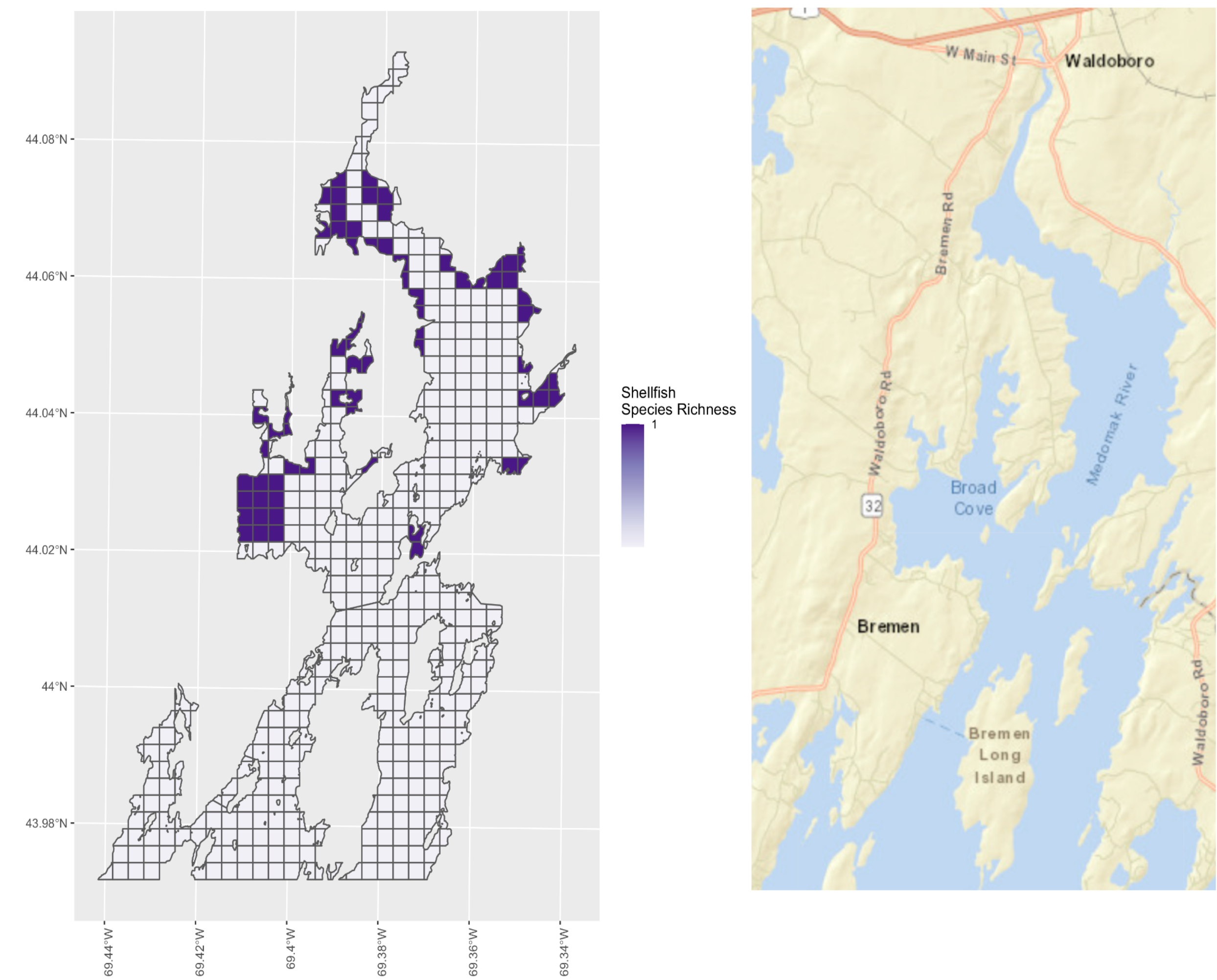
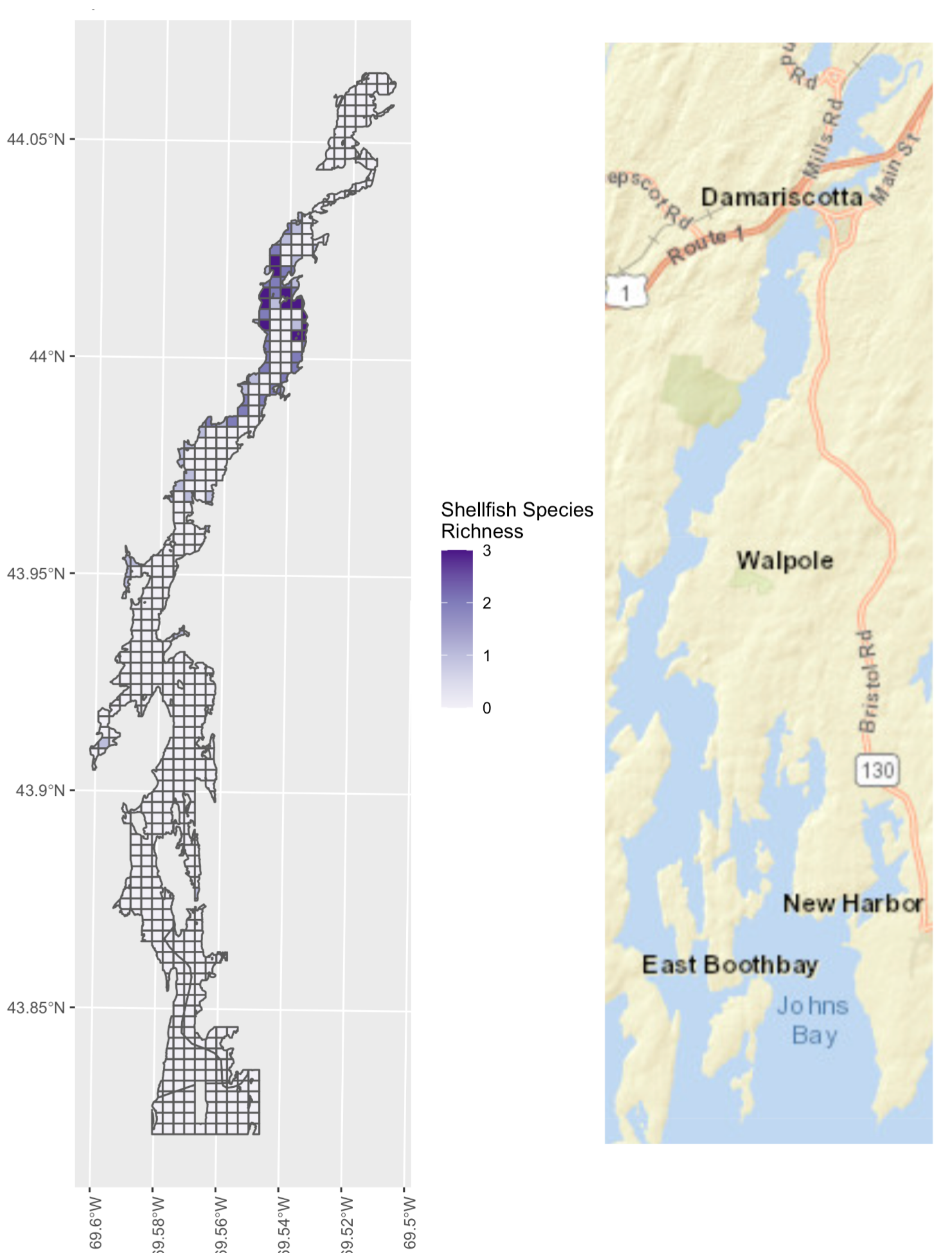


Figure 2.5 Damariscotta River estuary shellfish species richness. (a) The number of shellfish species observed by Damariscotta study participants, including soft-shell clams, wild oysters, razor clams, and quahogs. (b) Topographic map for reference. For detailed methods, see Appendix B.



2.3.1.3 Harvesters adapt to stochastic shellfish populations

Participants expressed how they have tried to identify connections between soft-shell clam abundance and other environmental variables. However, they are frustrated time and again because the patterns and relationships that they identify may appear true for one year and then change the next. A Medomak participant described the many potential variables impacting shellfish populations in the estuary:

> "The other one's just a big variable, I don't know why sometimes there are no clams in the river. I don't. I don't see the predators, so I don't tend to blame them, although they still could be there. Maybe it's the horseshoe crabs, which I don't pay much attention to. Maybe it's the snails. Maybe it's acidification, maybe it's the great warming. But she'll have years where she just doesn't have clams. And that's puzzling to me. I don't know why we take those dips. I don't know if it's overfishing. You know what I mean? I don't know why that is."

Harvesters have adapted to the stochasticity of the shellfish populations by altering their harvesting behavior. This includes rotating harvesting activity among mudflats depending on shellfish abundance. Harvesters also apply their own form of selective harvesting, and only target the largest clams at a particular mudflat or harvest less per tide to sustain shellfish populations throughout the season. Within the Damariscotta, harvesters have also adapted by targeting wild oysters. Wild oysters have ostensibly appeared in the Damariscotta because of shellfish aquaculture within the estuary (a phenomenon discussed in more detail below). Because the increase in wild oysters occurred synchronously with a decline in soft-shell clam species, harvesters chose to offset the loss of soft-shell clams by diversifying their shellfish harvest. One participant described this development:

> "So, I kind of just adapted to go for what was plentiful. So, I do the wild oysters now. When I originally started a long, long time ago, I was a soft-shell clam harvester. But as the years have progressed, you know, they kind of disappeared for the most part, and the quahogs and oysters got plentiful. So, you know, I switched gears into doing that."

The push to harvest wild oysters was coupled with the growth of the oyster market in Maine. "And now that the market has taken off with oysters, the natural flow is to go harvest oysters because there's a greater market and a lot more oysters," explained one participant who previously targeted quahogs and soft-shell clams. Many participants ultimately felt that shellfish populations fluctuated in a cyclical manner and that working to establish generalized relationships between shellfish populations and other variables was both challenging and, in many cases, impractical. When recounting the rise and fall of soft-shell clam abundance over the last 40-50 years, a Medomak participant hypothesized that,

> "I think it's kind of a big cycle. And everybody's always guessing they're gonna save the world, they're gonna save the clam but it's like, I always say when the clam gets ready, conditions are right, it will be there…So, but I think it's more just nature and that's the way it works."

‘Nature’ at large, sometimes described as ‘Mother Nature’, was often referenced as an unpredictable force driving changes in shellfish populations. Participants described how this force was largely unknowable and that efforts to develop theories about what was driving change in shellfish populations were ineffective:

> “You come up with the theories that [clams] tend to like the shores and then you'll go through and they're gone…So a generalization is really tough…I've seen years when you couldn't get enough to eat, and I've seen years in the Medomak, I think 2016, we had a million pounds…Mother nature is an interesting girl, when she's giving, she's giving, and when she's not she's not.”

For many study participants, these population fluctuations are not novel. Harvesters are used to high environmental variability and are experienced with adapting to changes. Our findings suggest that these estuarine systems and the shellfish populations they support are changeable. This characterization is vital for framing appropriate scope and timescales of shellfish research in estuarine systems. Without this information, research efforts may be too brief to reveal patterns or trends. Most research on Maine shellfisheries to date have been short-term experiments (e.g., Beal et al., 2018; Beal, Coffin, et al., 2020; Beal, Randall, et al., 2020a), although recently research organizations and state agencies have begun to document shellfish population trends over broader geographic and temporal scales (Beal, Randall, et al., 2020b). Our results complement these approaches and illustrate how local knowledge held by harvesters and other community members can be systematically documented. These local knowledge data have been leveraged by harvesters and community members through the state-mandated community-led shellfish management process in this area (see Chapter 3 for details).

2.3.2 Local knowledge characterizes change and generates hypotheses about drivers of change

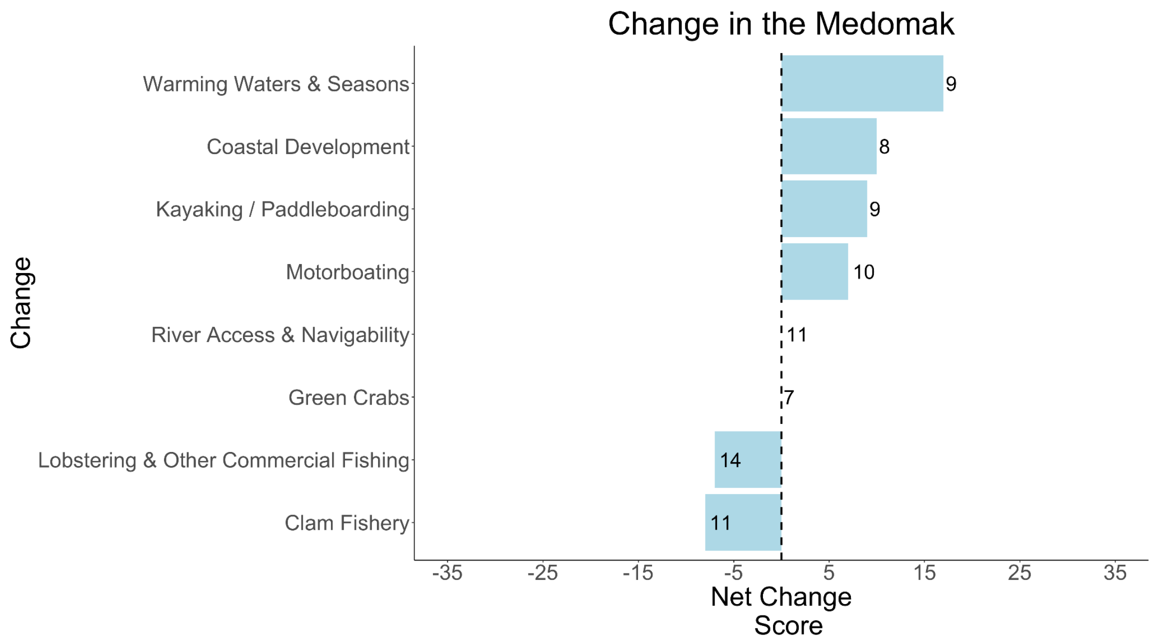
Beyond descriptive information, local knowledge also characterizes changes in the system by quantifying both the magnitude and direction of change. These data also reveal hypotheses about the potential drivers influencing how and why systems are changing. Local knowledge observations and hypothesized drivers introduce harvester voices into the research process, helping to contextualize existing research and highlight new lines of potential inquiry.

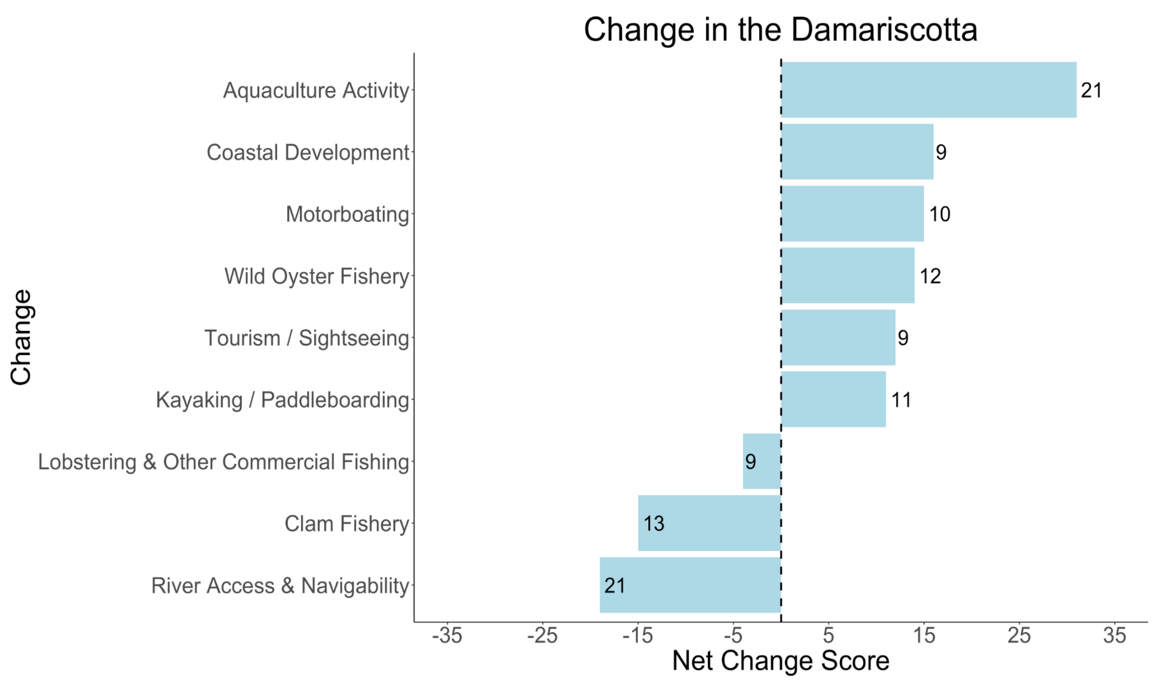
2.3.2.1 Magnitude and direction of change and hypothesized drivers of change

The Medomak and the Damariscotta River estuaries have experienced many changes, as documented through local knowledge (Figure 2.6). The aggregated observations and understandings of change are unique to each estuary. There are shared changes–such as the increases in motorboating, kayaking/paddle boarding, and coastal development and the declines in lobstering, clamming, and other commercial fishing–but also significant changes specific to each system. Aggregated observations showing participant perceptions of the direction and intensity of changes can help managers and researchers prioritize the focus of research and management decisions.

As highlighted in Figure 2.6, study participants have detailed knowledge of the complex changes and relationships at play in the focal systems. Local knowledge generates relevant hypotheses about how and why SESs are changing through time, laying a compelling foundation for further environmental or social inquiry. Based on the interview data, we also identified key observations of change and associated drivers of change in the estuaries (Table 2.3).

Figure 2.6 Changes identified by study participants (Medomak n=22, Damariscotta n=28). The bars show the magnitude (longer bars indicate more significant change) and direction of net change (increase=right of 0; decrease=left of 0) documented by the local knowledge study. For example, if an increase in kayaking was mentioned three times and a decrease in kayaking was (Figure 2.6 continued) mentioned once, the bar would have a value of positive two, taking the sum of these positive and negative values. The number at the end of each bar shows the total number of participants who identified each change and contributed to the net value shown. Each participant contributed one or more mentions to the total net change scores.





Notably in the Damariscotta, increases in aquaculture activity and the wild oyster fishery were observed by many participants (Figure 2.6). Our results demonstrate that aquaculture, and its interaction with wild shellfish populations, is significant for the system. An increase in aquaculture activity was highly cited by participants (n=10), with multiple hypotheses about the factors driving this change (Table 2.3). Drivers influencing the growth of the aquaculture industry included financial incentives, such as the increased market demand for oysters (n=2) and aquaculture as a professional or economic opportunity (n=4), and infrastructure-based drivers, including improvements in aquaculture technology (n=3) and training support and advances in aquaculture research from key organizations (n=3). The Damariscotta estuary was also identified as an ideal location for aquaculture, based on ecological and oceanographic factors (n=3). The drivers identified by participants help to explain why aquaculture activity is prevalent in the Damariscotta and could serve as key indicators for the expansion of aquaculture in other systems sharing these characteristics.

Study participant observed that aquaculture was a driver of ecological and economic impacts, including how structures like oyster cages could impact water flow in the estuary and larval clams may be “caught up in those cages", but also stressed that the “oysters are fantastic for the river and [are] great for commerce.” These observations highlighted that estuary users see the ecosystem as a whole and understand that changes have both positive and negative effects. For example, participants observed that wild oyster populations have increased (n=3) because aquaculture provides a larval supply for wild oyster populations (n=3). The emergence of wild oyster populations can offer benefits by introducing a new commercial shellfish species or providing important ecosystem services, including water filtration and shore structure (Olivier et al., 2020). It also could affect the ecosystem in ways yet to be fully understood. Shellfish harvester participants tended toward a precautionary outlook of aquaculture and felt that aquaculture activities and oysters could negatively affect soft-shell clam populations. The drivers of negative impacts on soft-shell clam populations included bottom dragging (n=2) and competition for food between oyster populations (both wild and farmed) and soft-shell clams (n=2).

These observations and drivers can frame dialogue between existing scientific studies, local knowledge, and future research, as well as outline approaches to remediating potential conflict among different uses in the estuaries (Moore et al., 2017). The local knowledge observations have also scaffolded the key variables, changes, and user group dynamics at play between aquaculture and wild shellfish populations. Without this information, our research group would not have had a comprehensive understanding of the social and environmental dynamics of this phenomenon. Now, equipped with this information, we are well-positioned to move forward with integrated environmental and social science research concerning these hypotheses in the context of ecosystem-level management.

Participants also observed changes to the shape and composition of the estuary and its shores. Sea level rise and resulting erosion (n=3), as well as dragging for farmed oysters (n=2) were put forth as drivers of changes in the channel shape. Participants connected the change of the estuary shape with the increase in aquaculture:

> "But the other thing that I've seen for sure is, with the growth of aquaculture especially the companies that drag…they're changing the channel…where people are dragging to harvest oysters, they're consistently suspending sediment and resuspending sediment from all the same spots...And all that material has to go somewhere, and it gets deposited where they turn or downriver of where they're working...it's narrowed the channel considerably."

This example demonstrates how changes in human activities in the estuary affect other human uses, such as boating, an activity that becomes more challenging with a narrowed channel. Changes in the channel are particularly significant if the physical shifts have occurred rapidly enough that Coast Guard maps are no longer accurate. Further, it shows how it is often challenging to determine the absolute drivers of change in a system–be it large scale shifts like climate change, or localized changes like increased bottom dragging activity. Regardless, this illustrates how local knowledge can reveal significant changes that have far reaching impacts for multiple user groups in a system.

Understanding how human activities, like aquaculture, may be driving change in the estuaries helps to identify the relationships between user groups and ecological processes. Thus, local knowledge provides important insights into the small-scale process, variability, and interactions in estuarine SESs (St. Martin et al., 2007). The observations and drivers presented through this research broadens the scope of available information, highlights new and important lines of inquiry, and engages shellfish harvesters and river users in a discourse of how estuary systems are changing and how they may look in the future.

Table 2.3 Changes observed, and drivers hypothesized by participants in the Damariscotta and Medomak estuary systems (total n=44). Participants shared their hypotheses about the drivers of these observed changes. Some participants provided multiple drivers for each observation, so total n-values for drivers may exceed that of observations. 'Aggregated' refers to cases where observations were pooled as they were mentioned by fewer than 3 participants.

Observed Changes	n	Hypothesized Drivers	n
Soft-shell clam populations have declined	13	Mud is not aerated by digging/harvesting activity	3
		Overharvesting	3
		Green crab predation	3
		Aggregated: Predation from milky ribbon worms and birds	6
Aquaculture activity has increased	10	Aquaculture is a good professional/economic opportunity	4
		Aquaculture technology has improved	3
		The Damariscotta has ideal aquaculture conditions	3
		Local research and educational organizations have supported aquaculture training and research	3
		Market demand for oysters has increased	2
Recreational boating activity and kayaking has increased	9	Human population growth	3
		Tourism activity has increased	2
The shape and composition of the estuary and its shores is changing	8	Climate change/ Sea level rise	3
		Dragging of the benthic environment to harvest farmed oysters	2
Soft-shell clam populations fluctuate and are hard to predict	6	Natural cycles/ nature	4
		Overharvesting	2
Development has increased	5	Human population growth	3
Mussel populations have declined/disappeared	5	Green crab predation	2
The number of shellfish harvesters has declined	5	Water quality has declined, increased flat closures make it hard to calm for a living	2
		There are a limited number of licenses/ difficult to get licenses	2
		Social and cultural changes	2

Table 2.3 Continued.

Tourism activity has increased	5	Aquaculture industry growth (the focus of tourism)	3
		COVID-19 pandemic	2
Green crab populations fluctuate with temperature	5	Green crab populations fluctuate with temperature	5
Green crab populations have increased	4	Climate change/ Warming seasons	2
River access has decreased	4	Increased use, congestion	3
River navigability has declined	4	Aquaculture gear, like floating cages (affect navigation)	4
Water quality flat closures have increased	4	Aggregated: Continued poor water quality, combined with more extreme weather events	4
Aquaculture is negatively impacting soft-shell clam populations	3	Aquaculture bottom dragging	2
Conservation closures are good for shellfish populations	3	Closures allow for stock regrowth	3
Eelgrass habitat has declined	3	Green crabs dig out eelgrass	2
Mussel distributions have shifted from intertidal to subtidal areas (attached to ropes/lobster traps/other gear)	3	Aggregated: Green crab predation, overharvesting, or natural cycles	3
Oyster populations negatively affect soft-shell clam populations	3	Wild oyster-food competition	2
		Aggregated: Wild oysters eat clam spat or aquaculture dragging	2
Quahog populations have increased	3	Aggregated: Climate change/warming waters, resistance to predation pressure, or benefits of living near the surface	3
Soft-shell clam intertidal distribution has changed from fine sediments to firmer sediments	3	Aggregated: Fine sediments have more predators, the shells in the firm sediments buffer water acidity, or Harvesters like to dig the soft mud, and these areas get dug out first	3
Wild oyster populations have increased	3	Aquaculture supplies wild oysters	3

2.3.3 Connections among shellfish aquaculture and the wild shellfish fishery

The hypotheses that relate to the causes and consequences of connections among the wild and farmed shellfish populations in the Damariscotta River estuary are perhaps most intriguing. They illustrate how local knowledge research provides ecosystem-level understandings of interactions and complexity in SESs. Leading with local knowledge creates a blueprint for research into the complex relationships between aquaculture and wild species populations. It forms the guiding questions and identifies the connections between the social and ecological systems and key variables at play in these interactions. Below we discuss these hypotheses in greater detail and how they are shaping ongoing research

2.3.3.1 Larval dynamics and population connections

Farmed and wild oyster populations both depend on larval oysters. These larvae are mobile and live in the plankton for several weeks, in contrast to the adult oysters that reside in the benthic environment (either attached to rocks or held within bottom or surface-deployed cages). Harvesters and other local experts observe and hypothesize both positive and negative effects of this population connectivity. The mapping and interviews confirmed that wild oysters are observed in both estuaries. Study participants connected the presence of wild oysters to aquaculture. A Medomak participant noted, "I'm seeing oysters, where I can't say I have ever seen them in my lifetime…But I understand that somebody down in the Bremen area was raising oysters so that wouldn't surprise me…it could have brought up the seed[1]." A Damariscotta participant echoed this observation:

[1] Recently settled juvenile oysters are referred to as 'seed' by many harvesters.

> "When I started there were not many oysters to be found on the rocks, the 'wild oysters.' I think the general conclusion and assumption is that the oysters that are now showing up on the rocks are spawned from the farmed population."

Participants linked the presence of wild oysters directly to larvae produced by farmed oysters. Therefore, although individual farmed oysters may be confined to aquaculture farms, the species' life history, which includes a pelagic larval phase, connects the farmed and wild populations with one another and the broader ecosystem. Local experts, including both wild shellfish harvesters and shellfish farmers, agree that wild oysters in these estuaries were produced by farmed oysters. There is some indication that these wild populations may now be self-sustaining, specifically in the Damariscotta. One participant described this phenomenon in detail:

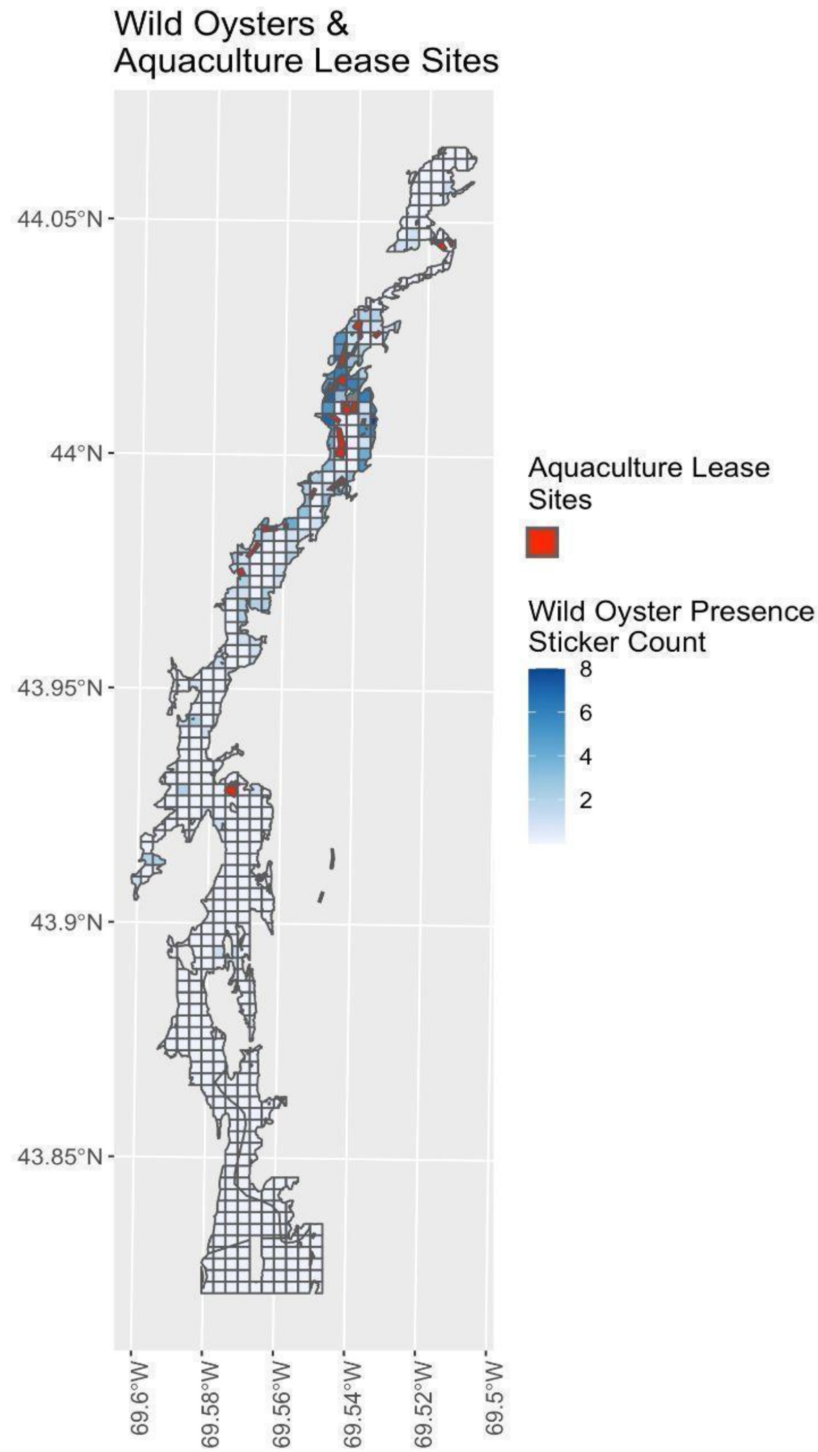
> "There're millions of oysters being grown on its farms, okay. But they're still wild animals and they still go through a reproductive phase. And when they do that, the oyster is a free-swimming larva for two or three weeks. And it may or may not land on the farm. And could just equally land on the rocks along the shore and into the intertidal zone. And it's a very interesting point that it's because of the farms that generated populations of oysters that have now migrated into the wild. Now the wild sets–I see wild oysters all over the place–they are now coming into their own and will start to self-develop. But it really was predicated by the oyster industry."

The appearance of wild oysters and the concurrent decline of soft-shell clams has changed the composition of shellfish populations in the Damariscotta and altered how commercial harvesters perceive and use the estuary. A participant from the Medomak observed:

> "...in the past 30 years oysters and oyster farming has taken off in Damariscotta, it's nothing but oyster farming on the river right now. And it's solid full of natural oysters because of the overflow from the farms. They obviously spit out seed in their own oysters and everything like that. So, it's become an oyster river, much more than clamming."

The mapping data we gathered supports the observed spatial overlap and connection between oyster aquaculture and wild oyster populations. Figure 2.7 synthesizes shellfish harvesters' observations (n=10) of wild oysters in the Damariscotta and how these observations relate to the boundaries of current aquaculture farms in the upper estuary.

Figure 2.7 Wild oyster distribution in the Damariscotta River estuary, as indicated by total sticker count by 10 participants. Also shown are the aquaculture lease sites permitted by the Maine Department of Marine Resources. For detailed methods, see Appendix B.



Our results accentuate the interconnectedness between aquaculture and wild shellfish industries. Although distinct in many ways, these industries share both species and physical space. The local knowledge documented by our study is an important first step in understanding the environmental and human dimensions of phenomena like this, an essential first step in unpacking the complexity of the relationship between aquaculture and wild shellfish populations. Local knowledge observations raised important, testable questions about the life histories of farmed oysters: Are wild oysters spawning? If yes, then when and under what conditions? Are farms the sole source of larvae, or have wild oysters begun to self-seed? These observations will guide our future research of oyster growth, development, and larval recruitment. This example underscores how local knowledge is the first step in our understanding of the interactions between shellfish aquaculture and wild shellfish populations and understand the variables influencing shellfish populations at large within the estuaries.

2.3.3.2 Diverse observations of aquaculture and wild shellfish interactions

According to many local knowledge holders, the Damariscotta has become “an oyster river” and now supports a wild oyster population. Wild oysters have become a target of commercial shellfish harvesting in the Damariscotta and, as one participant explained, “there are wild [shellfish] harvesters who are making money on harvesting oysters that are quote unquote wild.” Wild oysters are now a source of income for wild shellfish harvesters in the Damariscotta.

However, participants also referenced aquaculture as impacting the ecosystem and wild shellfish populations in less positive ways. Within the Damariscotta, dragging to retrieve bottom-cultured oysters was often cited as an aquaculture activity with negative impacts. Aquaculture farms in the Damariscotta typically use two methods to raise oysters: surface culture and bottom culture. In surface culture, oysters are placed in plastic mesh cages that float on the water surface. For bottom culture, oysters are spread on the seabed bottom for final grow out and harvested by 'dragging' (a drag pulled behind a boat), raking, or hand harvesting by divers (Maine Sea Grant, 2022). Numerous participants (n=7) explained that oyster dragging on aquaculture leases was affecting not only the shape and composition of the river channel, but also the shellfish living in the sediment. Participants explained that they felt that dragging can "silt out" the mudflats: that is, the sediment suspended in the water column by the dragging activity "chok[es] that spat (i.e., 'seed') out before it gets a chance to set in somewhere as it's floating around in the water column." Participants believe that the sediment could inhibit the process of reseeding or suppress the growth and survival of adult soft-shell clams. The observations about possible negative implications of dragging activity demonstrates how local knowledge can generate important questions about how and why the estuary ecosystem is changing in response to aquaculture activity. Our results indicate that there is potentially the need to research the effects of dragging activity on the ecosystem and on wild shellfish populations, both adult and larval stages. These are testable observations, the results of which could inform how aquaculture activity is understood and carried out within the estuaries.

Numerous participants also discussed observations about species interactions between oysters, both wild and farmed, and soft-shell clams. Some participants pointed to the oyster, with its high filtration capacity, as a potential predator of soft-shell clam larvae: "Basically like a whale that eats the plankton…when the clams lay their spawns, they float, and the oysters siphon them in." Some pushed back on this observation and explained:

> "It seems like the conclusion is that those damn oyster farms are sucking up all the clam larvae or they're taking all the feed. And my guess is that that is the broad assumption under the categories of shellfish harvesters. Personally, I'm not convinced at all that that's true. And I think that…the recruitment boxes [show] pretty clearly that there are places that have plenty of larvae. But those larvae just don't survive post settlement because the predation is too high. So, I suspect it's much more of a predation problem than oyster farms killing off the feed or killing off the larvae problem."

Beyond predation, participants identified another concern: competition for habitat between wild oysters and other commercially important wild shellfish species. One participant noted that soft-shell clam populations declined as wild oyster populations increased, but also observed the reciprocal of this relationship: "...in the last two or three years, once we've gone around and cleaned up a lot of the oysters off of the shorelines, that's when I started noticing clams starting to come back." In this observation "cleaned up" refers to harvesting oysters from the shores. This implies that harvesters are diversifying their harvesting practices to include wild oysters. Interestingly, however, wild oysters are framed as a threat to soft-shell clam populations rather than a new income source. Understanding such perceptions is important in facilitating interactions between shellfish harvesters and aquaculture, but also in aiding the transition in the Damariscotta to a more diverse, multi-species shellfish fishery.

Many harvesters are familiar with both the Damariscotta and Medomak ecosystems and have harvested on both estuaries throughout their fishing careers. As a result, observations recorded from our Damariscotta participants are often shared, either through first-hand experience or from conversations with Damariscotta harvesters, across the two systems. In general, the Damariscotta's shift to an 'oyster river', and the observations about how the introduction of oysters may affect other shellfish populations, has made shellfish harvesters wary of welcoming shellfish aquaculture into their home estuaries. As expressed by a Medomak participant regarding how harvesters address any oysters that they encounter in the Medomak estuary: "Everybody [who] finds oysters…takes them home, gets rid of them. We want to stay soft-shell clam because of what we are and who we are and where we are. And river aquaculture is frowned on in Waldoboro…none of that's welcome. We are wild clammers and we want to stay that way."

The views expressed by participants regarding wild oysters illustrate the tensions between traditional shellfish industries (i.e., wild shellfish clam harvesting) and emerging shellfish industries (i.e., oyster aquaculture and wild oyster harvesting). This study highlights issues of concern for both sectors and raises important human dimensions questions related to areas of potential conflict and collaboration. These findings have informed important lines of inquiry for our research group, specifically related to the feasibility of a wild oyster fishery and the possible challenges and co-benefits of the development of such a fishery for both wild shellfish harvesters and aquaculture farmers. Based on local knowledge findings, our research team intends to pursue the potential for a wild oyster market and explore in greater depth the various narratives that both sectors regarding the wild oyster. Our local knowledge results can extend beyond this research plan, however, to support other lines of inquiry into other complex relationships identified through this work, including questions on oyster and soft-shell clam interactions, such as competition for food or habitat, or the effects of dragging in the estuary. In sum, this example illustrates how local knowledge can inform complex, integrated, and ecosystem-level research that integrates ecological and social dimensions from its inception.

2.4 Conclusion

Synthesizing local knowledge requires the engagement of knowledge holders from study design to data sharing (Brook & Mclachlan, 2008). In this study we demonstrate how we did this work, by systematically documenting local knowledge in collaboration with shellfish harvesters and other local experts (Figures 2.2-2.7). We also highlight how the observations of local experts can be curated to identify hypotheses of local and scientific interest (Table 2.3). Through participatory mapping and the companion interviews, we were able to document and organize local knowledge in a replicable and methodologically robust manner (Gerhardinger et al., 2009; Lima et al., 2017; St. Martin & Hall-Arber, 2008). The data we have generated has been used to design social-ecological field studies of interest to both researchers and community members (see Chapter 3), to document change, and also to support community-driven shellfish and estuary management (Britsch, Leslie, et al., 2021). The fine-scale, place-based ecological and social information that shellfish harvesters and others who have extensive lived experiences in coastal and marine places can be critical elements of fisheries management plans, as well (Ames, 2003; Dey et al., 2020).

Engaged research like this also creates opportunities for collaboration (Brody, 2003). Effective collaboration builds trust among resource users, managers, and researchers while creating a space for dialogue, that in turn leads to improved future compliance and community capacity (Innes, 1996; Pearce & Pearce, 2004). By encouraging collaboration and dialogic communication (after Pearce & Pearce 2004), participatory mapping can facilitate data sharing and validation, and ultimately, improve both the procedural and substantive elements of community-led resource management. In our study system, that has certainly been our experience; the local knowledge mapping we report on here has been the subject of multiple meetings of the local shellfish committee and local governance bodies and has catalyzed engagement in shellfish management not only by local harvesters but also by local high school students and other community members (Houk, 2020).

2.4.1 Linking local and scientific knowledges

We show that local knowledge holders have detailed insights and observations on how and why the social-ecological systems they live and work in are changing. Local knowledge has a critical role to play in decision-making and management as a complement to scientific knowledge. As Agrawal (1995) argues, the division between scientific knowledge and local knowledge is a false dichotomy (Agrawal, 1995). Local knowledge and scientific knowledge can engage in dialogue to illuminate the dynamics of complex relationships and present data that are current and relevant to individuals living and working in the ecosystems. Linking local and scientific knowledges can be challenging, but common ground can be negotiated and valuable insights can be gained through the effort (Davis & Ruddle, 2010; Dey et al., 2020; Wilson, 2006). Such efforts can help to advance understanding and management in coastal marine SESs by providing timely, locally relevant, information grounded in fisher experience (St. Martin et al., 2007; Wilson, 2006).

Many of the hypotheses identified through this work are well aligned with published scientific studies. For example, participant observations of the change in the intertidal distribution of soft-shell clams, from muddier, mid intertidal areas to rockier, upper intertidal sediments are supported by some empirical information on soft-shell clams and sediment habitat selection. Thomson and Gannon (2013) found that living in coarse sediments may be more metabolically costly for clams, but results in lower predation risk than fine sediments do

(Thomson & Gannon, 2013). It is possible, therefore, that the center of soft-shell clam abundance intertidally may have shifted because of increased predation (Beal et al., 2018; Tan & Beal, 2015). Other studies have identified a relationship between aquaculture operations and ecosystem impacts. For example, studies have demonstrated that mussel farms may attract more fish predator species (Šegvić-Bubić et al., 2011) or modify flow, sedimentation, and increase habitat area for benthic species, leading to aggregations of epibenthic and macrofauna at farm sites (McKindsey et al., 2011). Bottom culture of oysters has also been shown to increase habitat for juvenile fish and mobile invertebrates (M. J. Powers et al., 2007). When placed in dialogue with our study participant's narratives of the relationship between increased aquaculture with increased presence of shellfish predators, like green crabs, local knowledge is beginning to help us to formulate scientifically valid, locally relevant hypotheses that connect the social and biophysical dimensions of these estuarine SESs.

Participant observations such as this can complement existing biophysical scientific research to develop comprehensive research questions that frame ecological phenomena within relevant social and economic contexts. Ultimately, local knowledge helps to adapt biophysical scientific knowledge and research to unique SESs because it identifies the specific research and management priorities of a community. Local knowledge questions and observations can help to fine-tune future biophysical scientific inquiry, leading to the production of applicable information. The interaction between local knowledge and biophysical scientific knowledge can also function in a reciprocal manner, in which biophysical scientific knowledge can be assessed by local knowledge holders to determine which pieces of scientific exploration are of greatest value or importance to resource users or fishers within a system. In order to make management effective, this dialogue should be central to social and environmental studies that engage fishers, scientists, local decision makers, and other stakeholders in an ongoing, long-term relationship (Wilson, 2006).

<u>2.4.2 Outstanding questions</u>

Local knowledge data is highly complex and heterogeneous in nature. It may contain contradictions–in much the same way as the imperfections of scientific knowledge and traditional scientific research, argues Dey et al. (2020) – and is often difficult to standardize according to scales of time, spatial coverage, and expertise (Dey et al., 2020; St. Martin et al., 2007). Regardless, it is a rich body of knowledge and experience.

Considering timescales, local knowledge is primarily a snapshot of a specific period. As one participant in our study clarified, the data collected, in this instance on soft-shell clam abundance in specific locations, “could fluctuate big time” and that what was recorded through the study could change based on “observations day to day.” It is therefore important that local knowledge data not be considered the final word on the shellfish resource in our focal systems. Rather, it is a detailed account of a distinct period. This snapshot is an invaluable tool for framing not only how shellfish populations may change in the future, but also contextualizing understandings of their history. Therefore, each effort to document local knowledge helps to scaffold a broad view of the focal ecosystems and their shellfish resources over time.

For our research group, the fact that local knowledge is “time sensitive and time rich” only supports the case for continued documenting of this essential information (Davis & Ruddle, 2010, p. 891). Our study demonstrates the need for the sustained dialogue between social science research, particularly that focused on local knowledge, and ecological study to support ecosystem-wide understandings of complex systems like the Damariscotta and the Medomak.

Validation of local knowledge through scientific methods is a contentious issue, and the local knowledge literature is divided on whether validation is a disrespectful process or a necessary step in local knowledge's application (Berkes, 1993; Davis & Ruddle, 2010). However, if founded in cooperative efforts among fishers, scientists, and other stakeholders, local knowledge and scientific knowledge can test and affirm each other in ways that enrich both knowledge cultures. Ideally, this work is done in a systematic, replicable, and rigorous way (Davis & Ruddle, 2010). This is an approach we are currently pursuing in this area.

2.4.3 Concluding thoughts

Our study demonstrates how local knowledge can be used to characterize multiple dimensions of a social-ecological system, highlight priorities of key actors, and generate locally relevant observations, questions, and hypotheses about how and why a system is changing. Through participatory mapping and interviews, we documented fine-scale observations of shellfish abundance and diversity, and how those changing patterns influence harvester behavior in two focal estuaries in midcoast Maine, USA. These observations and the associated hypotheses shared by local experts provide essential baseline information upon which to build future long-term studies relevant to both scientific and management goals. This engaged approach also enables researchers to assess the status of shellfish populations in a cost- and time-efficient manner. Identification of the complex interactions among farmed and wild shellfish populations in the Damariscotta River estuary was a particularly exciting aspect of this work and is catalyzing ongoing collaboration among local managers, harvesters, researchers, and other community members. Through this effort both local knowledge and scientific knowledge are growing and community capacity to gather and to integrate these knowledges is growing as well.

CHAPTER 3

COMMUNITY SCIENCE IN SUPPORT OF SHELLFISH MANAGEMENT: A CASE STUDY FROM THE DAMARISCOTTA RIVER ESTUARY, MAINE, USA

3.1 Introduction

Knowledge of coastal and marine social-ecological systems (SESs) often is incomplete, due to challenges created by the marine environment and the spatially and temporally variable behavior of human and non-human species within these systems (Levin & Poe, 2017). These knowledge gaps challenge those who manage human interactions with marine ecosystems, whether they are managing at the local, regional, or larger geographic scales (Young & Gasser, 2002). To address these challenges, researchers have sought novel methods to study marine systems.

One approach that has gained traction in this field is community science. Community science is defined as scientific research or monitoring grounded in inquiry that is (1) community-led, (2) centered on place-based knowledge, collective action, and community empowerment, and (3) aimed at improving governance processes with the goal of stewardship and social-ecological sustainability (Charles et al., 2020). Researchers have used community science to address marine fisheries related questions in multiple social-ecological contexts, including investigating variation in species distribution and abundance (Spyridopoulou et al., 2020), enhancing data collection by management agencies (Bonney, 2021), assessing the ecosystem impacts of specific fisheries (Pérez-Jiménez et al., 2022), and generating fisheries datasets at large geographic scales for fisheries stock assessments (Fairclough et al., 2014). These studies demonstrate the value of community science for marine fisheries, particularly to gather, analyze and interpret data in ways that meet local community needs and management goals.

Community-based research programs that engage fishermen, managers, scientists, and students in collaborative research have many benefits and are increasingly viewed as an effective and important approach to ecosystem-based fisheries management and environmental sustainability (Ebel et al., 2018; Johnson, 2011; Schroeter et al., 2009). Community-based research and relatedly, citizen science, have a long history dating back centuries to amateur researchers and naturalists (Miller-Rushing et al., 2012). *Citizen science* can broadly be defined as the involvement of the public in scientific investigations to collect data (Bonney et al., 2009; Miller-Rushing et al., 2012). *Community science*, by contrast, meaningfully engages the public in collaborative research addressing community-defined questions (Bonney et al., 2021; Dosemagen & Parker, 2019). It is important to recognize that community science and citizen science are distinct terms defining unique research paradigms. To be *community science*, a project must truly be community-led and community-driven (Charles et al., 2020). These efforts are tied with social action, address place-based challenges, and elevate the voices of local knowledge holders (Heaney et al., 2007). Researchers have often erroneously applied the term community science to citizen science research, effectively "woke-washing" projects and co-opting language from a distinct school of research processes and methods (Bonney, 2021; Cooper et al., 2021). The term 'citizen' is also problematic, as it may be seen to exclude those without citizenship status within a nation (Lowry & Stepenuck, 2021).

Citizen science typically occurs at large scales, where data are gathered and curated across broad spatial and temporal scales. Community-based projects are often comparatively small-scale and focused on issues of local importance (Bonney, 2021). However, local scale community-based projects can be connected to geographically large-scale networks. For instance, The Waterkeeper Alliance program (including Riverkeeper, Baykeeper, etc.) extends across 15 nations with the goals of water quality and ecosystem protection (Conrad & Hilchey, 2011). In fact, the distinctions between community science and citizen science are relatively blurred in both theory and practice (Dosemagen & Parker, 2019). Both citizen science and community science are already recognized for their contributions to management, governance, and conservation science—although the role of these approaches in management and governance is not fully established (Conrad & Hilchey, 2011; McKinley et al., 2017). Additionally, both citizen science and community science encourage the democratization of scientific practices by engaging diverse communities in conservation science and local issues, in effect improving community member scientific literacy while also making professional scientists more aware of local knowledge and expertise (Carolan, 2006; Conrad & Hilchey, 2011).

Citizen science and community science can enhance capacities for conservation and natural resource management because they aid in the production of scientific knowledge, inform policy, and encourage community action and participation (McKinley et al., 2017). Community-centered research and monitoring processes provide multi-layered benefits, all leading to conservation resilience and enhanced management practices. These benefits include: (1) scientific benefits, such as research findings or scientific publications, (2) SESs benefits, including community action, strengthened relationships between stakeholders, or new legislation or management initiatives, and (3) individual benefits, like new skills, knowledge, or strengthened facets of identity (Shirk et al., 2012). Community science and citizen science enhance research capacity by providing a volunteer workforce that allows for research spanning spatial and temporal scales (Thiel et al., 2014). Specifically, volunteer efforts can help to identify environmental changes (Bonney, 2021; Spyridopoulou et al., 2020); detect shifts in fishery populations that require management responses (e.g., age structure, stock status, catch data, species abundance, distribution, and habitat (Bonney et al., 2021; Fairclough et al., 2014; Schroeter et al., 2009)); or review the effectiveness of management practices (Conrad & Hilchey, 2011). Research is only one dimension of how citizen science and community science can enhance capacity for conservation and engage diverse individuals to address ecological challenges through numerous activities. Community and citizen scientists can support education, civic engagement, and management—all activities that can complement traditional approaches to conservation and can bring together diverse groups working towards common goals (Conrad & Hilchey, 2011).

Community science and citizen science can facilitate research that might not otherwise have been feasible due to project scale or other logistical issues. Further, it engages the community and resource users in both the research and decision-making process (McKinley et al., 2017). In co-management contexts, such as the co-managed shellfish fishery, monitoring and research conducted in collaboration with stakeholders provides opportunities for feedback on management and opportunities to improve and adapt management practices (Armitage et al., 2011). The process of collaborative and participatory monitoring can enhance SESs reliance through the social learning processes that come from these types of engagement (Berkes, 2009). Citizen science and community science—when of appropriate scale, well-designed, and evaluated—can produce locally-relevant, quality data to help solve marine conservation and management problems (McKinley et al., 2017).

Past research has demonstrated the importance of scale in effective approaches to marine conservation challenges (Leslie, 2005). For example, marine protected areas (MPA) for coral reefs have begun to merge community and regional MPA management approaches. Taking local-scale approaches, while maintaining a regional perspective, emphasizes community concerns and livelihoods, while ensuring that regional efforts are aligned (Ban et al., 2011). The scale and scope of institutions and management systems are most effective when they are congruent with the ecosystem scale (Wilson, 2006) . Marine systems are complex and require innovative management approaches that are inclusive of diverse actors and link multiple levels of management and governance institutions (Fidelman et al., 2012). Through this case study of a community science project in Maine, USA, we examine the contributions of community science for a small-scale coastal shellfish fishery.

We focus on a small-scale fishery with a co-management structure where governance occurs at the municipal scale. However, municipal managers lack the capacity to study these systems and require small-scale, novel approaches to document how these SESs are changing through time. We describe how community science is supporting community-led co-management, thanks to the focus on community engagement and participation by local knowledge holders. Maine's intertidal shellfish fisheries are often data-limited because: (1) intertidal mudflat habitats are difficult to survey, and (2) local and state level management bodies have limited capacity to monitor fisheries resources. By reporting on how the project aligns (or not) with the key conditions identified by Charles and colleagues (2020), we place this case in a broader context (Charles et al., 2020). This approach has the potential to be applied elsewhere to enhance capacity and support managing for resilience in the face of changing social-ecological conditions. Community science may be an effective strategy to support EBM approaches to Maine's shellfish fisheries. We follow the McLeod and colleagues' definition of marine EBM as an integrated management approach including humans and human use in ecosystem assessments and strategies for resilient SESs (McLeod et al., 2005).

3.2 Materials & methods

3.2.1 Study system

Coastal Maine is a site of significant socio-ecological change, including warming ocean temperatures (Pershing et al., 2015) and shifting human uses, like the expansion of aquaculture (Britsch, Leslie, et al., 2021; Hanes, 2018). These changes have affected multiple communities in Maine and beyond (Brierley & Kingsford, 2009; Gissi et al., 2021; Pershing et al., 2021). Here we focus on the Damariscotta River estuary, located in Maine, USA, and its wild shellfish fishery (Figure 3.1). The wild shellfish fishery is experiencing changes linked with both climate change and changes in human uses, including increased predation (Beal et al., 2018; Beal, 2006b, 2006a), over exploitation (Congleton et al., 2006; Lindsay & Savage, 1978), and water pollution (Chen, 2018; Evans et al., 2016). These factors, and their growing intensity, has made it more challenging than ever to manage the fishery. Ecosystem-based approaches to management are an effective strategy in rapidly changing coastal SESs and may be an appropriate fit for Maine's shellfish fishery (McLeod & Leslie, 2009; Xavier et al., 2022). However, fishery managers are challenged by data limitations and the limits of local institutions (McGreavy et al., 2018).

Maine's shellfish fishery is community-based in nature and has integrated local knowledge and locally generated scientific information into its co-management process throughout its history (Hanna, 1998). Co-management is a system of governance based on shared responsibility and power between government institutions and resource users (Berkes et al., 1991; Plummer & Fitzgibbon, 2004). It has a long history in Maine, dating back to the 1641 Massachusetts Bay Colony Ordinance, which established intertidal fishing, fowling, and navigation rights for all residents (Hanna, 2000). Today, the state has enacted a statute (Title 12, Part 9, Chapter 623) that allows coastal towns to establish municipal shellfish committees and shellfish ordinances. Shellfish committees can charge license fees, establish areas open or closed to harvest, and create harvesting limits, among other activities. The Maine Department of Marine Resources (DMR) provides guidance to the town and sets broad standards for fishery, including a license requirement, a minimum harvest size and tolerance, accepted harvest tools, as well as monitoring public health (Hanna, 2000). Together, DMR and Maine's coastal towns co-manage the shellfish populations across the state.

The Joint Damariscotta-Newcastle Shellfish Committee, in partnership with the state of Maine, co-manages the wild shellfish populations within the towns' municipal boundaries. Commercially harvested shellfish species in the estuary include soft-shell clams (*Mya arenaria*), quahogs (*Mercenaria mercenaria*), and wild American oysters (*Crassostrea virginica*). Maine's co-management process is unique in that it is adapted to the specific ecological and cultural conditions of each municipality (Hanna, 1998). Co-management recognizes the expertise and experience of harvesters, while also relying on scientific knowledge provided by the state and other organizations (McGreavy et al., 2018). It is also shown to be an adaptive management approach that can effectively respond to environmental change (McClenachan et al., 2015). Co-management's capacity to be locally tailored and the structure of municipal shellfish committees – groups composed of shellfish harvesters and other community members – makes engaged research approaches and community science initiatives an apt fit for Maine's shellfish fishery. Further, the physical accessibility of intertidal shellfish habitats makes community science a feasible option for studying these environments. Engaged approaches have already been employed to address challenges facing the fishery, and have modeled methods to engage harvesters and the community in research efforts (Hillyer, 2019; Hillyer et al., 2021; McGreavy et al., 2018). Due to these reasons, and other contextual factors explained below, our research group initiated a community science project in partnership with others to better understand the SESs associated with the shellfish fishery in this estuary and to contribute to coastal marine stewardship. Here we report on the work to date (2019-2022) as a case study analysis.

Figure 3.1 Damariscotta River estuary and surrounding towns (Map data: *Maine Boundaries Town and Townships Polygon,* 2019; *States Shapefile*, 2015).

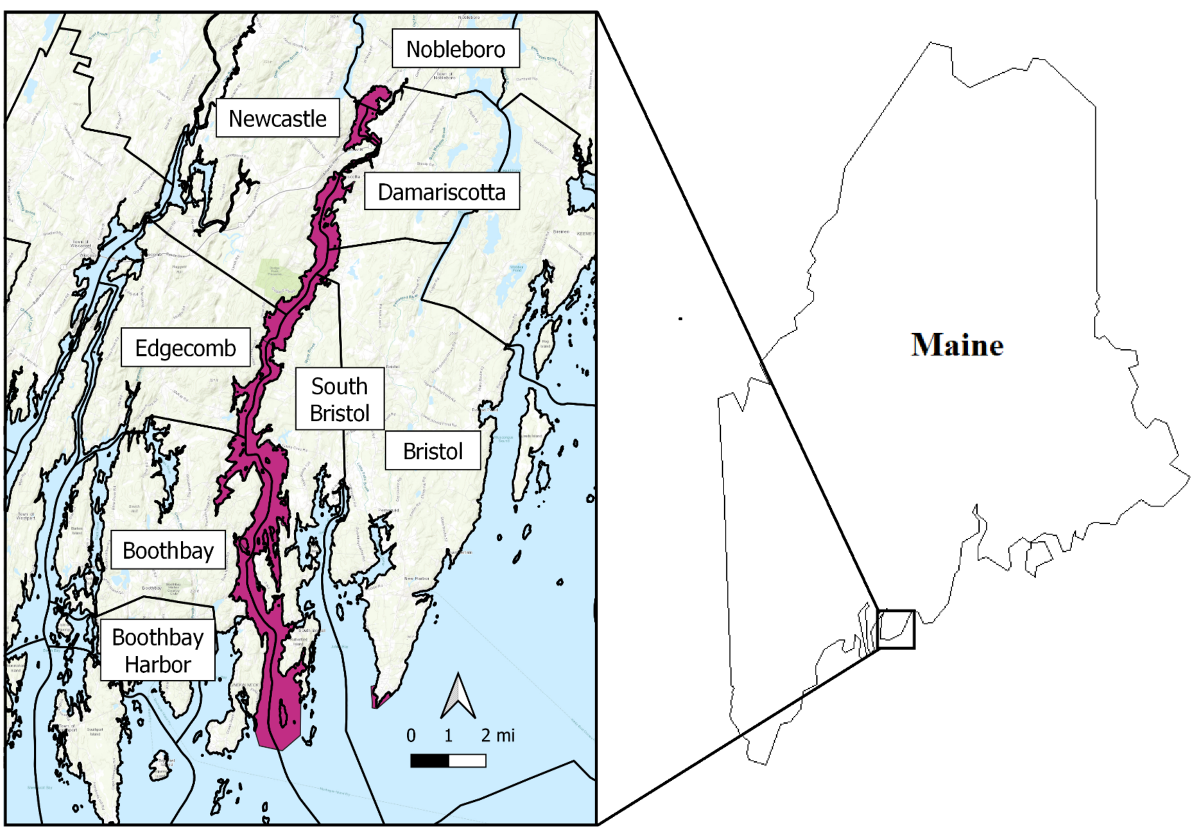
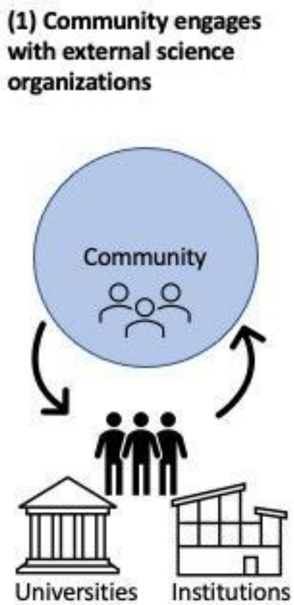


Figure 3.2 Three community science models: (1) the community engages with external bodies (universities, governmental research institutions, etc.) to provide the needed scientific knowledge, (2) the community draws on internal volunteer scientific expertise, and (3) the community hires or contracts in-house professional science expertise. Adapted from Charles et al. (2020).



<u>3.2.2 Case study analysis</u>

Case study methods are used by researchers to examine contemporary phenomenon that are integrated into a broader context, for example phenomenon that occur in dynamic SESs with diverse factors, participants, and complex direct and indirect outcomes (Yin, 1981). These methods are also an important tool for evaluation (Yin, 1992). According to Yin, 1992, ‘evaluations’ can be considered a form of research that assesses real-life projects or programs (vs. controlled research projects) that are often are designed for the purpose of knowledge-development, education, or social change at the community level (Yin, 1992). Case studies are a particularly advantageous tool for evaluation because they assess outcome and help to test hypotheses about causal relationships among variables and outcomes (Yin, 1992). We chose to utilize case study methods because they enabled us to evaluate the conditions for the development of community science and to examine how and why specific community science outcomes were produced.

To place this case in a broader context, we use a community science model typology and key principles and conditions for community science developed by Charles et al. (2020). We evaluate the progress of the Damariscotta community science project and the conditions that make community science appropriate, and then discuss how this analysis informs further development of this project, into the future. The typology includes three variations in the processes through which local communities engage with scientific expertise, either at the individual or organizational level (Figure 3.2, adapted from Charles et al., 2020). All three of the models share the key characteristic that the community determines with whom they will engage. We first identify the models that most align with our project structure. Charles and colleagues also define the key principles and conditions for community science (Charles et al., 2020, p. 83 Table 2). Here, we present a modified version of this table that we will apply to our community science project (Table 3.1). We then use the principles and conditions to reflect on our project. Overall, our guiding goals were:

1) To assess project progress,
2) To enhance understanding of the conditions in which community science is appropriate, and
3) To determine how to further develop the project in the future.

3.2.3 Motivation for community science

In 2019, the Joint Damariscotta-Newcastle Shellfish Committee approached researchers at the University of Maine Darling Marine Center about assessing the status of the Damariscotta

River estuary's wild shellfish populations. Shellfish harvesters had observed changes in shellfish abundance and diversity, including a decline in soft-shell clam populations and a parallel increase in quahog and wild oyster populations. The 2019 study included a field study of shellfish populations and interviews with shellfish harvesters (n=7). The results of the 2019 study were presented to the committee and to the town's leadership, the Board of Selectmen (Pellowe & Leslie, 2019). The research partnership continued in 2020 through a local knowledge mapping study to document harvester and other river user knowledge of shellfish populations and human use activity (Britsch, Risley, et al., 2021). The results of this study highlighted the importance of local knowledge. In 2021, the shellfish committee and University researchers began a community science project to study shellfish populations in collaboration with a local high school, Lincoln Academy (LA). The program was designed to gather ecological data and to document local knowledge. Data collection was designed to address management and educational goals articulated by the shellfish committee and LA, respectively. Through the project, the Damariscotta-Newcastle Shellfish Committee is seeking to answer the following questions:

a. How many harvestable shellfish are on the flats now, and how many can we anticipate in the future?
b. Relatedly, how diverse is our shellfish resource (i.e., how many different species are harvested and where)? And how does this species and habitat diversity influence harvester behavior–where they harvest, which species, how much–and earning potential?
c. What environmental factors affect shellfish populations, and on what temporal and spatial scales?

Additional goals include enhanced community engagement with the shellfish fishery by:

a. Increasing local student engagement in the Damariscotta ecosystem and civic involvement through place-based experiences and connections with local shellfish harvesters and the shellfish committee.
b. Increasing capacity for long-term and ecosystem-level information by enhancing collaborations with scientific and educational institutions in the area.

The community science project was designed to expand the shellfish committee's scientific and volunteer capacities while simultaneously addressing pressing social and ecological questions posed by shellfish fishery managers. Below we describe the development of the project and results to date.

Table 3.1. An adaptation of 'Table 2: Key Principles and Conditions for Community Science' from Charles et al. (2020). We condensed some conditions to facilitate analysis.

Principles/ Conditions	***Explanation***
Connection to Place & Local Knowledge	Community science emerges from a connection to place (Chapin & Knapp, 2015). In strong community science initiatives both local knowledge holders and scientific knowledge holders share this sense of place (Charles et al., 2020). We believe that local knowledge is inherently linked to connection to place, and therefore we have integrated these principles. Local knowledge is blended with other knowledge forms through community science, improving understanding of the social-ecological system (Charles et al., 2020).
Leadership & Links to Governance	There are many leadership models, ranging from formal government systems to community approaches (Charles et al., 2020). Governance, as defined by Charles et al. (2020), "is the processes and institutions through which communities and societies take action to improve the environment" (Armitage et al., 2012; Charles et al., 2020). We combined these conditions for the purposes of this paper because the leadership (the shellfish committee and the DMC) is striving to improve the environment and is closely linked to governance.
Empowerment, Collective Action & Credible Trust	Community science not only generates knowledge and provides learning opportunities, but it also empowers communities by increasing their ability to impact decisions and improve capacity for stewardship. The process of community science also needs a high level of agency and knowledge sharing across the community science network, including partners outside the community. The sharing of knowledge depends on a level of trust between the community and its scientific partners (Charles et al., 2020). The level of trust will impact the ability of collective action.
Availability of Capacity & Resources	Capacity, in terms of human or financial resources, will influence the scope, time scale, and impact of community science. Charles et al. notes that community science often requires significant time and effort, and that many communities do not have the leadership, agency, funds, or other circumstances to engage with all the different models of community science (Charles et al., 2020).
Community-Driven	A key requirement of community science is that the research is driven by the community and the community determines with whom they will engage (Charles et al., 2020).

3.3 Results & discussion

3.3.1 Case study: The wild shellfish fishery in the Damariscotta River estuary, Maine, USA

3.3.1.1 Model of community science

The results of the 2019-2020 studies inspired the development of several community science activities. First, researchers developed a shellfish ecological survey to address the shellfish committee's key questions. The survey itself is grounded in the results of the 2019 and 2020 studies in that it: (1) seeks an effective, but less labor- and time-intensive, survey that can realistically be accomplished by high school student researchers and (2) employs local knowledge guiding scientific methodology, generating information that meets local needs. Local knowledge informed the development of survey methods that target specific shellfish habitat identified by local harvesters, rather than an exhaustive survey across the intertidal zone. The survey also documents information on environmental variables, including sediment type, percent algal cover, number of visible siphon holes, and the presence of other species, like marine worms.

Second, researchers employed an existing survey methodology (McMahan, 2020) to quantify the abundance and distribution of green crabs (*Carcinus maenas*), a primary predator of soft-shell clams (Beal et al., 2018; Beal, 2006b). Third, the research team developed a survey to document local harvester knowledge of shellfish populations and harvesting effort and behavior. The results presented here were documented through semi-structured interviews as part of the initial local knowledge mapping study. Starting first with semi-structured interviews allowed the researchers to refine the interview instrument by identifying key questions to develop a short-form, structured survey to be conducted by high school students and completed annually. And finally, researchers quantified how many young clams recruit onto the flats managed by

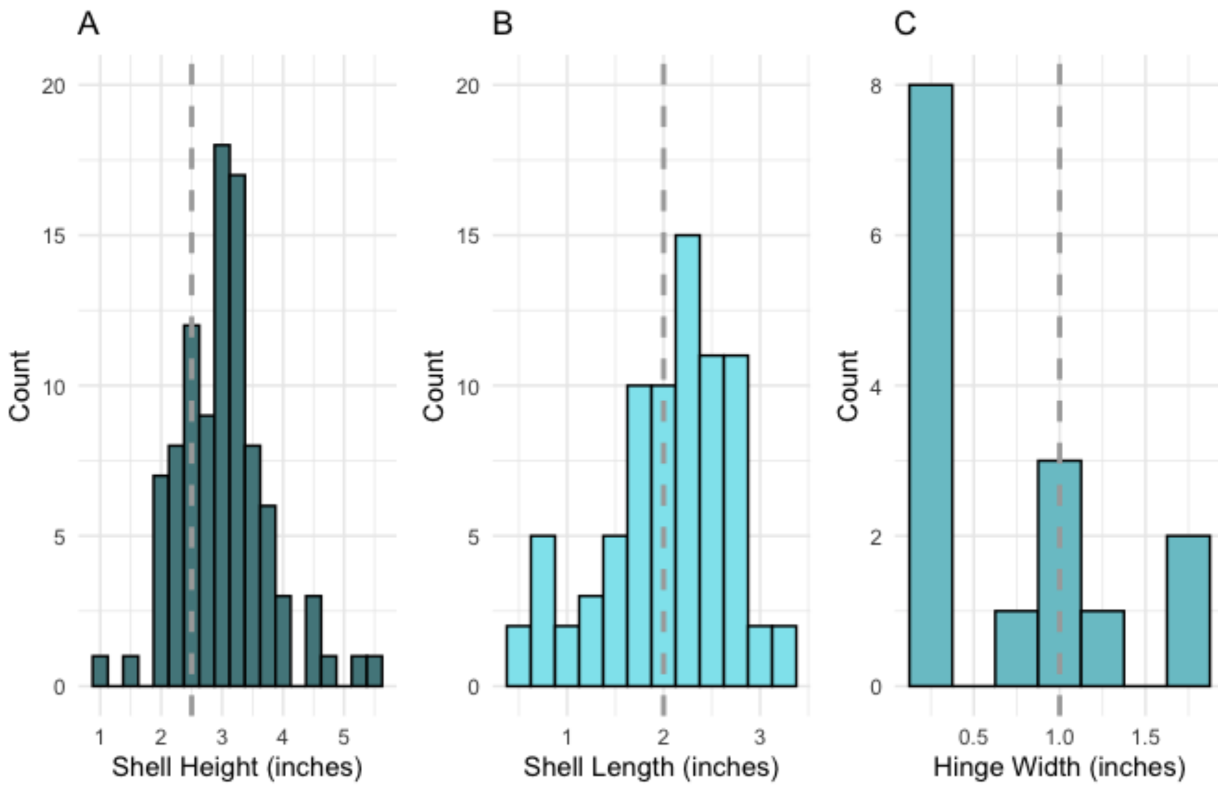
Damariscotta and Newcastle, using an established protocol (Beal, Randall, et al., 2020). We compiled these methods in a community science handbook geared towards high school educators and high school students, to facilitate future collaboration (Appendix H). Community science project activities are led by University researchers and local high school students, harvesters and other community members are involved in collecting data and analyzing information for management and scientific purposes.

3.3.1.2 Concrete results of community science

The ecological and social components of the community science project generated information that addresses the committee's key questions concerning the shellfish fishery. These data can help the shellfish committee forecast future abundance of harvestable shellfish and explore relationships between environmental variables and shellfish abundance, diversity, and distribution. These analyses will help inform decisions about future conservation and management measures, which the committee is required to consider as part of the state statute.

The ecological shellfish survey results provided information on shellfish species abundance and size structure frequency in the estuary. Survey data were collected in late July to early August 2021 across the monitoring sites. The results help to illustrate the current standing stock of harvestable shellfish based on legal harvesting size for each species (Figure 3.3). Size frequency data helps managers predict the current and future abundance of harvestable shellfish populations and directly addresses the shellfish committee's first key question: How many harvestable shellfish are on the flats now, and how many can we anticipate in the future?

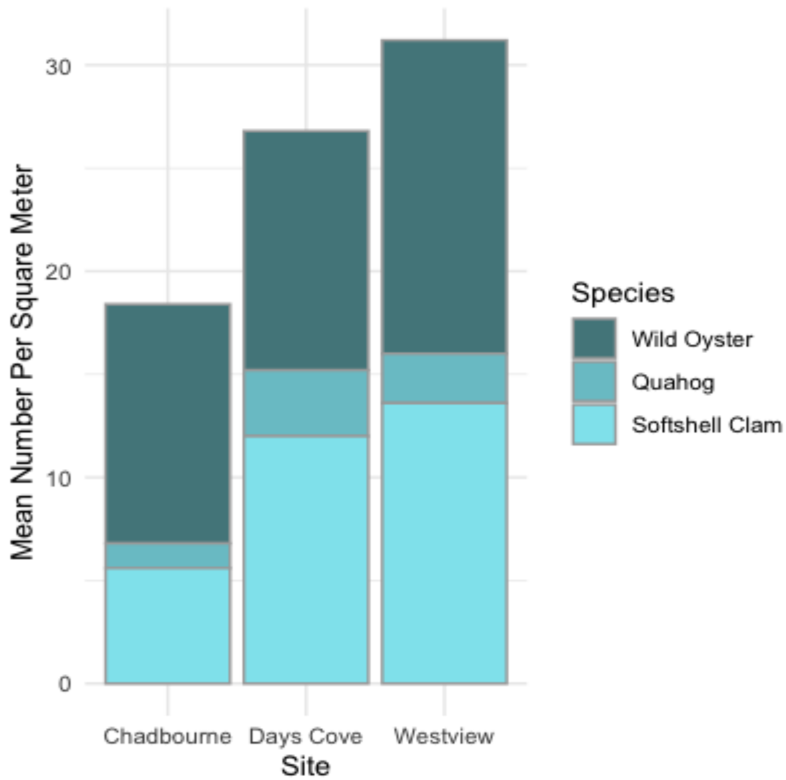
Figure 3.3 Size frequency distribution for three commercially important shellfish species in the Damariscotta River estuary: (A) oysters (B) soft-shell clams (C) quahogs (n=3 sites). Gray lines represent the legal size for harvest (2.5 inches length for wild oysters, 2 inches length for soft-shell clams, and a 1-inch hinge height for quahogs). Note variation in axis values. See Appendix H for detailed survey methods.



The ecological survey data also provide insight into the diversity of harvested shellfish in the estuary, answering the committee's second question: How diverse is our shellfish resource (i.e., How many different species are harvested and where?) (Figure 3.4). The Damariscotta is distinct from many estuaries in Maine because it hosts wild oyster populations. These populations represent a new shellfish product for Damariscotta-Newcastle commercial shellfish license holders, most of whom previously focused their activities on soft-shell clams. Unlike most estuaries in Maine, the Damariscotta also has a significant number of quahogs. The presence of both wild oysters and quahogs, in addition to soft-shell clams, illustrates that the

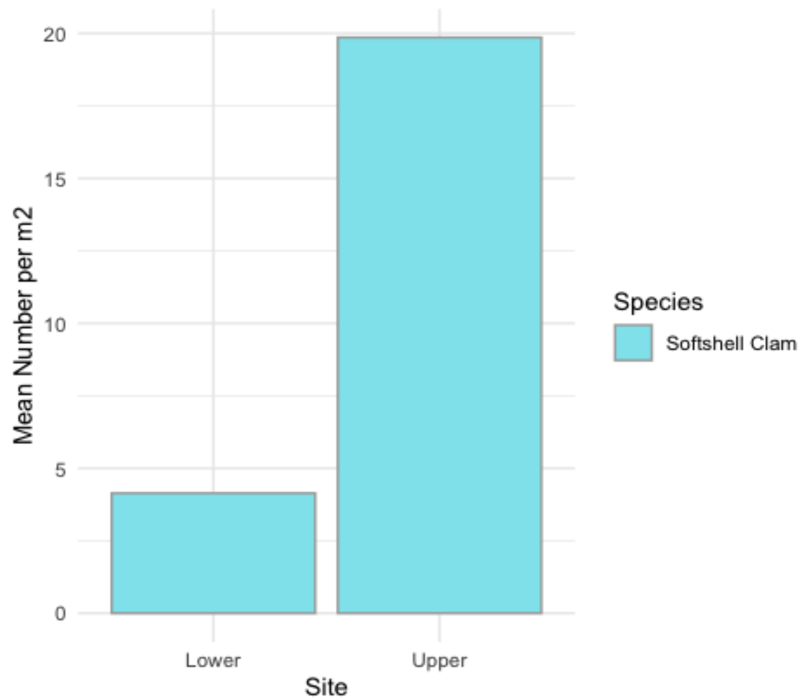
Damariscotta is an estuary with relatively high shellfish diversity (Britsch, Risley, et al. 2021; see Appendix E & Appendix F).

Figure 3.4 Shellfish abundance in the Damariscotta River estuary. Shellfish populations were quantified in the upper Damariscotta River estuary via ecological surveys in summer 2021(n=3 sites). See Appendix H for detailed survey methods.



The soft-shell clam recruitment study quantified larval supply and analyzed predation as a variable affecting shellfish populations. These data illustrate spatial variability among sites (Figure 3.5). Mean number of soft-shell clams per square meter found in recruitment boxes ranged from 4.14-19.86 across sites (n=2). This range of values is comparable to neighboring estuaries, where a range of 5.4- 471.5 mean number of soft-shell clams per square meter has been reported (Beal et al., 2021). The upper Damariscotta has relatively lower recruitment rates compared to other midcoast Maine estuaries (Figure 3.5). We also documented spatial variability in green crab abundance: the mean number of green crabs ranged from 0.83 per m^2 at the upper site (Chadbourne) to a mean number of 19.0 per m^2 at the lower site (Lowes Cove), near the southern mouth of the estuary. Based on this first year of what we anticipate will be a long-term program, the southern site in the Damariscotta may have above average numbers of green crabs compared to neighboring estuaries. Soft-shell clam recruitment data, as illustrated in the results of the project's first year, offer insights into the committee's key questions concerning future shellfish abundances and variables influencing shellfish populations.

Figure 3.5 Soft-shell clam recruitment in the Damariscotta River estuary (n=2 sites). The number of soft-shell clam recruits per square meter collected from recruitment boxes (n=8) deployed in June 2021 and collected in November 2021 was significantly greater in the upper site vs. the lower site (Three-Way ANOVA: $F = 7.257$, $P < 0.0001$, df = 8, 189, followed by a Tukey test comparing the number of soft-shell clam recruits found in the Petscreen© treatments at the upper vs. the lower site) For detailed methods, see Appendix H.



We also synthesized local knowledge information on harvesting behavior and observations of the variables influencing shellfish populations. Damariscotta harvesters reported that they harvest shellfish on average four days a week but could range from a minimum of 1-7 days to a maximum of 3-7 days a week (n=6). Harvesters explained that they typically only harvest one tide each day but may go out for two tides depending on tide timing, tide intensity, and market prices of shellfish. Harvesters also shared information about the species they harvest, and which species are their primary targets for harvesting. Harvesters tend to target multiple species in the Damariscotta. Soft-shell clams and oysters were identified as the main species harvested, followed by quahogs and razor clams. As one study participant explained:

"I just walk along the shore…and look for wild oysters, wild American oysters. Sometimes I go for quahogs…once in a while I'll go for soft-shell clams…Razor clams too, when tides are really huge around the full moon."

Tide timing and intensity, in addition to the market price for certain shellfish species, were cited as drivers of harvesting behavior. One harvester elaborated on these factors:

> "It all depends. It goes back to…what people are looking for in the market at the time. I mean usually I try to find quahogs, steamers [soft-shell clams], and obviously wild American oysters. I'd say predominantly it also depends on tide. For the big tide I try to go for wild American oysters because they're deeper out in deeper water that make them harder to get on a regular low tide...And then quahogs depending on where you are, you can do on a regular tide and for steamers, too."

Information on harvesting behavior, including the primary species targeted by harvesters and harvester effort, helps to address the shellfish committee's key questions, and supports their decision-making process for determining license allocation and area closures. Harvesters also observed the following potential shellfish predators in the Damariscotta: green crabs and other crabs, ribbon worms (milky ribbon worm, *Cerebratulus lacteus*), and boring snails (*Euspira heros*) (n=8). Participants pointed to aquaculture activity and the introduction of oysters, as well as decreased access (both physical walk-in access to shore and the barrier of license access) and predation pressure as the three most pressing threats to the shellfish fishery (n=11). Information on how variables, such as predation or aquaculture activity, may affect shellfish populations can guide further research investigations and inform conservation initiatives.

3.3.2 Application of community science typologies

The Damariscotta community science project aligns most closely with the 'Community engages with external science organizations' model (Charles et al., 2020). However, the project is nuanced and can also be classified as the 'Community engages with resident scientists' model because the project's lead researcher is a member of the shellfish committee and that the University researchers and local high school students contributing to the project often live and work on the Damariscotta. Although the committee is engaging with the University and Lincoln Academy on an institutional level, the students and researchers participating in the project are, as individuals, residents of the community. Therefore, the project can be best classified as a resident scientist model nested within the model of external science organizations. The committee will continue to engage with both the University and the local high school as organizations, but the students and University researchers who pass through the project belong to the community at large. These typologies are useful because they allow project partners to clearly identify their roles, areas of expertise, and specific contributions to the project effort. Although typologies may be limited in their ability to capture nuance and adapt to changing relationships over time, they help to define how project partners relate to one another and aid in comparisons of community science projects that share the same or different typologies.

3.3.3 Application of community science principles & conditions

Although the project is still in the early stages, we use the framework presented above (Table 3.1) to reflect on how our approach aligns to the foundational conditions of community science research identified by Charles and colleagues.

3.3.3.1 Connection to place & local knowledge

Underlying the Damariscotta community science project is an inherent connection to place, on the part of both the shellfish committee, shellfish harvesters, and University researchers. Each group is committed to the Damariscotta in different ways but share the objective to understand the social-ecological system and support a resilient shellfish fishery. For shellfish harvesters and committee members, the Damariscotta is a place of work and recreation that holds deep cultural significance. For University researchers, the estuary is a focus of scientific inquiry and hosts the Darling Marine Center, a place of personal and academic growth. Both local knowledge holders – the shellfish harvesters and committee members – and scientific knowledge holders – the University researchers–share a sense of connection to the Damariscotta, contributing to a strong foundation for community science (Charles et al., 2020). And as many local high school students and their families live, work, and play on the estuary, the project aims to strengthen connections to coastal livelihoods and the Damariscotta social-ecological system through community science.

The project leaders fortified the project's connection to place by positioning local knowledge as a central feature of the project design and methods, and as a focus of continued data collection. The local knowledge documented through the project grounds the research in the experience of shellfish harvesters and is intended to ensure that the project process is rooted in their voices, concerns, and questions.

Shellfish committees considering community science should look to engaging local institutions, high schools, or other organizations with strong ties to the community and environment. Often, these groups are pursuing existing programs or initiatives with overlapping research or learning goals that could facilitate the development of a strong, place-based community science project.

3.3.3.2 Community-driven & community-controlled

The shellfish committee's initial request for current, usable information about the Damariscotta's shellfish populations and how they are changing through time inspired the development of the community science project. After the completion of the 2019 and 2020 studies – important first steps that generated information that guided research questions and goals – the committee and its University partners arrived at a community science project as an appropriate way forward.

Although meetings and information sharing have provided opportunities for committee members to offer input on the project progress and guide future steps, our team needs to think critically about how to effectively solicit feedback from partners going forward. A formal feedback structure would allow us to be responsive to the requests of the committee and keep project control in their hands.

In general, community science projects that bring together local knowledge holders and scientific knowledge holders must be attentive to how communication and feedback processes occur. Information should be provided in an accessible way and information sharing should occur in culturally appropriate environments with diverse means of engagement (Hill et al., 2020). For example, a town hall meeting may be a more appropriate site for information sharing and feedback than an academic conference. Effective project communication processes are essential for community members to maintain leadership and project control.

3.3.3.3 Leadership & links to governance

Leadership for the project arises from the Joint Damariscotta-Newcastle Shellfish Committee as the project lead, supported by a partnership with University researchers. There is a University graduate research fellow whose primary role is to facilitate partner interactions and coordinate project activities. This leadership structure has two major benefits in that it (1) allows the committee to maintain control over the prioritization of research questions and provide support to University researchers and (2) identifies a key point person to move the project forward, facilitate partnerships, and synthesize results and feedback. Partnerships also play an important role in the project, including those with local high schools and local knowledge holders. As of 2022, there are only two current committee members who are active shellfish harvesters. Documenting and implementing local knowledge from shellfish harvesters enables harvester voices to be heard to guide the community science process, even though they are not directly engaged in leadership. The project has clear links to governance, as the committee is the primary institution determining which actions to take to improve the health of shellfish populations. The scale of co-management is congruent with the complex and variable marine environment, allowing municipal managers to respond to fine-scale ecosystem changes. Knowledge brought to the committee can be integrated into decision-making within the co-management process to enhance and support the shellfish fishery.

3.3.3.4 Availability of capacity & resources

Partnerships facilitated much of the project team's ability to identify funds. The primary resource for the project came from the Broad Reach Fund on behalf of the Maine Shellfish Restoration and Resilience Project. Recipients of the funding must be fishermen, shellfish wardens, town officials, or other stakeholders in partnership with a town or nonprofit and should be involved with Maine's shellfish fisheries. The partnership between the committee and the University helped to secure three years of funding to support the beginning stages of the project and its first year of study. When the project developed to include local high school Lincoln Academy, anonymous donors provided additional support. Therefore, the partnerships inherent in the project were critical for obtaining the necessary resources.

The inclusion of local high school students also significantly increased the committee's volunteer capacity. In recent years, prior to the expansion of the project, committee-lead studies relied on the research efforts of University students. Historically, the committee solicited help from shellfish harvesters, by way of required 'conservation hours' for commercial shellfish license holders, to carry out conservation activities. Although many towns across the state have requisite conservation hours associated with commercial shellfish licenses, the Damariscotta-Newcastle committee chose to no longer pursue this approach. The partnership with local schools provides the means to complete the community science activities each year and establish the effort as a long-term monitoring project.

We would like to note that most funders or funding institutions function on a one- or two-year timescale, with the expectation that concrete results are reached by the end of the grant term. However, based on our experience and that of other community science projects, developing the trust and relationships required for community science takes time (Charles et al., 2020). There are no shortcuts, and although the generous grants we have received were pivotal in beginning this project, more time and resources need to be invested to see the full outcomes of this effort manifested. Project developers may need to think critically about how community science projects may be integrated into existing scientific research or ongoing educational activities with long-term funding sources. Allowing the time to fully develop a community science program is rare, and we hope that our program offers a strong case for the benefits of long-term approaches.

3.3.3.5 Credible trust & collective action

The partnership and trust between the shellfish committee and the University grew in large part out of the working relationship established during the 2019 and 2020 studies. Short-term projects of this nature help to establish trust through the sharing of knowledge, authentic requests for feedback, and the establishment of clear roles for the various parties involved. In the context of the project, trust was both performative and relational, built on an intimacy of communications and interactions between University researchers and the harvesting community. Trust was demonstrated by participants' willingness to connect in an ongoing way with University researchers and engage with the studies from the recruitment phase to the sharing back of results and the solicitation of feedback. The 2019-2020 studies strengthened relationships between the committee and the University, helping to solidify a sense of trust. The shellfish committee and harvesters continue to be willing to engage with University researchers, both by providing feedback and directly engaging with project activities. The desire to continue to interact with University researchers, and in fact increase the level of contact, indicates a development of trust.

The integration of local knowledge into the work has helped to begin to build trust among shellfish harvesters and those outside the harvesting community, primarily shown in their willingness to share their knowledge with individuals outside the community. However, tensions and skepticism still exist between academic researchers and commercial harvesters (Runnebaum et al., 2019). Continued efforts over the coming years to elicit harvester input and validate local knowledge as an integral component of the research is necessary to build trust. Further, efforts to involve harvesters in the research process as experts, for example by having harvesters demonstrate harvesting techniques to high school students participating in the project, are essential if a relationship of trust is to be established.

Regarding empowerment, the social and ecological knowledge results improve the committee's capacity to enact its management functions. Here, we define empowerment as having the tools, information, capacity, and agency to make decisions and take action to shape future outcomes at either the individual or community scale. The project aims to provide useful knowledge to support decision-making—an important tool for conservation and management. Although still in the early stages, the project creates a pathway through which students could be empowered to engage in their local environment and the coastal livelihoods it supports. Through place-based study, students improve their understanding of place, gain scientific and communication skills, and are given opportunities to interact with community members (A. L. Powers, 2004). Place-based education has been shown to increase civic engagement and environmental stewardship (Stevenson et al., 2014). The Damariscotta community science project is interdisciplinary and will require that students communicate results to community members. As a result, students are likely to develop better socio-ecological understandings of the Damariscotta and become more engaged in the human and environmental processes that play out in this environment. The annual level of student engagement with both the project and with the community at large will serve as indicators of empowerment.

Our project demonstrates that community science may be an appropriate option for shellfish committees that have low engagement or a small pool of harvesters to support conservation initiatives. Shellfish committees with low engagement may be able to most benefit from community science and the influx of volunteer student scientists. Perhaps this is a model that works best when other models–for example required conservation hours–fail to produce results.

3.3.3.6 A framework addition: Data quality & communication

One aspect of the community science process that was not explicitly discussed (although certainly referenced) by Charles and colleagues is the condition that community science produces quality data, and that this data is effectively communicated to the community. At the core of the Damariscotta community science project is the question: Does the project provide the shellfish committee with the information that they need? We are in a unique position because the scale of our research matches the scale of the co-management system–both focus on local systems at the scale of the municipality. Commonly, there is a mismatch between ecological and management scales that limits the ability of resource managers to respond to fine-scale changes in coastal ecosystems in time to avoid negative social-ecological impacts to the system (Wilson, 2006). The fact that the data collection and data analysis are occurring at the same scale as management means that the results can directly answer management questions with a specificity that is difficult to reach in research-management relationships at the state, regional, or national level.

Our project has communicated the project results through informational meetings with the shellfish committee, the Town of Damariscotta Board of Selectmen, the University, and the community at-large invited to a public event. We have also produced technical reports to share our results (Britsch, Risley, et al., 2021; Pellowe & Leslie, 2019) and presented the results to local elected leaders as well as at the statewide 2020 Maine Fishermen's Forum and 2021 Maine Water and Sustainability Conference. However, there is still a gap in communicating information that is immediately useful and meaningful to the shellfish committee. While the first-year data provide information on how the Damariscotta compares with neighboring estuaries and laid the groundwork for more extensive social science data collection, more data is required to understand how shellfish populations are changing through time. Further, the learning process continues in terms of how best to present project data. For example, we are reflecting on questions such as: Is it meaningful to share shellfish abundance data as the number per square foot or square yard, or is there a more effective metric? Or how can shellfish ecological survey data best inform site selection for conservation efforts? These are questions that we will continue to tackle during the coming years of the project and are challenges that other communities applying community science to shellfish co-management will surely encounter.

3.4 Conclusions

This paper uses Charles and colleagues (2020) community science typology to examine a model of a community science in Maine, USA. It explores how community science generates ecosystem-level information to support decision-making, fosters place-based learning, and links knowledge sources by creating horizontal discussions among local and scientific knowledge holders. It discusses how the key conditions of community science programs such as this are suited for long-term, ecosystem-level explorations of coastal co-managed fisheries. Two main takeaways were identified from the analysis of this project.

3.4.1 Community science can be an effective approach to studying co-managed fisheries

The development of this project revealed compelling connections between community science approaches to research and co-management systems for fisheries. For one, co-managed fisheries are inherently community-based. The Damariscotta-Newcastle shellfish committee includes diverse members of the local community, including shellfish harvesters and marine researchers. Through existing connections and its local scale, co-managed fisheries are well-equipped to launch community science programs. The shellfish committee is also an accessible institution with a collective leadership structure–any community member may attend these meetings and the horizontal structure of the committee itself allows for community voices to be shared and heard, particularly those of local knowledge holders. Second, because co-managed fisheries systems often lack the capacity to obtain current data on species populations, community science programs are an effective means to increase capacity by involving volunteers, students, and researchers into the management process.

3.4.2 Community science is, by its nature, an ecosystem-level approach to research

Community science is also effective for coastal ecosystems, particularly intertidal ecosystems, because they are accessible environments in which community members already engage in through other activities. For example, in the case of our program, a boat or other costly equipment is not required to access our study sites. Students and volunteers can simply walk into the intertidal mudflats and begin their research. These habitats are also extremely visible and well-known by the community at-large. The Damariscotta estuary and the shellfish fishery is of great cultural and historic importance to many residents. Through our work, we found that these conditions were well-suited to conducting community research, because local community members are already invested in these habitats and species. This focus on the environment is advantageous because it lays the foundation for a research program that emphasizes the importance of the ecosystem, including its human uses, from the program's inception. This positions the program to be ideally suited to addressing real world questions by generating information that extends beyond a single-species and encompasses the ecosystem.

CHAPTER 4

CONCLUSIONS

Dynamic marine coastal environments pose unique stewardship and conservation challenges (Levin & Poe, 2017). Ultimately, supporting resilient SESs and their small-scale fisheries requires novel research and EBM approaches that integrate social and ecological dimensions (McLeod & Leslie, 2009). This thesis explored how linking local knowledge and community science approaches can bolster EBM and coastal stewardship. Used together, these approaches can lead to robust social, ecological, and spatial data across long timescales to understand change in variable marine coastal SESs. While many researchers explore local knowledge and community-based research independently, here I highlighted their connections and model how they can be applied to small-scale coastal fisheries.

Chapter 2 examined how local knowledge can inform understandings of ecosystem change and relationships among human and non-human species in coastal SESs. The results documented a snapshot of the spatial distribution of shellfish populations and human use activities in the system. The maps generated from this study are useful tools to identify areas of overlap between human activities and highlight locations of importance in the estuary for shellfish populations. In the future, this information could be applied to spatial planning by helping to identify how and where conflicts may arise between certain human activities or how ecosystem services could be enhanced or conserved (Klain & Chan, 2012; Moore et al., 2017). Additionally, the shellfish population distribution and diversity data provide a valuable spatial baseline from which the Damariscotta-Newcastle shellfish committee can benchmark change in shellfish populations going forward.

Study interviews also documented study participants' observations of change, and their hypotheses about what is driving those changes. I proposed that the observed hypotheses and drivers can frame a dialogue between existing scientific knowledge and future research, and outline approaches to address potential conflict among diverse uses in the system. I emphasized that the generation of local knowledge hypotheses is valuable because it can directly inform future research by prioritizing specific variables or relationships among the ecosystem, humans, and non-human species that could benefit from further study. Research that addresses these hypotheses can in turn support responsive and effective management through the generation of locally relevant, place-based knowledge.

Perhaps most importantly, the local knowledge results equipped us with the foundational information to move forward with an integrated ecological and social community science research initiative of our own. As the project continues, we hope that it demonstrates how leading research with local knowledge is critical to supporting actionable and responsive research and management by: (1) characterizing the social-ecological system at a fine spatial scale; (2) highlighting stakeholders' priorities and observations; and (3) generating hypotheses about how and why the system is changing, and what drivers may be influencing these changes.

Chapter 3 explored how the characteristics and process of a community science project support community-led ecosystem-based shellfish fisheries management. Using a typology of community science (Charles et al., 2020), I assessed the conditions for community science and how it can generate ecosystem-level information and link knowledge sources by fostering dialogue among local and scientific knowledge holders. The work revealed two primary conclusions: (1) community science can be an effective approach to studying co-managed fisheries and (2) community science is, by its nature, an ecosystem-scale approach to research.

The first conclusion was linked to the small scale of co-managed fisheries and the community engagement inherent to this system of governance. The second, community science is an ecosystem-level approach to research because it integrates social and ecological dimensions of the system and is led by community stakeholders who see the dynamic, multidimensional uses and relationships that occur in SESs. This work underscores that by beginning with local knowledge and community engagement, research can address real world, ecosystem-level questions.

Together these research projects represent a journey through engaged, community-based research in a coastal social-ecological system. The work highlights how the integration of diverse knowledges and community partners can contribute to holistic understandings of dynamic marine coastal systems and support ecosystem-based approaches to stewardship and management. These approaches can be applied to fisheries locally and regionally and have the potential to support management to address pressing challenges in marine coastal environments in Maine and beyond.

It should also be acknowledged that our research team completed this work during the COVD-19 pandemic. While the pandemic presented logistical challenges, it also offered opportunities to reimagine the research process and approach our questions from a different perspective. It is likely that the participatory mapping study that inspired this research effort would not have occurred, or at least not at the same scale or scope, in a world without the pandemic. Despite the tragedy, collective sadness, and incredible loss of human life, this work serves as a reminder that challenges breed creativity and that learning from one another can continue, even under challenging circumstances. At its heart, this work is about connections among people who care deeply about a place and its future.

Importantly, this work modeled an innovative mode of participation that may be appropriate for future participatory studies. Our study was unique in that it pursued a fully remote approach to participatory mapping and semi-structured interviews. Every step of the research process occurred at a distance—study maps were distributed and returned by mail and interviews took place solely over the phone. The success of this study can be attributed largely to a precise research design and a significant upfront investment in study design, planning, and recruitment. Our research group conducted extensive testing of all participatory mapping materials to ensure instruction clarity and ease of use of the participatory mapping booklet. We also dedicated a significant amount of time to outreach, completing multiple points of contact during the recruitment process and adjusting the timing of both our recruitment calls and interviews to align with our study participants' schedules. This meant numerous evening phone interviews, frequent call backs when cell phone signals dropped (a common occurrence in rural Maine), and conversations with family members to help reschedule interviews that were accidentally missed. In hindsight, this remote mode of participation was well-suited for our target population, which included individuals who often worked multiple jobs with changeable schedules and others who simply preferred the comfort of their own homes over face-to-face interactions in unfamiliar places. Remote modes of participation may be a way forward for participatory research in rural locations with hard-to-reach participant populations. Through our remote study, we were able to connect with many Maine residents whose voices may otherwise have not been heard.

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APPENDIX A: DETAILED DESCRIPTIONS OF THE FOCAL ESTUARIES

Damariscotta River estuary: oysters, aquaculture, and tourism

The Damariscotta River is a tidal estuary that stretches 19 miles (30 km) between the towns of Newcastle, Nobleboro, Damariscotta, Edgecomb, South Bristol, Bristol, Boothbay, and Boothbay Harbor, Maine (Fig. A.1) (Chandler, 2016; McAlice, 1977). The estuary originates in Great Salt Bay, where the fresh waters of Damariscotta Lake empty into the estuary at the Damariscotta Mills dam. Despite these freshwater inputs, the estuary is classified as tidally dominated with moderate to high salinity levels (19-32 ppt) in the upper portion north of Glidden Ledges, ranging to full-strength seawater salinity (35 ppt) from the middle to the mouth of the estuary in the south (Maine EPSCoR, 2022). The Damariscotta is home to varied marine habitats, including rocky intertidal zones, eelgrass beds, rocky bottom, and salt marshes, but largely consists of soft, fine sediment bottom with areas of extensive mudflats (Anderson et al., 1981; Anderson, 1974; Chandler, 2016). The estuary can be divided into three intertidal habitat zones (Fig. A.1).

The Damariscotta River has multiple locations where the channel narrows significantly, constricting the flow of water and creating distinct basins. One such basin occurs in the upper river between the mouth of Great Salt Bay and Glidden Ledges (Fig. A.1). Here, water can be retained for four or even five weeks in the summer months (McAlice, 1977). This long retention period contributes to warm water temperatures in the basin. Late summer water temperatures within the upper basin can reach 68-77 °F (20-25 °C), while temperatures range from 59-68 °F (15-20 °C) in the lower part of the estuary (Maine EPSCoR, 2022). As a result of these warmer temperatures, the upper estuary is an ideal location for the growth of many shellfish species, including wild-harvested soft-shell clams (*Mya arenaria*) and quahogs (*Mercenaria mercenaria*), as well as farmed American oysters (*Crassostrea virginica*).

Commercial activities, including wild shellfish harvest and shellfish aquaculture, are common throughout the estuary and provide essential income for many residents. Lobster (*Homarus americanus*), menhaden (also known as pogies) (*Brevoortia tyrannus*), marine worms (*Glycera dibranchiata* and *Nereis virens*), as well as sea scallops (*Placopecten magellanicus*) and elver (*Anguilla rostrata*) are commercially harvested in the estuary (Maine DMR, 2022b). There are approximately 17 aquaculture farms and 29 aquaculture leases in the estuary that produce shellfish, including American oysters, mussels, and experimentally scallops, as well as kelp (Maine DMR, 2022a). Commercial fishing and aquaculture contribute considerably to the local economy. In 2020, the value of publicly available landings of quahogs, soft-shell clams, razor clams, and lobster from Damariscotta, Boothbay, and South Bristol totaled $5,638,554 (Maine DMR, 2022b). Additionally, the 2019 dockside value of oyster aquaculture harvest in Maine was approximately $9.7 million, $6,575,668 (~68%) of which came from the Damariscotta River (Maine DMR, 2020).

The Damariscotta River is also host to numerous recreational activities and a thriving tourism industry. Boating activities, such as motor boating and kayaking, are popular throughout the estuary, as are shore-based activities such as hiking and wildlife viewing. There are multiple recreational and tourism business outfits that cater to these recreational needs, including regional staples like the River Tripper, a local wildlife and oyster farm tour boat that docks in the Damariscotta Town Harbor. The extent and intensity of recreation has increased during the pandemic, as in many other communities nationwide, contributing to even more active summer tourism seasons for the estuary than in years past (Rice et al., 2020).

Medomak River estuary: soft-shell clam

The second study system, the Medomak River, is an approximately 10-mile (6 km) estuary also located in midcoast Maine. The Medomak River estuary is situated to the northeast of the Damariscotta River and traverses the towns of Waldoboro, Bremen, and Friendship (Fig. A.1). Its headwaters are sourced near Coastal Highway U.S. in Waldoboro, Maine and the estuary flows southward until it reaches broad Muscongus Bay (Mills et al., 2020). The Medomak River is relatively wide with broad mudflats that border the estuary's deep central channel (Hillyer, 2019). Beyond its prominent mudflats, the Medomak River is also home to salt marshes and eelgrass beds (Hillyer, 2019; Mills et al., 2020). In contrast to the Damariscotta River, the estuary has only one distinct narrowing point located at Havener Ledge (Fig. A.1). The narrows here separate the Medomak River into one upper and one lower basin. In later summer, upper basin water temperatures reach 68-77 °F (20-25 °C), while the lower river reaches 59-68°F (15-20 °C) (Thornton & Mayer, 2015).

The Medomak is renowned for its soft-shell clam fishery and is frequently reported as the Maine town with the highest landings in the state (Hillyer, 2019). Other commercially fished species include lobsters, quahogs, razor clams (*Ensis directus*), elver, menhaden, and marine worms (Maine DMR, 2022b). Commercial fishing contributes considerably to the local economy, and in 2021 the value of publicly available landings of quahogs, soft-shell clams, razor clams, and lobster from Waldoboro and Bremen totaled $2,911,322 (Maine DMR, 2022b). There are less than 10 aquaculture farms located in the estuary, growing shellfish and kelp (Maine DMR, 2022a).

The Medomak River is a quiet estuary in terms of human activity in comparison to the Damariscotta. Although the estuary is extensively fished, it experiences light recreational use.

Occasional recreational motor boating occurs throughout the river, while sailing is popular in the southern portions of the river nearest Muscongus Bay. Activities such as kayaking have increased in frequency over recent years, and the estuary's conservation lands are a destination for hikers and sightseers. The estuary is also home to multiple Maine Island Trail Islands with boat accessible campsites, as well as Keene Neck and Hog Island (owned by Maine Audubon) that play host to summer camps and other seasonal visitors (Maine Audubon, 2022; Maine Island Trail Association, 2022).

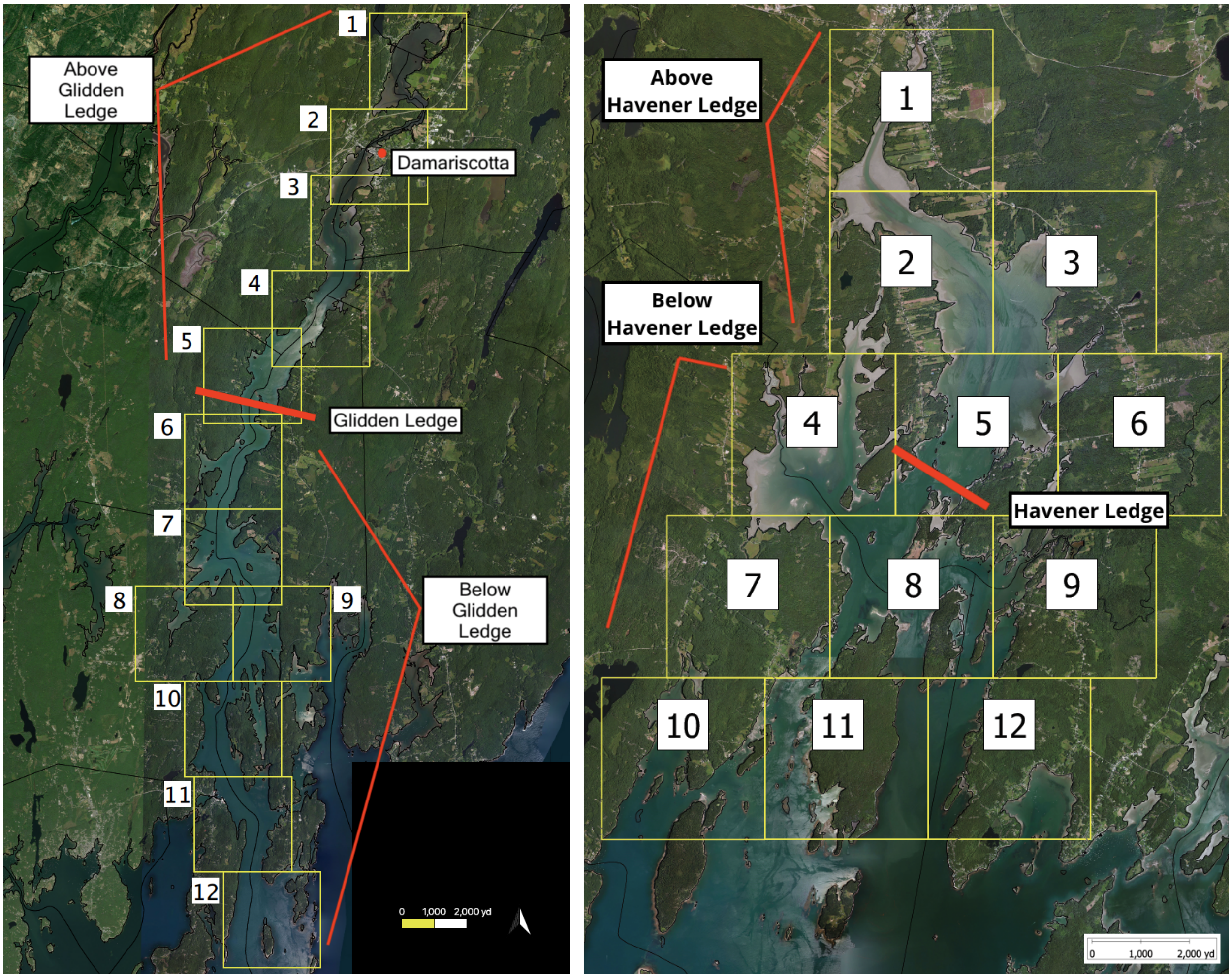


Figure A.1 Upper and lower sections of the Damariscotta River estuary (left) and Medomak River estuary (right). Glidden Ledges divides the Damariscotta into two sections (as delineated by the red lines) with distinct characteristics, while Havener Ledge divides the Medomak into two sections. The numbered squares (1-12) denote the sections of the river where participants were asked to share their knowledge.

APPENDIX B: LOCAL KNOWLEDGE MAPPING STUDY METHODS

B.1 Local knowledge mapping study

We used maps to gather information about overlapping species and human uses in the Damariscotta River Estuary. These were then followed by interviews with all participants.

B.2 Participant recruitment

We divided the study into two types: USE, which was oriented towards human use activities like recreational boating or aquaculture, and SHELLFISH, which was oriented towards commercial shellfish harvesting (See Table B.1 for a breakdown of types of participants in each study). All participants needed to have experience with the rivers and be active on the river within the last 2-3 years.

	Study Type	
	General User	**Shellfish Harvester**
Participants	Recreational users	Commercial shellfish harvesters
	Lobster fishermen	Recreational shellfish harvesters
	Aquaculture farmers	Commercial marine worm harvesters
	Harbor masters	Shellfish committee members
	Harbor committee members	
	Local business owners and employees	

Table B.1 Descriptions of potential participants for each study type.

We identified participants using town recreational and commercial shellfish license lists, state commercial shellfish, lobster, and worm harvesting license lists, and our prior knowledge of people involved in the aquaculture industry, environmental conservation, and waterfront businesses. We prioritized contacting people who live and work in Damariscotta, Newcastle, and Bremen, but also contacted participants from other towns surrounding the estuaries, including Bristol, South Bristol, and Waldoboro. During the initial recruitment phone call, participants were asked about their knowledge and activity on the estuaries; this information was used to determine whether they got stickers related to the USE or SHELLFISH. No map packets were sent unless a potential participant agreed to participate in the study.

Due to COVID-19 restrictions, we mailed the maps to participants, who filled them out by placing stickers representing different species or uses onto the maps and returned them in the mail. We sent our participants a map packet, stickers corresponding to either shellfish or general use activities, and areas of significant change (Table B.2), and a pen for writing notes. We also sent an overview map showing the entire estuary (Figure B.1) with boxes representing individual pages in the map packet, which divided the river into smaller, zoomed-in sections. We overlaid a grid on each of these map packet pages to help with sticker placement and data entry (Figure B.2). Terrestrial areas and areas with less than 25% water coverage were hashed out to reduce confusion.

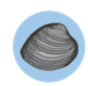
Survey	Image	Description	Survey	Image	Description
General User		Aquaculture	**Shellfish Harvester**		Soft-shell clam abundance (low)
		Recreational Fishing			Soft-shell clam abundance (medium)
		Sailing			Soft-shell clam abundance (high)
		Tourism & Sightseeing			Razor Clams
		Kayaking			Quahog/Hard Clams
		Area of Significant Change			Wild Oysters
					Marine Worm Digging
					Area of Significant Change

Table B.2 Stickers for the two types of surveys (use and shellfish, left and right, respectively) for the participatory mapping study. Participants received only one version of the study. **(**Sticker Size: 0.5").

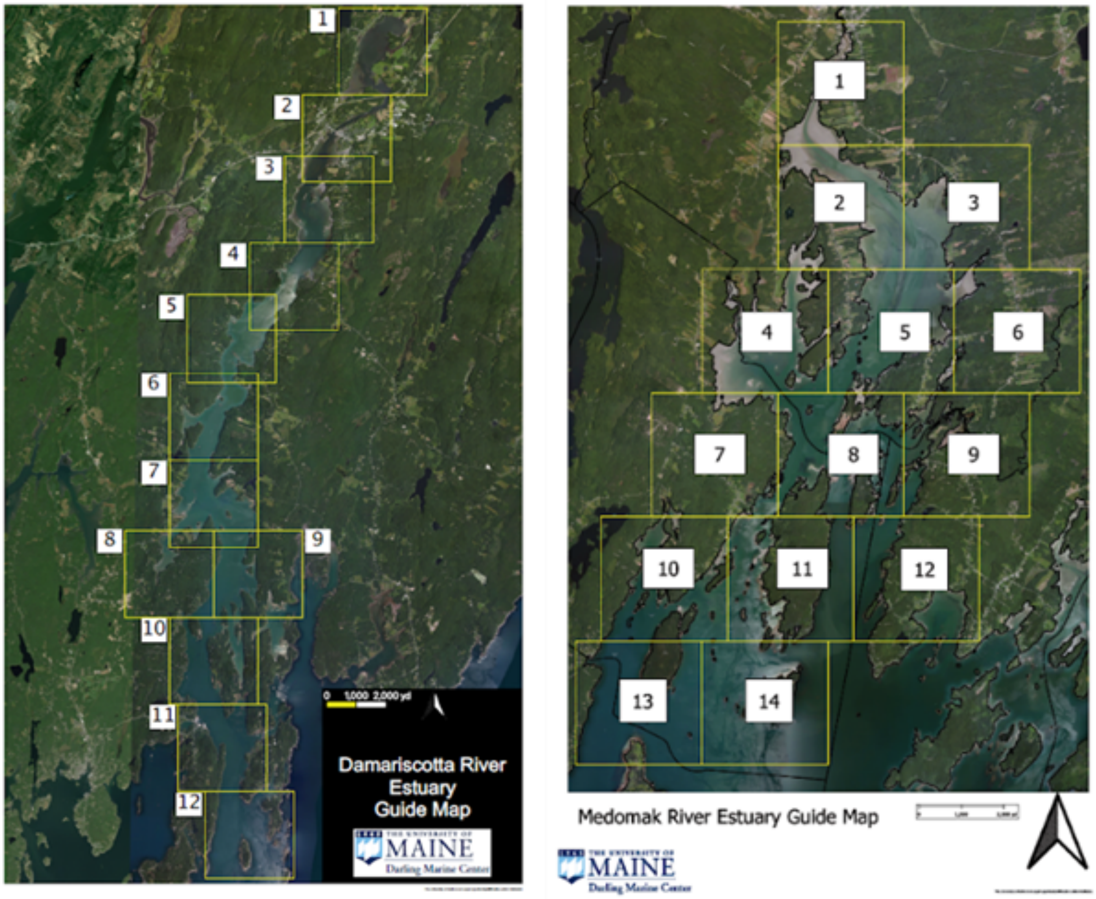


Figure B.1 Guide map of the Damariscotta River estuary (left) and Medomak River estuary (right). Each numbered box represents a different page in the map packet.

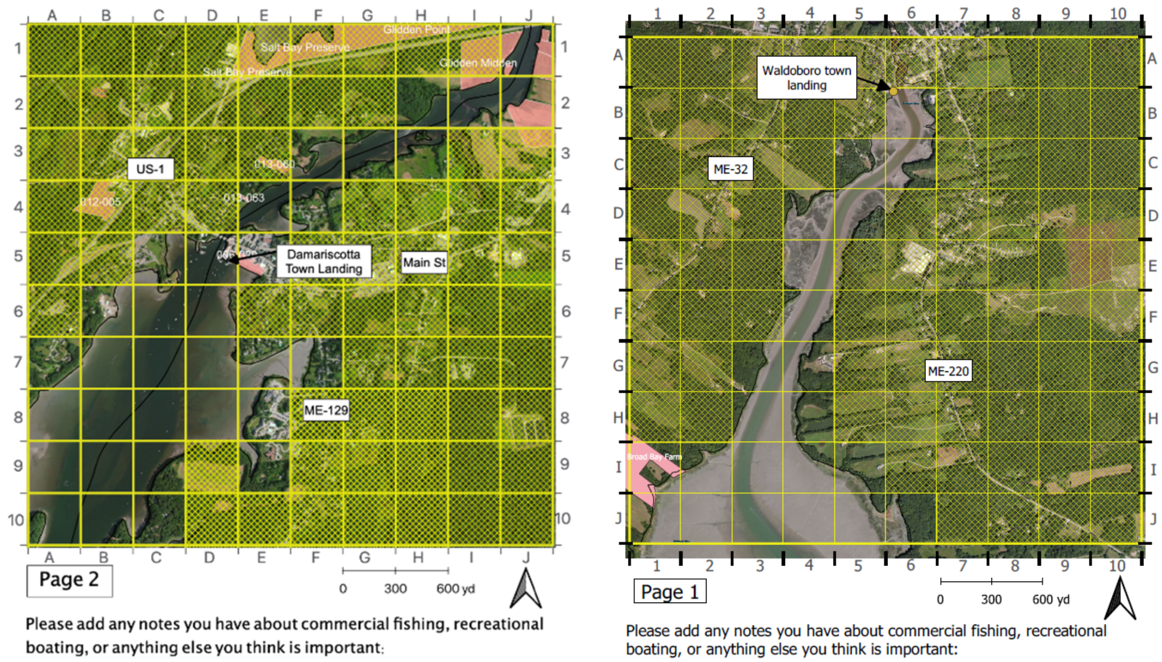


Figure B.2 Example of a page the Damariscotta River estuary (left) and Medomak River estuary (right) map packets. The unfilled grid cells will be filled with stickers, while the boxes hashed out in yellow will not be filled. All remaining pages in both map packets are similar.

Participants were sent stickers associated with common intertidal shellfish in the estuary or different human uses (Table B.1). They were instructed to 1) place stickers onto the unfilled grids in the map packet to represent where different shellfish or uses occurred, 2) write an 'X' mark to indicate that no activity occurred in a grid square, or 3) write a '?' mark to indicate that they did not know which activities occurred in that place. Participants were encouraged to write notes on the map to provide additional context and identify species or activities that were not represented in the stickers. Participants were asked to fill out entire map pages but were allowed to only fill out the map sections they felt most comfortable with. Participants filled out an average of 6.5 pages with a range of 1-12 pages completed (Figure B.3 for an example of a completed map page).

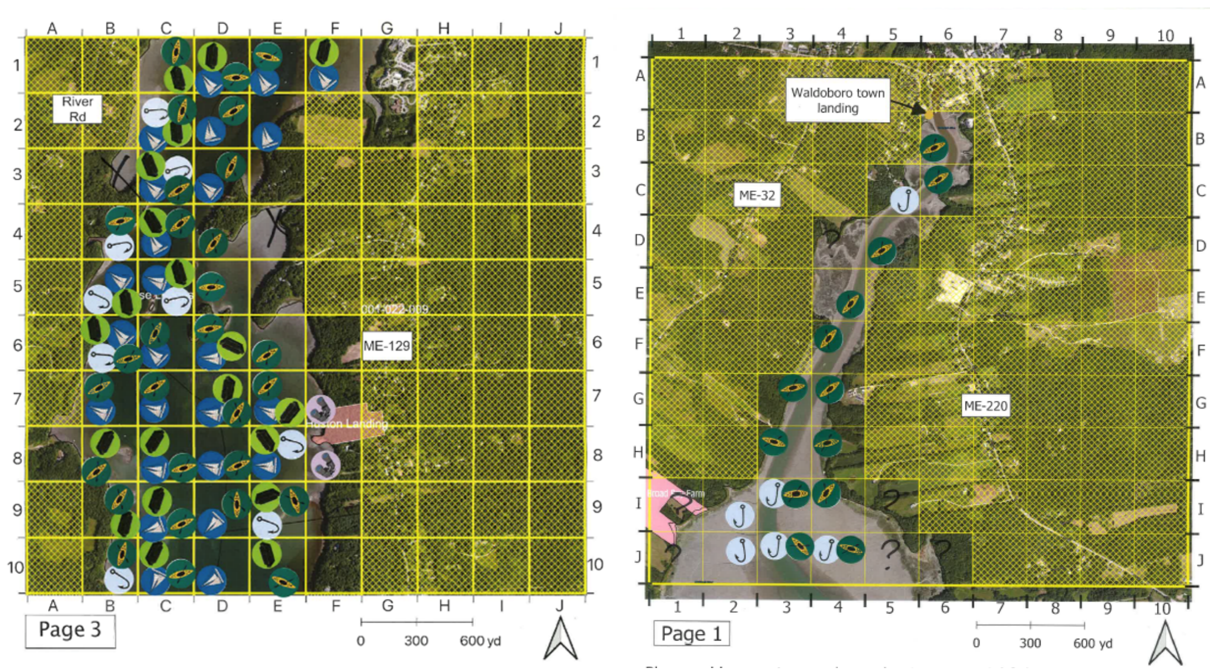


Figure B.3 Example of a filled in map page from a Damariscotta River estuary "General user" study (left) and a Medomak River estuary "General user" study (right).

B.3 Local knowledge interviews

We used semi-structured interviews to clarify responses to the mapping exercise and learn about changes that have occurred in the estuaries over time. This interview process was approved by the University of Maine Institutional Review Board (IRB) (#2020_06_16_Risley). These interviews were completed after the maps were finished and were an opportunity to debrief the mapping exercise, provide additional context to the maps, and learn about change in the estuary over time. These interviews took place over the phone and were between 30-60 minutes. Participants were asked if they knew what caused the changes they have observed, their responses to those changes, and if there were other factors the study should consider to understand use and change on the river. We also asked participants if we missed any species or activities in the estuaries. The follow-up interviews were scheduled to take place shortly after the mapping study was completed; they were usually scheduled during the initial recruitment process for a date about two weeks after participants were expected to receive the maps. This was intended to serve as a deadline for map completion and we did not do the interview until the participant finished the map. Participants were instructed to text or email pictures or scans of the maps to the researchers before the interview so that researchers had a digital copy of the completed map, and the participant had the paper map to reference in the interview. The combination of the mapping study and follow-up interview were intended to add context to the maps, generate common local hypotheses about drivers of change in the estuaries, and help identify study topics and locations for future research in the estuaries.

B.4 Analysis

Map data

The maps were created using QGIS (Version 3.12). Each individual map page covered an area that was 3000 x 3000 yards, and each of the grid cells within the map page covered an area of 300 x 300 yards. We assigned each grid cell a unique identifier and calculated the centroid, which was the value pulled into spreadsheets and used to recreate the maps later in R.

As maps were returned, each individual map was digitized, and the sticker information was manually added to a spreadsheet. Individual maps were then aggregated to show the overlap of information for the river. This data was then turned into maps. To preserve confidentiality, grid cells with fewer than three stickers of a given type were not shown on the final maps. We needed to have more than three stickers of a given type for that data to be shown on the final map.

The aggregated maps of sticker data were used to create maps showing the density of stickers for USE, SHELLFISH, and individual activities or species like soft-shell clams. We also asked participants about the relative density of soft-shell clams (high, medium, or low), and this information was converted into maps to show the spatial distribution and density of clams or other species and activities in the river. This data was also compiled with existing databases like the Maine Department of Marine Resources aquaculture lease map, to show both individual and overlapping activities in the estuary. All maps were made in R (Version 1.2.0553).

The shellfish maps were used to identify areas of high shellfish density for forthcoming community science shellfish monitoring initiative. These maps will help scientists target future fieldwork and will help the towns understand the distribution of their shellfish resources, as well as how they have changed over time. Additionally, understanding how activities overlap will help managers at both the state and municipal levels anticipate use conflicts in heavily used areas and manage the estuary as an ecosystem instead of managing individual species or uses.

Interview data

The interviews were recorded and then transcribed. We used the online audio transcription service otter.ai for the initial transcription and then manually corrected the interviews. We analyzed the interviews using NVIVO (MLB: Pro 12, SCR: Version 2). MLB and SCR designed the codebook and coded four interviews together for practice. Their intercoder reliability was >90% in nearly all nodes. After the initial coding was complete, we pulled the information about specific topics, like species in the estuary, and added that information to spreadsheets for a second round of coding and to build tables.

We analyzed river activities by counting each participant who mentioned a specific activity, and then grouping those activities into more general categories. We also counted each mention of the location of a specific activity and then grouped these locations into three broad categories: 'Above Glidden Ledges', 'Below Glidden Ledges', and 'Whole River'. The tables related to the shellfish resource were generated by summarizing participant descriptions of shellfish habitat and distribution. Only characteristics that were identified by three or more participants were included in these summaries.

Figures relating to changes identified by participants were generated using a two-step process. Changes identified by participants were first grouped into broad categories, for example 'Aquaculture Activity' or 'Erosion / Sediment'. Each change was coded as a +1, -1, or 0 depending on if the participant referred to an increase/positive change, decrease/negative change, or no change. Next, broad categories were further grouped into top level categories and the total net score (based on the sum of the +1/-1/0 codes) was calculated.

APPENDIX C: INTERVIEW GUIDE FROM LOCAL KNOWLEDGE MAPPING STUDY

General Characteristics

1. What is your age?
2. What is your gender? Male/Female/Nonbinary
3. Where were you born? (Town and state)
4. Where do you live now?
5. (If other than where they were born) How many years have you lived in [the current location?]

Place-based Experience

6. Please tell me how you spend your time on the [Damariscotta/Medomak] river.
7. During what times of year do you spend time on the [Damariscotta/Medomak] river?
8. How many years have you been harvesting/recreating/using the river?
9. Where do you primarily harvest shellfish/sea farm/boat/etc.?
    a. How frequently? (Ask to reference maps)

[For harvesters only]

10. Which species do you harvest? (If soft-shell clams: how would you describe high, medium, and low abundance?).
11. What is the habitat like where you find that species?
12. What other types of shellfish do you find in the intertidal mudflats?
    a. What is the habitat like where you find that species?

13. Are there predators that affect that shellfish species (positively or negatively)
14. What environmental or river use factors affect shellfish species (positively or negatively)?
15. What environmental or river use factors affect predator species (positively or negatively)?
16. Where do you access the river from? (Ask to reference maps)
    a. Has that changed over time? If so, in what way?
17. What are the most common activities that you observe on the river?
    a. Where do they take place?
    b. When do they take place?
    c. Have they changed? If so, in what way?
    d. Have you observed any commercial fishing on the river?
        i. If so, what types?
        ii. If so, where does it take place?
        iii. If so, during which times of the year?
    e. Have you observed any recreational boating on the river?
        i. If so, what types?
        ii. If so, where does it take place?
        iii. If so, during which times of the year?
18. During or after completing the mapping exercise did you notice any patterns in the stickers? Can you describe them?
    a. If you feel that kayaking/sailing, etc. are widespread, have you noticed any areas where it is particularly common, like a hotspot of activity?

b. Where did they take place?

c. What do you think caused those patterns?

d. For razor clams, quahogs, and wild oysters are the densities uniformly distributed across the estuary?

    i. If not, in what ways do they vary?

19. What has changed on the river since the start of your career/use to present? [Prompt to discuss economic, social, and environmental changes

    i. Did you use the significant change sticker? If so, where/why?

b. How has the river changed? Is the change uniform across the river?

c. Where have those changes taken place?

d. When did you start to notice them? Did they occur quickly or over time?

e. In your opinion, how would you rank the most significant changes (up to 3)?

f. In your opinion, what do you think caused those changes? (Ask specifically about the 1-3 changes listed)

g. Have those changes impacted how you use the river? In what ways?

h. Have those changes impacted how others use the river? In what ways?

20. Is there anything else you would like to add? Or any questions for us? Suggestions of what we might consider.

Debriefing

21. Did you have any problems completing the mapping exercise?

22. Question about uses of the river (split by initial allocation of stickers)

    a. River Use participants:

i. You were a Use Expert, so you received stickers for aquaculture, recreational fishing, sailing, kayaking, tourism & sightseeing, and areas of significant change. We also asked other participants about shellfish populations and marine worms. Between these two groups, did we miss any important activities or species in the river?

b. Shellfish Harvester participants:

i. You were a Shellfish Expert, so you received stickers for high, medium, and low abundances of soft-shell clams, as well as the locations of razor clams, quahogs/hard clams, wild oysters, marine worms, and areas of significant change. We also asked other participants about aquaculture, recreational fishing, sailing, kayaking, and tourism & sightseeing. Between these two groups, did we miss any important activities or species in the river?

23. Do you know anyone else who might be interested in taking this study?

APPENDIX D: CODING SCHEMA & DEFINITIONS

Table D.1 Participatory mapping coding schema. Schema includes top level themes (bold), secondary themes (italic), and secondary theme definitions (plain text).

Access								
Access: Physical	*Access: Financial*	*Access: Legal*						
Participant refers to access to a physical place, such as the town boat ramp or shoreline. Also includes mentions of where a participant accesses the river from.	Participant describes limited access due to financial barriers. For example, limited access to certain fisheries due to the cost of the license.	Participant discusses legal restrictions that limit access. For example, the move from state to town licenses that limited access to only town of residence mud flats. Also flat closures.						
Change								
Change: Species Change	*Change: Spatially Widespread*	*Change: Spatially Isolated*	*Change: Physical habitat*	*Change: Access*	*Change: Demographic*	*Change: Uses*	*Change: Aquaculture*	*Change: Economic*
Participants mention changes in the abundance and distribution of species	Participants describe a change that occurred over the entire river system (sub-codes for gradual vs. rapid change).	Participants describe a change that occurred over a small area of the river (sub-codes for gradual vs. rapid change).	Participants describe changes that explicitly reference the physical habitats of the river, like sediment, temperature, salinity, depth, etc.	Participants mention changes in how they access the water.	Harvester changes, property ownership, general demographics, loss of young people.	Kayaking, paddleboards, boating, sailing (Decrease)	Sub-codes: Aquaculture growth, Aquaculture ecosystem effects.	Like changes in fisheries or increases in tourism. Discussions about the opportunities that aquaculture provides will be coded separately in "Economic Opportunity"

Table D.1 continued.

Climate Change								
Climate Change: Sea level rise	*Climate Change: Water temperature*	*Climate: Changes in Seasons*						
Participant discusses observations of sea level rise in the river.	Participant refers to warming water temperature and its possible effects.	Participant references milder winters, longer summers, and the possible effects.						
Conflict								
Conflict: Crowding	*Conflict: Tourism*	*Conflict: Shore Use*	*Conflict: Worm harvesting industry*					
Participant discusses conflict related to crowding in the river. This includes boat activity (kayakers vs. powerboats, sailing vs. aquaculture lease sites) in the open water, or crowding in important public spaces like boat launches.	Participant describes conflict related to tourist activity in the river. This includes issues related to increased noise pollution due to tourist activity or concerns related to inexperienced tourist boaters.	Participant describes conflict related to accessing or using the shore or intertidal zone. This most often relates to access to the shore for shellfish harvesting activity.	Participant describes conflict related to marine worm harvesting activity.					
Demographics								
Age	*Gender*	*House Location*	*Occupation*	*Use Frequency*	*Use Location*	*Use Season*	*Use Years*	
Age of participant.	Gender of participant.	Location of current home.	How the participant uses the river. Can be occupation or other experience using the river.	Number of times per week/month/year that participant is on the river.	Locations in the river used most frequently by the participant.	Season of use/activity on the river by the participant.	Number of years the participant has used the river.	

Table D.1 continued.

Development & Growth								
Development: House-Dock Construction	*Development: Long-Term Population Growth*	*Development: COVID-19 Growth*	*Economic Opportunity*					
Participant describes the building of new homes or infrastructure on the river. For example, the building of docks and the development of previously uninhabited land.	Participant discusses long-term trends in population growth. For example, the popularity of Damariscotta as a retirement location and the subsequent increase in seasonal or year-round residents.	Participant discusses the short-term population growth as a result of the COVID-19 pandemic. For example, increased housing prices as a result of more people permanently moving to Maine to get away from big cities.	Participant discusses economic opportunitie s related to the river systems. Due to aquaculture, growth of tourism, or the return of commerciall y important marine species.					
Hypothesis								
Hypothesis: Hypotheses	*Hypothesis: Drivers*	*Hypothesis: Hyps about the resource*						
**The hypotheses are any description of change that has a clear driver, so the participant articulates why a change has happened. This node is developing. For now, we're coding all changes to this node and will subdivide if needed. We'll code positive and negative interactions later*	Within the coded hypothesis, code the thing causing the change. This may need to be further subdivided?	This can also include ideas from harvesters about why clams declined in the first place and what they think needs to be done (like turning the mud regularly) to improve the health of the clam resource.						

Table D.1 continued.

Local Knowledge (LK) Ecological Understandings								
LK: Complexity	*LK: Cycles*							
When participants are talking about environmental processes, they refer to the complexity of marine ecosystems - this is usually a comment in reference to the difficulty in predicting environmental change and/or the difficulty of understanding why things have changed. They refer to "mother nature" and trust in nature to find a balance and recover from disturbance.	When participants are talking about environmental processes, they refer to nature as cyclical. They might seem unconcerned about current declines because they have seen increases and declines in the past. This might also be a comment about the difficulty of making predictions and understanding change							
Management (Mgmt)								
Mgmt: State	*Mgmtt: Town Licenses*	*Mgmt: Conservation Efforts*	*Mgmt: Uncertainty*	*Mgmt: Power*	*Mgmt: Illegal Harvest*			
Participant describes management of the rivers/species and refers to state-level agencies like DMR	Participants describe management rivers/species and refer to town-level management, including shellfish and harbor committees. This will likely mostly involve the management of shellfish. *Updated to include general comments about town licenses that don't mention access changes	Participants describe things that are or could be done to contribute to shellfish management. This includes shellfish committee conservation work and proposed alternative methods, like closures or brushing.	Participants mention difficulties navigating the management system, either for themselves or others. This could include uncertainty about how the management system works or observed uncertainty of other people.	Participant mentions power imbalances between harvesters /users and management agencies (either state or town).	Participant mentions 'illegal' or unpermitted/ unlicensed harvest of species from the river.			

Table D.1 continued.

Power								
Power: Hierarchy among river user groups								
Participant refers to hierarchy or class structures/economic inequality that influence access, control, or decision-making in the river system.								
River Activities								
Activity Seasonality	*Activity Intensity*	*Activity Location*	*Aquaculture*	*Commercial Fishing*	*Other*	*Rec Boating*	*Rec Fishing*	*Research*
Participant describes the time year when certain river activities take place.	Participant describes the density and intensity of activities in different parts of the river. For example, the participant mentions an increase in kayaking or an area of high boat traffic.	Location of activities, including shellfish harvesting.	Aquaculture	Sub-codes: Elvering, Lobstering, Other Commercial Fishing, Shellfishing		Sub-codes: Kayaking, Motorboating, Other Boating, Sailing		Participant describes research activities that they have observed, lead, participated in, or heard about on the river.
River History								
River History								
Participant mentions activities that took place on the river or species that were present >100 years ago								

Table D.1 continued.

Sediment								
Sediment: Erosion	*Sediment: Suspension*	*Sediment: Restructuring*						
Participant describes shore loss due to erosion.	Participant discusses suspended sediment in the water column and its possible effects. For example, suspended sediment due to bottom aquaculture dragging.	Participant describes changes in the channel shape, sand bars, or other structures in the river due to the movement of sediment.						
Shellfish								
Shellfish Habitat	*Shellfish Distribution*	*Shellfish Abundance*	*Public Health*	*Predators*				
Participant describes the shellfish habitat for specific species. This includes the physical environment description, including substrate type. Includes wild oysters.	Participant describes the physical distribution of the shellfish. This includes tidal height or depth in sediment, as well as seasonal and temporal variations in distribution. Includes wild oysters.	Participant describes the abundance of shellfish species. This can either be spatial (i.e., There are a lot of clams here...) or temporal (i.e., The number of clams has declined in the last 15 years).	Participant mentions public health concerns related to shellfish. This can include references to vibrio, flat closures due to bacteria, or poor harvesting practices that could cause public health concerns.	Participan t mentions predators that affect shellfish species, such as green crabs or milky ribbon worms.				

Table D.1 continued.

Shellfish Fishery								
SSClam: Decreasing #/ aging harvester pop	*SSClam: Percent of total income*	*SSClam: Harvesting methods, strategies and species*	*SSClam: Harvesting locations*	*SSClam: Threats to the fishery*	*SSClam: Methods to improve the fishery*	*SSClam: Views of occupation*	*Harvest Rate*	
Participant discusses demographic changes or changes in the total number of shellfish harvesters. Participants refer to harvesters 'aging out' or retiring, as well as a lack of young harvesters entering the fishery. Subsets include decreasing harvesters due to 1) Harvester aging and retirement and 2) Limited entry of young people to the fishery due to how labor intensive and seasonal nature of the work.	Participant discusses financial or circumstantial aspects of the work (more of a part-time/seasonal job, difficulty to make it year-round work due to town restrictions).	Participant describes which species they harvest and how. For example, 'picking' for oysters and digging for clams, or harvesting a suite of different species so that they can respond to changes in market prices.	A means to capture the important harvesting sites in both river systems. To track the names and locations of important coves, or cove of historical importance.	Includes flat closures due to pollution, overharvesting, too many harvesters, licenses, aquaculture harming clam pops/settlement, or aquaculture industry threatening livelihood of clammers.	This can also include ideas from harvesters about why clams declined in the first place and what they think needs to be done (like turning the mud regularly) to improve the health of the clam resource.	Participant refers to shellfishing as work similar to farming--the mudflat as a garden, or other agricultural metaphors.	Participant describes the quantity of shellfish harvested in a tide/day/etc.	

Table D.1 continued.

Tourism								
Tourism: Increased activity	*Tourism: Inexperience*	*Tourism: Aquaculture-related*	*Tourism: Increased activity due to COVID-19*	*Tourism: Development*				
Participant mentions increases in tourism activity on the river but not with respect to COVID-19?	Participants mention tourists who are inexperienced being on the water and put themselves in danger, either by illegally gathering shellfish or kayaking where they shouldn't.	Participant links tourism to the aquaculture industry on the DRE. This could be general, like how oysters are cool now and people want to learn about real-life farmers, or it could be one of many mentions of the red tour boat.	This refers to an observed (or not) spike in river tourism in 2020 and linked to COVID-19.	This refers to property conversions (either seasonal or short-term rentals) and longer-term demographic changes in the area that are driven by tourists.				
Water Quality								
Water Quality: Pollution	*Water Quality: Improvement*							
Participants mention water pollution and declines in water quality. *Do we care about the type of pollution mentioned? And the cause.	Participants mention improvements in water quality in an area. Capture where this has occurred.							

Table D.1 continued.

Inductive								
Inductive: General Map Feedback	*Inductive: What we Missed*	*Other*	*Interesting things to think about*	*In-Vivo*	*River Species: In Vivo*			
Participant comments about the map.	Things the participants identified that we missed in this study.	This node developing, MLB and SCR check in periodically and adjust if needed.	Open-ended: MLB and SCR tag interesting ideas that aren't necessarily relevant to coding but might be useful.	Open-ended: MLB and SCR using this to grab quotes that might be useful later	We code the first time a participant mentions each species.			

APPENDIX E: 2021 STATE OF THE DAMARISCOTTA RIVER ESTUARY REPORT

2021 State of the Damariscotta River Estuary Report

Local knowledge of trends in the shellfish resource and human activity in the Damariscotta River Estuary

Prepared by Melissa Britsch, Sarah Risley*, Joshua Stoll and Heather Leslie*
University of Maine Darling Marine Center

Presented to the Damariscotta-Newcastle Joint Shellfish Committee
October, 2021

Land Acknowledgement

The Darling Marine Center recognizes that it is located in South Bristol along the Damariscotta River in the homeland of the Wabanaki Tribal Nations, where issues of water and territorial rights, and encroachment upon sacred sites, are ongoing. The historic Walinakiak Abenaki Tribe and other tribal peoples of the Pemaquid Peninsula area are connected to the modern, consolidated Abenaki Tribal Nation in Quebec and other Wabanaki Tribal Nations—the Passamaquoddy, Penobscot, Maliseet, and Micmac—through kinship, alliances, and diplomacy. The Darling Marine Center recognizes that the Wabanaki Tribal Nations are distinct, sovereign, legal and political entities with their own powers of self-governance and self-determination.

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Darling Marine Center

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** Shared first authorship.*
Cover photo: View of the Chadbourne intertidal area, looking south from the Damariscotta River's western shore, just south of Jack's Point in Newcastle. Photo by Kara Pellowe.

Executive summary

This project emerged from questions identified by the members of the Damariscotta-Newcastle Joint Shellfish Committee and the Bremen Shellfish Committee and a shared interest in the stewardship of town-managed shellfish resources. Specifically, these municipal leaders requested information on the current status of wild shellfish resources and information on how these resources, and the many human uses of the estuaries, are changing through time. The project represents a partnership between the towns of Damariscotta and Newcastle and the University of Maine Darling Marine Center that began in 2019 (Pellowe & Leslie, 2019). With additional support from the Broad Reach Shellfish Restoration and Resilience Fund, the project expanded in 2020 to include the town of Bremen and the Medomak River Estuary.

This work was supported by multiple sponsors, including local donors to the Darling Marine Center and grants from the Broad Reach Fund, Diana Davis Spencer Partnerships for a Sustainable Maine program, National Science Foundation (NSF), and National Oceanic and Atmospheric Administration (NOAA). In kind support from the Towns of Damariscotta and Bremen, and UMaine's Darling Marine Center also have been vital to our work in the last 18 months.

With this study, we aimed to answer the following questions:

1. What areas are most important for the wild shellfish fishery and farmed shellfish production in Damariscotta River Estuary, and why?
2. How and where do people in the estuaries interact, particularly those involved with aquaculture and the commercial soft-shell clam fishery?
3. What biological and social changes have estuary users observed and what is driving those changes?

To answer these questions, we conducted a mapping study to document local knowledge about the abundance and diversity of wild-caught shellfish and the spatial distribution of different activities in each estuary. Here we report on the results of the Damariscotta River Estuary study. We found that a wide variety of recreational and commercial activities co-occur in the estuary, particularly in the upper river (see Figure 2, page 5). The upper river also is where clams and other wild-harvested shellfish are most abundant (see Figure 6, page 16). The 28 participants in our study - including harbor masters, shellfish harvesters, aquaculture farmers, conservationists, lobster fishermen and other marine-dependent business owners, and residents who live and recreate on the estuary - have observed substantial changes through time in the magnitude and type of activities that people engage in on and around the waters of the Damariscotta River estuary. These changing patterns of use present both challenges and opportunities for future stewardship of the estuary. As scientists and citizens, we look forward to working with the Joint Shellfish Committee and other community members to support integrated and thoughtful stewardship of the estuary into the future.

Motivation

Intertidal shellfish resources in Maine are co-managed by coastal towns and the Maine Department of Marine Resources (Webber et al., 2021). Towns are responsible for managing the shellfish resources and issuing licenses through their shellfish committees. The towns of Damariscotta and Newcastle jointly manage the intertidal shellfish resources of the Damariscotta and Sheepscot River estuaries. In 2019, the Damariscotta-Newcastle Joint Shellfish Committee initiated a collaboration with scientists at the University of Maine Darling Marine Center to fill data gaps and learn more about the status of the shellfish resource in the Damariscotta River Estuary. They wanted to learn how the shellfish, and the many human uses of the estuary, have changed through time.

To support this objective, UMaine scientists, in collaboration with local harvesters, launched a survey in 2019 of upper river shellfish populations and gathered local knowledge about changes through time. In 2020, due to COVID-19 restrictions, the research team pivoted to documenting local users' ecological knowledge of the estuary using participatory mapping, focusing on abundance, distribution, and diversity of shellfish species, as well as the diversity and spatial distribution of activities. In addition to supporting the integration of local knowledge data and environmental data, this project also highlighted the value of long-term monitoring to inform understanding and management of this rapidly changing estuary system. This project identifies areas where differing species and human activities overlap, which is important for identifying and understanding areas of conflict among user groups in a changing and increasingly crowded estuary. Focusing more broadly than on a single species will help managers weigh tradeoffs among different uses and manage the entire estuary ecosystem in a more integrated, ecosystem-based manner.

Study Area

The Damariscotta River is a 19-mile (30 km) long estuary in midcoast Maine. It is surrounded by seven towns: Boothbay Harbor, Boothbay, Edgecomb, Newcastle, Nobleboro, Damariscotta, Bristol, and South Bristol (Figure 1). The head of the estuary is at the Damariscotta Mills Dam, where Damariscotta Lake empties into Great Salt Bay (Figure 2). Great Salt Bay is a large, shallow salt pond separated from the rest of the river by a constriction and reversing falls between Route 1 and the bridge connecting the towns of Damariscotta and Newcastle (McMahon, 1999). Damariscotta Lake is the primary source of freshwater into the estuary, which is classified as a tidally dominated estuary because the influence of tides is much stronger than the fresh water (Chandler, 2016; McAlice, 1977). The Damariscotta River has several narrow points that separate it into basins and trap water in the upper river, allowing it to warm up. There are many possible division points in the estuary, but the three major ones are, from north to south: at the mouth of Great Salt Bay, Glidden Ledges (between the upper and mid river sections), and Fort Island Narrows (between the mid and lower river sections (Figure 2).

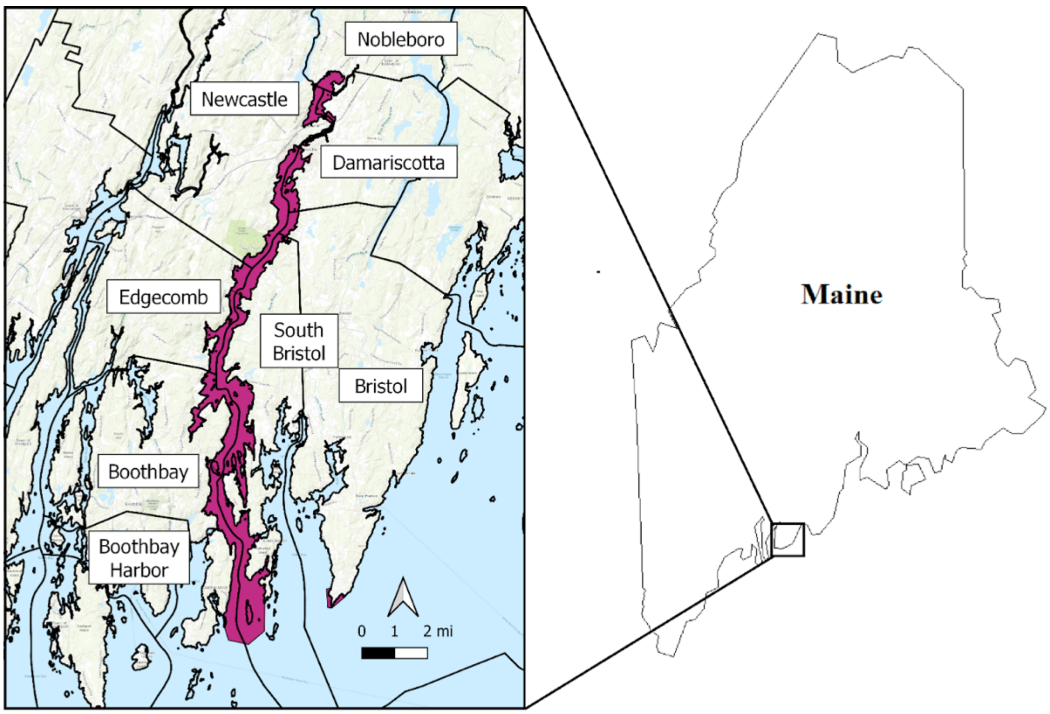

Figure 1 Damariscotta River estuary and surrounding towns.

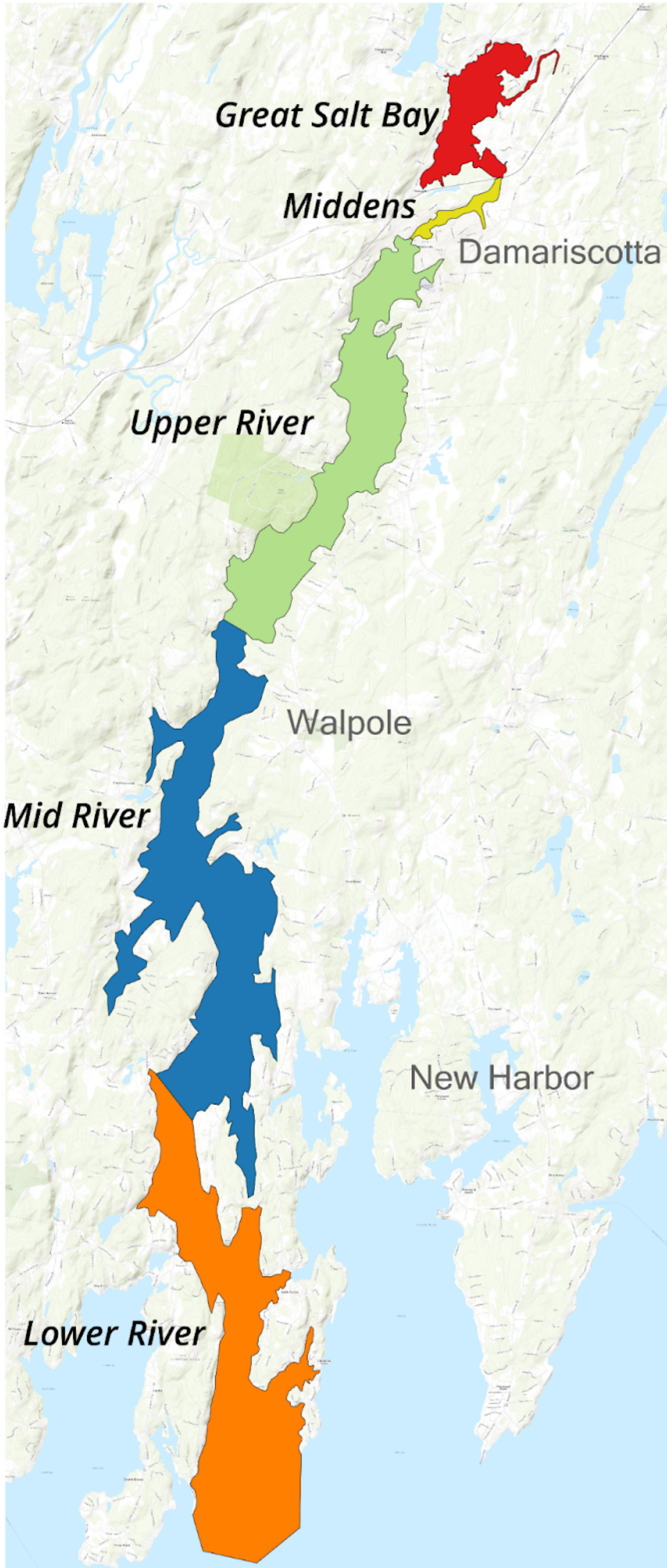

Figure 2 Major basins and areas in the Damariscotta River estuary.

The estuary has moderate to high salinity (19-32 ppt) in the upper section of the river, and full-strength salinity (35 ppt) in the mid and lower portions (Maine EPSCoR, 2019). Great Salt Bay experiences the largest salinity fluctuations - between 1 and 26 psu (McAlice, 1993). The constrictions separating the basins slow the flow of water leaving the estuary and it can stay in the upper river for four to five weeks in the summer (McAlice, 1977). Late summer water temperatures in the upper DRE reach 68-77 °F (20-25 °C), while the lower river reaches 59-68 °F (15-20 °C) (Maine EPSCoR, 2019). This makes the Damariscotta River a very good location for growing some species of shellfish, including softshell clams (*Mya arenaria*), American oysters (*Crassostrea virginica*), and quahogs (*Mercenaria mercenaria*).

The Damariscotta River Estuary is composed of a variety of different marine habitats. The bottom is primarily soft mud and extensive mudflats can be found in the upper river and in protected coves (Anderson et al., 1981; Anderson & Mayer, 1986; Chandler, 2016; Shipp, 1989). Other habitats include eelgrass beds, rocky intertidal, rocky bottom, and salt marshes. Great Salt Bay is distinct from other parts of the river because it is shallow, warmer, and less salty than the rest of the estuary (Chaves, 1997; McMahon, 1999; Petrie, 1975). Most of the Great Salt Bay is a state-designated marine shellfish preserve and is closed to most harvesting (Maine Legislature, 2001). The Damariscotta River has three main intertidal habitat zones: one from Great Salt Bay to the Damariscotta-Newcastle Bridge, the second from the bridge to Miller Island (1.2 km downriver from UMaine's Darling Marine Center), and a third zone from Miller Island to Inner Heron Island at the mouth of the river (Chaves, 1997). The first habitat zone is brackish and has more salt marsh coverage than the rest of the river; the second zone has large intertidal mudflats and experiences a range of salinities; and the third zone has a rocky shore and is primarily marine, with salinities usually over 30 ppt (Chaves, 1997).

The Damariscotta River is home to a wide variety of marine species; see Chaves, 1997 and McMahon, 1999 for detailed descriptions of habitats and species in the river. In this study, participants mentioned commercial species including oysters (American and European), softshell clams, razor clams, quahogs, lobster, crabs, worms, scallops, and elvers. Clams, oysters, and lobsters were discussed most frequently. Participants also discussed non-commercial species including striped bass, mackerel, wild birds, seals, and eelgrass. In total, 83 unique species were mentioned by study participants, highlighting the wide diversity of animal life in the Damariscotta River.

Commercial fishing is common in the Damariscotta River, specifically for American and European oysters, softshell clams, quahogs, razor clams, lobster, menhaden (pogy), alewives, scallops, elvers, and seaweed. Previously, people fished for sea urchins and peekytoe crabs (*Cancer irroratus*). Aquaculture farms grow American oysters, blue mussels, and kelp. Commercial fishing and aquaculture contribute considerably to the local economy. In 2020, the value of publicly available landings of quahogs, softshell clams, razor clams, and lobster from ports in Damariscotta, Boothbay, and South Bristol totaled $5,638,554 (Maine Department of Marine Resources, 2021). Additionally, the 2019 dockside value of oyster aquaculture in Maine was approximately $9.7 million, and 68% of that harvest came from the Damariscotta River (Maine Department of Marine Resources, 2020).

The Damariscotta River is also a popular tourism and recreation destination. Kayaking and paddle boarding are increasingly popular, particularly in the upper river. Likewise, hiking and wildlife viewing from the conserved lands on the shores is popular and became more so during the COVID-19 pandemic (Rice et al., 2020). Recreational motor boating is common throughout the river. The River Tripper, which docks in the Damariscotta village by the

Damariscotta-Newcastle bridge, runs daily wildlife and oyster farm tours in the summer, as well.

Methods

Study Participants

A total of 28 people participated in the study, which took place between October 2020 and January 2021. Participants included harbor masters, shellfish harvesters, aquaculture farmers, conservationists, lobster fishermen, other marine-dependent business owners, and residents who live and recreate on the rivers. All individuals needed to have been active and have experience on the river within the last three years to participate. Our study focused on activities like recreational boating or aquaculture (which we refer to as “general use”) and commercial shellfish harvesting (which we refer to as “shellfish”).

We had 17 participants complete the general use component of the study and 11 complete the shellfish component of the study. All but one of the shellfish survey participants were commercial shellfish harvesters; the other was a recreational harvester. See Table 1 for a breakdown of participant information.

Survey Type	# Participants	Male	Female	Average age	Average years of experience
Use	17	14	3	59	31
Shellfish	11	10	1	55	35

Table 1 Participant demographic information for the Damariscotta River.

Data Integration

Both interviews and maps were used to collect data for this study. Used together, maps and interviews become a powerful tool and are methods that simultaneously support each other. For example, maps - like those shown in Figures 2 and 3 - help to ground interviews in a place and facilitate discussion of specific geographic locations. Interviews provide opportunities to ask clarifying questions about maps and create space for open ended questions that help researchers learn about things that may not have been initially considered in the study. Our plan is to integrate the local knowledge data we have collected with existing environmental data. Overall, maps and interviews are important tools to document local knowledge and can be used to study change in the Damariscotta River Estuary by framing spatial and temporal shifts in shellfish resources, species composition, and human uses of the estuary. For a detailed description of the methods we used, please see Appendix I.

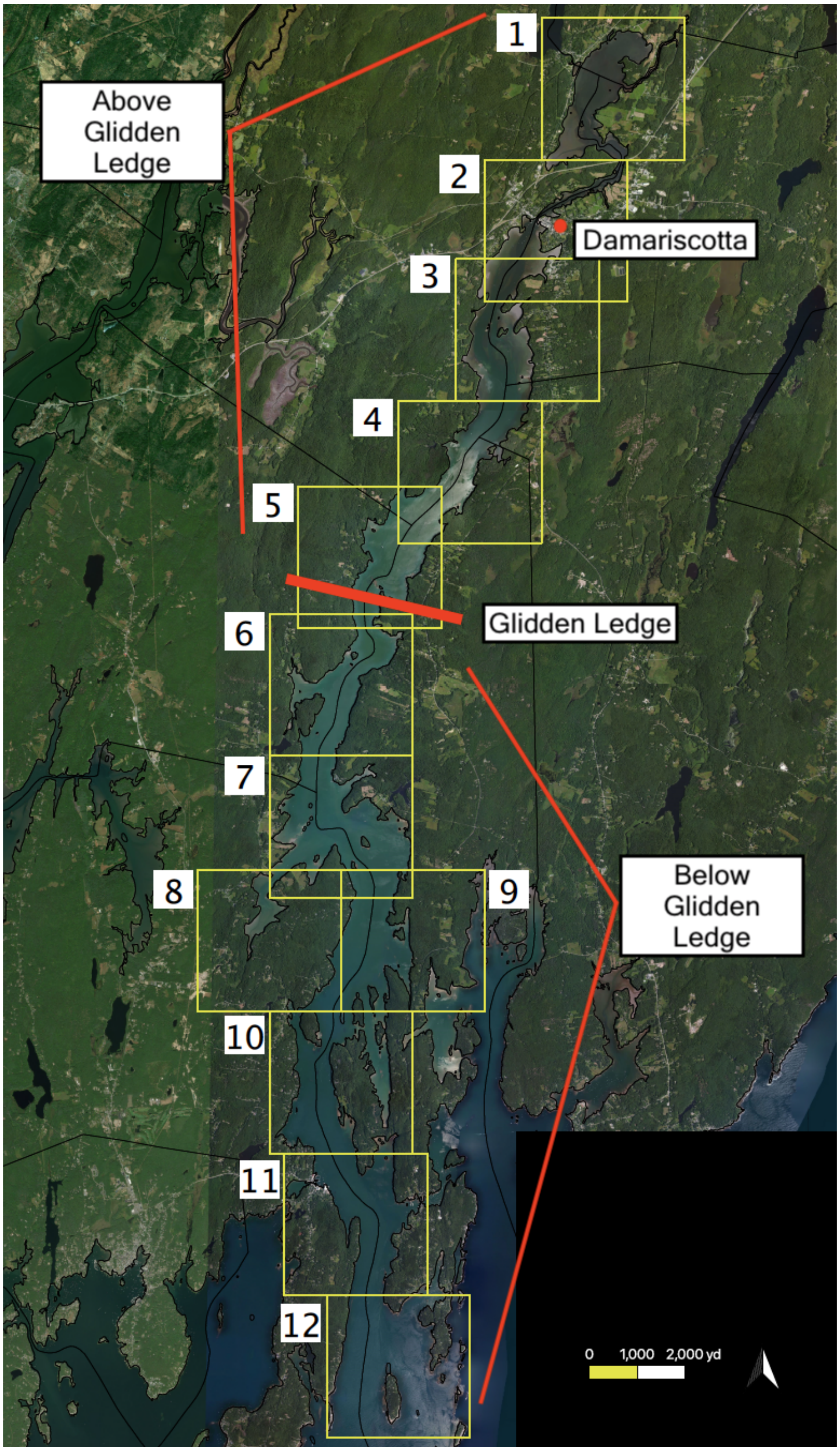

Figure 3 Upper and Lower sections of the Damariscotta River Estuary. Glidden Ledge divides the Damariscotta into two sections (as delineated by the red lines) with distinct characteristics. The numbered squares (1-12) denote the sections of the river where participants were asked to share their knowledge.

Results

Overview of Activities

The Damariscotta River Estuary is a unique estuary ecosystem that is home to a diversity of commercially important marine species and vibrant wildlife. It is also an ecosystem that supports a great range of human uses, from recreational activities to commercial industries and marine livelihoods. According to study participants, much of the river activity and use are concentrated in the upper river, near the Damariscotta-Newcastle bridge and Hog Island (Figure 5). Below we describe the types of activities identified through the local knowledge mapping study.

Commercial Fishing

The Damariscotta hosts several commercial fisheries that help to support local coastal economies. According to participant interviews, the two most cited fisheries include the lobster fishery (*Homarus americanus*) and the shellfish fishery targeting softshell clams (*Mya arenaria*), razor clams (*Ensis directus*), quahogs (*Mercenaria mercenaria*), and wild oysters (both European and American/Eastern oysters, *Mytilus edulis* and *Crassostrea virginica*). Other species that are targeted commercially include scallops (*Placopecten magellanicus*), worms (*Glycera dibranchiata and Nereis diversicolor*), crabs (*Decapods gen.*), Atlantic menhaden (or pogey, *Brevoortia tyrannus*), periwinkles (*Litorina*), and historically, green urchins (*Strongylocentrotus droebachiensis*).

Study participants observed commercial shellfishing primarily above Glidden Ledge, with only some activity occurring below Glidden Ledges (Figure 3). Other commercial fishing, like lobstering, was observed more frequently below Glidden Ledges, although commercial fishing activity was common throughout the whole river. Bait fishing, targeting menhaden/pogeys, was noted throughout the whole river and below Glidden Ledges (Figure 3).

According to Maine Department of Marine Resources landings data for 2019-2020, lobsters were the species with the highest landings by volume in the Damariscotta, followed by oysters (largely from aquaculture), menhaden, softshell clams, quahogs, crabs, and razor clams (Table 4). From 2019-2020, the number of lobster harvesters ranged from 85-89, 24-31 for oysters, 8-9 for quahogs, 25-42 for softshell clams, 3 for menhaden, and 6 for razor clams. Lobster was the highest value fishery, as well (Table 4).

Year	Species	Avg Annual Live Pounds Weight	Avg Annual Value	# Of Harvesters (range, among yrs.)
2019-2020	American Lobster	1,090,070	$ 5,049,279.59	85-89
2019-2020	Eastern / American Oyster	976,380	$ 2,553,218.62	24-31
2019-2020	Quahog / Hard Clam	30,054	$ 77,184.36	8-9
2019-2020	Softshell Clam	26,991	$ 55,577.90	25-42
2019-2020	Atlantic Menhaden	36,100	$ 9,783.10	3
2019-2020	Atlantic Clam Razor	579	$ 2,138.50	6

Table 2 *Average landings and values for fisheries in the Damariscotta River Estuary from 2019-2020. Averages were taken to account for fluctuations between years. The ports of Damariscotta, Newcastle, and Edgecomb were included in the totals for all species, excluding lobster. Lobster weight, value, and harvester number came from DMR landings data for South Bristol only. It should be noted that aquaculture accounts for most oyster landings and value. Data source: Maine DMR Landings webpage portal (https://mainedmr.shinyapps.io/Landings_Portal/).*

Aquaculture

In the Damariscotta, as of spring 2021, there are 29 active or pending aquaculture leases totaling approximately 162 acres (Table 5). Seventeen aquaculture farms manage these leases. There are 69 total active limited purpose aquaculture or LPA sites on the river currently. Study participants noted that aquaculture activity was most common above Glidden Ledges but was observed throughout the whole river. According to estimates provided by local experts and participants of the Damariscotta aquaculture industry, approximately 87-92 people are employed by aquaculture operations in the estuary.

Number of Farms (A/P/S/E)	Number Aquaculture Leases (S and E)	Total Lease Acreage	Total LPA Sites (A)	# Of People Employed (*estimated average for 2020-2021*)
17	29	~ 162	69	87-92

Table 3 *Information on aquaculture in the Damariscotta. Data were pulled from the State of Maine webpage on May 25, 2021, when the data had been last updated on April 30, 2021. Active (A) and Pending (P) sites were included in the totals. Each unique lease holder name was counted as an individual farm for these totals. Both Standard (S) and Experimental (E) leases were included in lease number total and total lease acreage. Data source: Maine DMR ArcGIS (https://maine.hub.arcgis.com/datasets/mainedmr-aquaculture-aq-leases/explore?location=43.969520%2C-69.377924%2C13.00) and personal communication with Dana Morse of Maine Sea Grant (August, 2021).*

Recreational Boating & Fishing

The Damariscotta is a waterway buzzing with active recreational boating and fishing use. The river is used for many forms of recreational boating including kayaking, motorboating, sailing, paddle boarding, and other recreational vessels like jet skis. Recreational fishing primarily targets striped bass (stripers, *Morone saxatilis*), as well as other species. The river is also commonly used for hunting, mainly of ducks.

Study participants observed extensive recreational boating activities, particularly kayaking, above Glidden Ledges. However, boating activity, including sailing and kayaking, was also observed throughout the entire river (Figure 4). Recreational fishing activities were commonly observed in the upper river, above Glidden Ledges, and more generally throughout the whole river (Figure 4).

Tourism & Sightseeing

Tourist activities in Damariscotta center around enjoying the river's wildlife and public trails and learning about local oyster aquaculture operations. Specifically, participants mentioned The River Tripper (a recreational tour boat), observing wildlife, swimming, and hiking as the primary tourist activities on or near the river. Study participants noted that tourism activity was most common above Glidden Ledges but does occur throughout the whole river (Figure 4).

Research

There is a long history of marine research activity in the Damariscotta, ranging from efforts led by professional research institutions to community scientists (*learn more about the history of Damariscotta marine research in this storymap by Britsch and Leslie (2021: https://arcg.is/jLqfq*). The Damariscotta is home to several marine research, conservation, and management institutions, including the University of Maine Darling Marine Center, Bigelow Laboratory for Ocean Sciences, Coastal Rivers Conservation Trust, and Maine Department of Marine Resources, among others.

The Darling Marine Center and Bigelow Laboratory for Ocean Sciences together employ well over 150 individuals, in Walpole and East Boothbay, respectively. These institutions provide a range of river-related employment, from employees who work to support the functioning of the facilities on the banks of the estuary, to employees and students whose research centers on the estuary and other coastal and marine ecosystems.

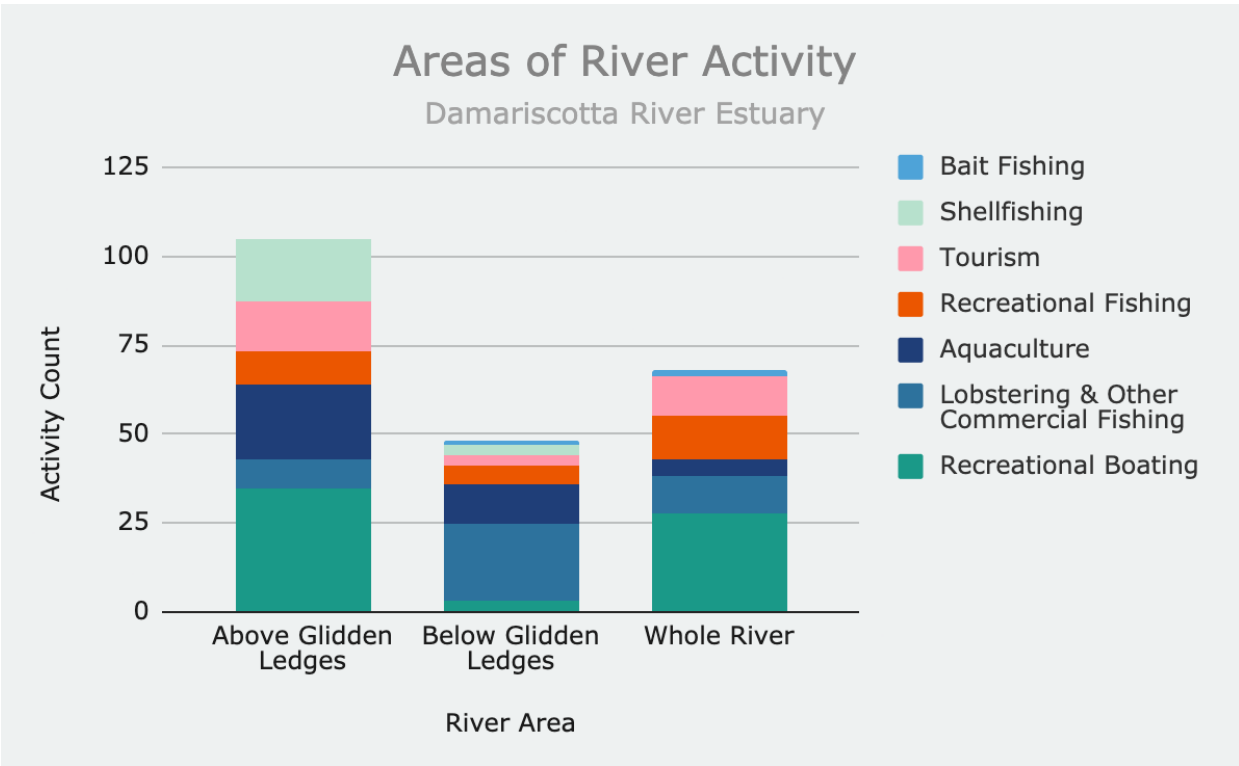

Figure 4: Count of the locations of different activities on the Damariscotta River mentioned by participants.

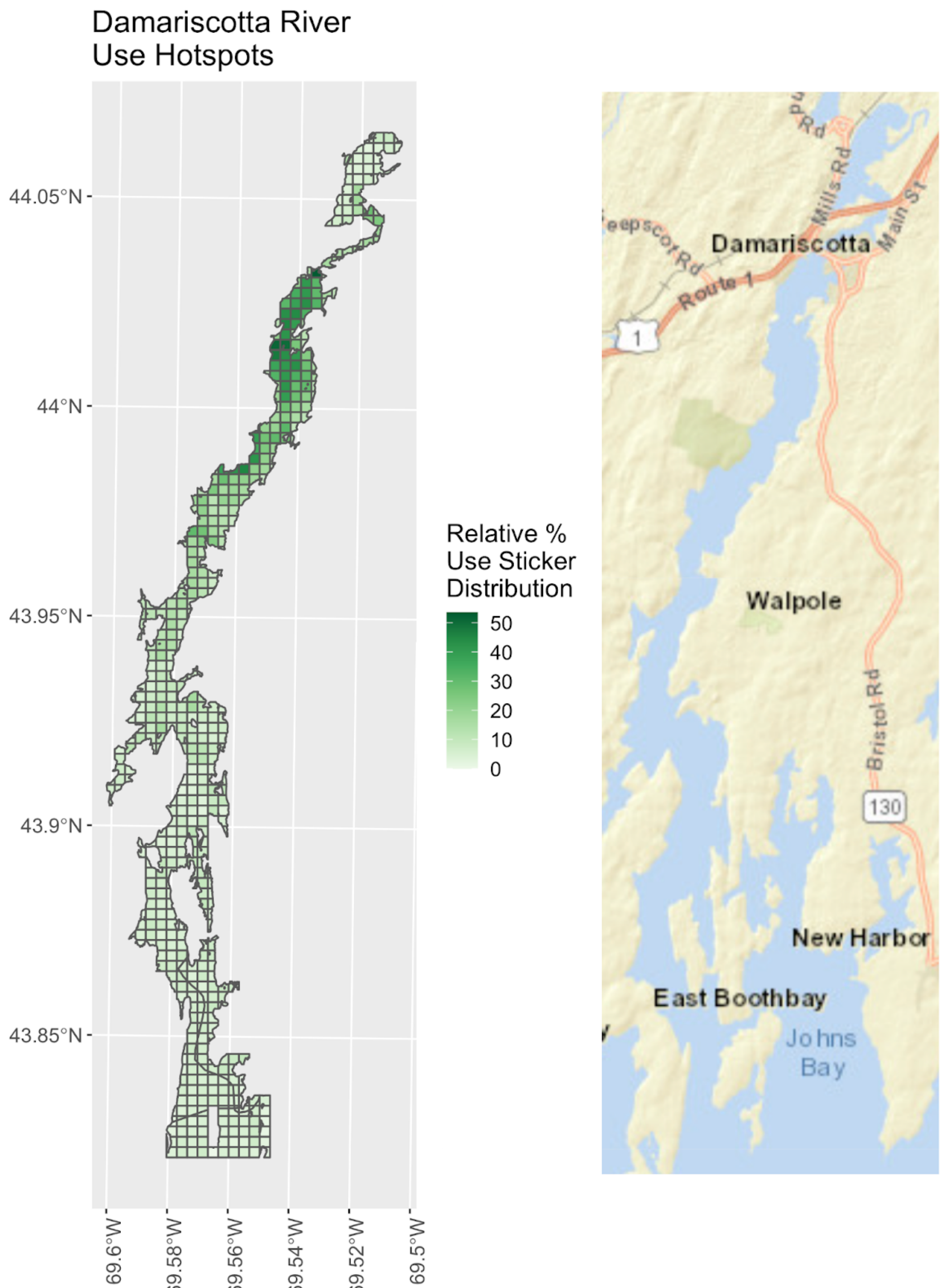

Figure 5 The map on the left shows the distribution of the intensity of human activities in the estuary. We describe how we generated these data in Appendix I. The map on the right is for reference.

Overview of Shellfish Resources in the Damariscotta River Estuary

Maine's intertidal shellfish populations help to support coastal livelihoods and have historically been Maine's second or third most valuable commercial marine fishery (Webber et al., 2021)). In 2020, 6.5 million pounds of softshell clams were landed with a value of $15.7 million in Maine, making it the second highest earning fishery in the state (Maine DMR, 2021b). Regardless, the shellfish fishery is changing and facing new challenges. Warming waters, increases in predator populations, and decreasing waterfront access are factors that are affecting the shellfish resource and fishery (Beal et al., 2018, 2020; Pershing et al., 2015). Therefore, improved knowledge about the state of the shellfish resource in the Damariscotta River Estuary and potential challenges facing the industry is essential for sustainable use and stewardship.

Commercially Targeted Shellfish Species

According to participant interviews with harvesters (n=11), commercial shellfish harvesters in the Damariscotta primarily target wild oysters (*Crassostrea virginica*), softshell clams (*Mya arenaria*), quahogs (*Mercenaria mercenaria*), and razor clams (*Ensis directus*). These species can be found from the low to the high intertidal zone and live in various habitats, ranging from rocky substrates to softer mud (Table 6).

Species	Habitat	Distribution
American Oyster	Attached to rock or other substrates, often under seaweed or on rocky, shell, and gravel areas of shore.	Upper intertidal zone or low intertidal zone.
Quahog	Sandy, rocky shore. Lives closer to the surface than soft shells.	Mid to low intertidal zone.
Softshell Clam	From soft mud to sandy, rocky areas.	Upper to low intertidal zone.
Razor Clam	Sandy areas or softer mud.	Low intertidal, almost sub-tidal.

Table 4 Habitat and distribution information for shellfish species in the Damariscotta based on interview data (total n=11).

Shellfish Predators & Threats to the Shellfish Fishery

Participants observed the following potential shellfish predators in the Damariscotta: green crabs (*Carcinus maenas*) and other crabs, ribbon worms (milky ribbon worm, *Cerebratulus lacteus*), and boring snails (*Euspira heros*). Participants pointed to aquaculture activity and the introduction of oysters, as well as decreased access (both physical walk-in access to shore and the barrier of license access) and predation pressure as the three most pressing threats to the shellfish fishery.

Shellfish Abundance, Distribution & Diversity

Overall, study participants observed that the Damariscotta, on average, has areas of low and medium clam abundance (Figure 6). Areas with the greatest clam abundance were concentrated around the section of the river near Goose Ledges and Hog Island. It should be noted that many of the study participants were Damariscotta-Newcastle license holders, and therefore are most familiar with softshell clam abundance within the bounds of these two municipalities. This area in the upper river was also identified as a location with the highest shellfish species richness (Figure 7).

Estuary Changes & Trends

The Damariscotta has experienced changes through time that have altered its physical habitat and characteristics, species composition, and human uses. The interview portion of this study offered important information about how this system is changing and the intensity and direction of these changes (see Figure 8 for a summary of these results).

In the Damariscotta, aquaculture activity was the greatest net increase observed by participants, followed by coastal development, motorboating activity, tourism/sightseeing, and kayaking/paddle boarding. Participants also observed a net increase in activity related to the wild oyster fishery. Diminished river access and navigability were the greatest net decreases, according to participants. This was followed by a decrease in the softshell clam fishery, both in fishery activity and harvestable softshell clam populations, and a smaller net decrease in lobstering and other commercial fishing activities.

Study Caveats & Limitations

It should be noted that the study participants were most familiar with, on average, six out of the 12 total river sections (Figure 3). Therefore, observations about activity may not be comprehensive for the entire river. Additionally, 48% of the participants were most familiar with the area above Glidden Ledge and only filled out river sections 1-5, while 52% were familiar with areas spanning both above and below Glidden Ledge. None focused exclusively on the area below Glidden Ledge (Figure 3). As a result, there may be an observation bias towards activities occurring above Glidden Ledge due to a limited number of participants most knowledgeable about the lower portion of the river.

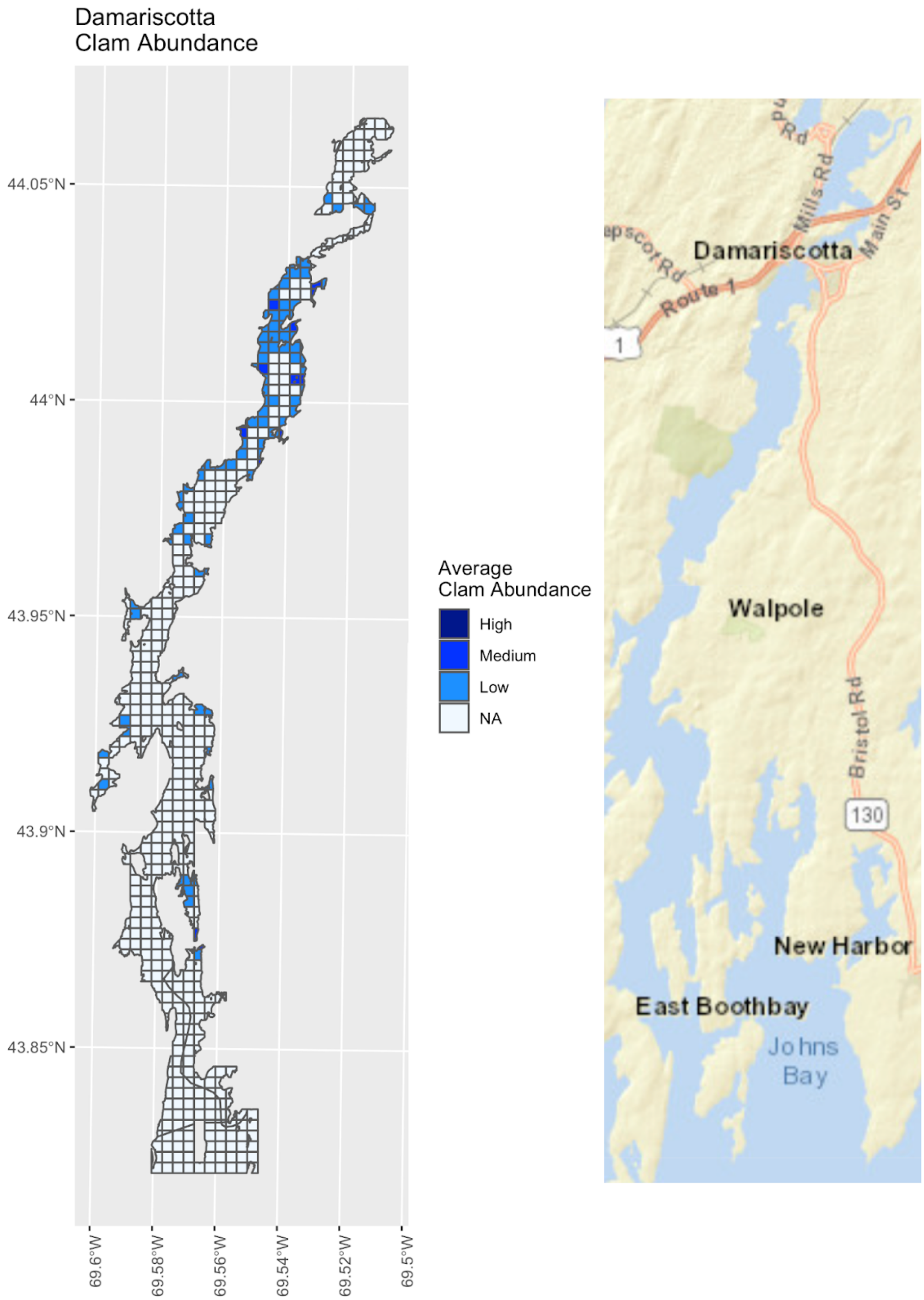

Figure 6*:* The map on the left synthesizes local knowledge of current clam abundance. Participants (n=11) identified areas with high, medium, and low softshell clam abundance. For detailed methods, see Appendix I. The map on the right is for reference.

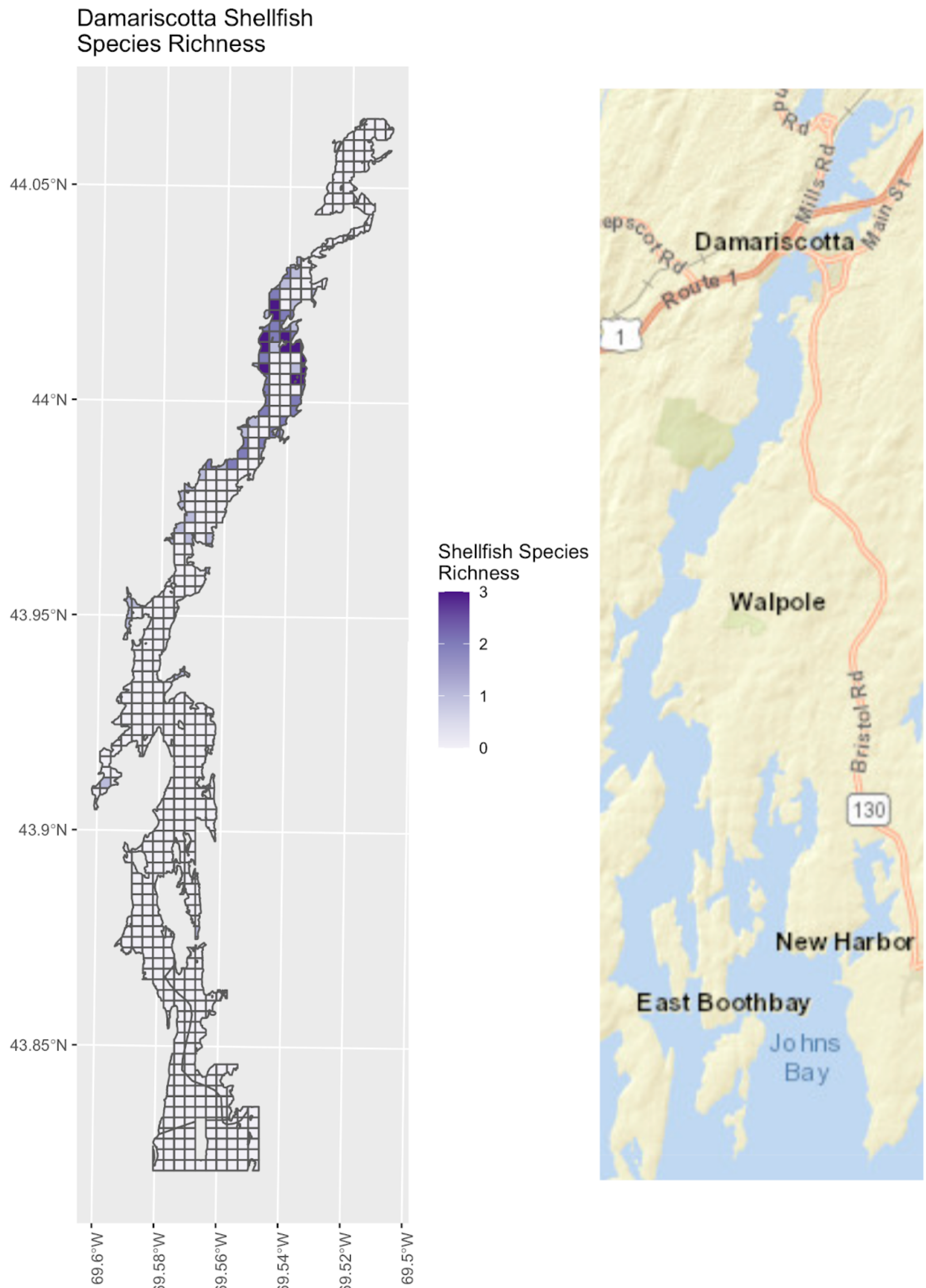

Figure 7*:* The map above (left) shows the shellfish species richness, or number of shellfish species, observed by study participants. Species included softshell clams, wild oysters, razor clams, and quahogs. Only shellfish species that were observed by three or more participants for a particular grid were included in this map. For example, a shellfish species richness score of 3 means that three shellfish species were observed by three or more people in a particular area.

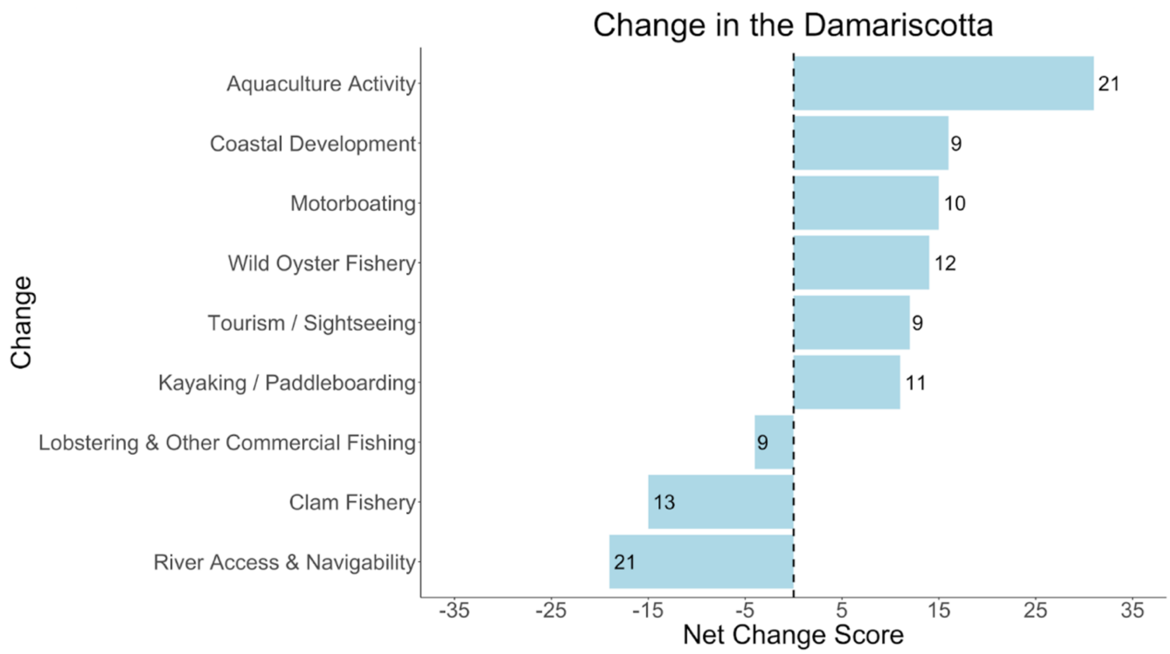

Figure 8*:* Changes identified by study participants (n=28). The bars show the magnitude (longer bars indicate more significant change) and direction of net change (increase=right of 0; decrease=left of 0) documented by the local knowledge study. For example, if an increase in kayaking was mentioned three times and a decrease in kayaking was mentioned once, the bar would have a value of positive two, taking the sum of these positive and negative values. The number at the end of each bar shows the total number of participants who identified each change and contributed to the net value shown. Each participant contributed one or more mentions to the total net change scores.

Conclusions

This study provided a snapshot of the human activities and how they interact with the ecology of the Damariscotta River Estuary. We also documented, thanks to deep local knowledge, how the social and ecological features are changing through time. We found that this estuary supports a variety of commercial and recreational activities, many of which overlap spatially. We also documented that the upper river is a hub for boating, aquaculture, and wild shellfish harvesting (Figures 5-7).

We interpret our findings with caution and believe that they will be strengthened with additional study in collaboration with harvesters and others in future years. Study participants were most familiar with, on average, six out of the 12 total river sections (Figure 3). Moreover, 48% of participants were most familiar with the area above Glidden Ledge and only completed information for river sections 1-5, while 52% were familiar with areas spanning both above and below Glidden Ledge. No participants focused exclusively on the area below Glidden Ledge (Figure 3). As a result, there may be an observation bias towards activities occurring above Glidden Ledge Additional observations throughout the estuary and particularly below Glidden Ledge are warranted.

This study highlights how important local knowledge is to understanding complex coastal marine ecosystems like the Damariscotta. Study participants observed both fast and slow changes in the estuary, including changes in the abundance of harvested populations, like the softshell clam, and shifts in the type and intensity of human use activities, like sailing and aquaculture. Local knowledge, generated and shared by the individuals who know the estuary best, can contribute to understanding of what is happening in the estuary at temporally and spatially fine scales, the scale at which people are interacting with this dynamic ecosystem.

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APPENDIX F: 2021 STATE OF THE MEDOMAK RIVER ESTUARY REPORT

2021 State of the Medomak River Estuary Report

Local knowledge of trends in the shellfish resource and human activity in the Medomak River Estuary

Prepared by Melissa Britsch, Sarah Risley*, Joshua Stoll and Heather Leslie*
University of Maine Darling Marine Center

Presented to the Bremen Shellfish Committee
October, 2021

Land Acknowledgement

The Darling Marine Center recognizes that it is located in South Bristol along the Medomak River in the homeland of the Wabanaki Tribal Nations, where issues of water and territorial rights, and encroachment upon sacred sites, are ongoing. The historic Walinakiak Abenaki Tribe and other tribal peoples of the Pemaquid Peninsula area are connected to the modern, consolidated Abenaki Tribal Nation in Quebec and other Wabanaki Tribal Nations—the Passamaquoddy, Penobscot, Maliseet, and Micmac—through kinship, alliances, and diplomacy. The Darling Marine Center recognizes that the Wabanaki Tribal Nations are distinct, sovereign, legal and political entities with their own powers of self-governance and self-determination.

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Darling Marine Center

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** Shared first authorship.*
Cover photo: View of the Medomak intertidal area. Photo by Gabby Hillyer.

Executive Summary

This project emerged from questions identified by the members of the Damariscotta-Newcastle Joint Shellfish Committee and the Bremen Shellfish Committee and a shared interest in the stewardship of town-managed shellfish resources. Specifically, these municipal leaders requested information on the current status of wild shellfish resources and information on how these resources, and the many human uses of the estuaries, are changing through time. The project represents a partnership between the towns of Damariscotta and Newcastle and the University of Maine Darling Marine Center that began in 2019 (Pellowe & Leslie, 2019). With additional support from the Broad Reach Shellfish Restoration and Resilience Fund, the project expanded in 2020 to include the town of Bremen and the Medomak River Estuary.

This work was supported by multiple sponsors, including local donors to the Darling Marine Center and grants from the Broad Reach Fund, Diana Davis Spencer Partnerships for a Sustainable Maine program, National Science Foundation (NSF), and National Oceanic and Atmospheric Administration (NOAA). In kind support from the Towns of Damariscotta and Bremen, and UMaine's Darling Marine Center also have been vital to our work in the last 18 months.

With this study, we aimed to answer the following questions:

1. What areas are most important for the wild shellfish fishery and farmed shellfish production in the Medomak River Estuary, and why?
2. How and where do people in the estuaries interact, particularly those involved with aquaculture and the commercial softshell clam fishery?
3. What biological and social changes have estuary users observed and what is driving those changes?

To answer these questions, we conducted a mapping study to document local knowledge about the abundance and diversity of wild-caught shellfish and the spatial distribution of different activities in each estuary. Here we report on the results of the Medomak River Estuary study. We found that a wide variety of recreational and commercial activities co-occur in the estuary, particularly in the upper river (see Figure 2, page 5). The upper river also is where clams and other wild-harvested shellfish are most abundant (see Figure 6, page 16). The 21 participants in our study - including shellfish harvesters, aquaculture farmers, conservationists, lobster fishermen and other marine-dependent business owners, and residents who live and recreate on the estuary - have observed substantial changes through time in the magnitude and type of activities that people engage in on and around the waters of the Medomak River Estuary. These changing patterns of use present both challenges and opportunities for future stewardship of the estuary. As scientists and citizens, we look forward to working with the Joint Shellfish Committee and other community members to support integrated and thoughtful stewardship of the estuary into the future.

Motivation

Intertidal shellfish resources in Maine are co-managed by Maine coastal towns and the Maine Department of Marine Resources (Webber et al., 2021). Towns are responsible for managing the shellfish resources and issuing licenses through their shellfish committees. The town of Bremen manages its intertidal shellfish resources on the Medomak River Estuary, and local harvesters have recently noted declines in softshell clam populations and changes in shellfish abundance and diversity. In 2020, the Bremen Shellfish Committee initiated a collaboration with scientists at the University of Maine Darling Marine Center to fill data gaps and learn more about the status of the shellfish resource in the Medomak River Estuary. They wanted to learn how the shellfish, and the many human uses of the estuary, have changed through time.

To support this objective, UMaine scientists, in collaboration with local harvesters, intended to launch initial population surveys in 2020 to quantify shellfish populations and gather local knowledge about changes through time. However, due to COVID-19 restrictions, the research team pivoted to documenting local users' ecological knowledge of the estuary using participatory mapping to document the abundance, distribution, and diversity of shellfish species, as well as the diversity and spatial distribution of activities. In addition to supporting the integration of local knowledge data and environmental data, this project also highlighted the value of long-term monitoring to inform understanding and management of this rapidly changing estuary system. This project identifies areas where differing species and human activities overlap, which is important for identifying and understanding areas of conflict among user groups in a changing and increasingly crowded estuary. Focusing more broadly than on a single species will help managers weigh tradeoffs among different uses and manage the entire estuary ecosystem in a more integrated, ecosystem-based manner.

Study Area

The Medomak River is an approximately 10-mile (6 km) long estuary in midcoast Maine. It is surrounded by three towns: Bremen, Waldoboro, and Friendship (Figure 1). The head of the estuary is near Route 1 in the town of Waldoboro (Figure 2) (Mills et al., 2020). The Medomak River is the primary source of freshwater into the Medomak River Estuary and drains a watershed of 106 square miles (275 square kilometers) (Mills et al., 2020). The Medomak River Estuary empties into Muscongus Bay (Mills et al., 2020). The Medomak River narrows at Havener Ledge but is relatively wide on either side and the estuary is characterized by broad mudflats surrounding a deep central channel (Hillyer, 2019). The narrows at Havener Ledge separates the Medomak River into two basins (Figure 2).

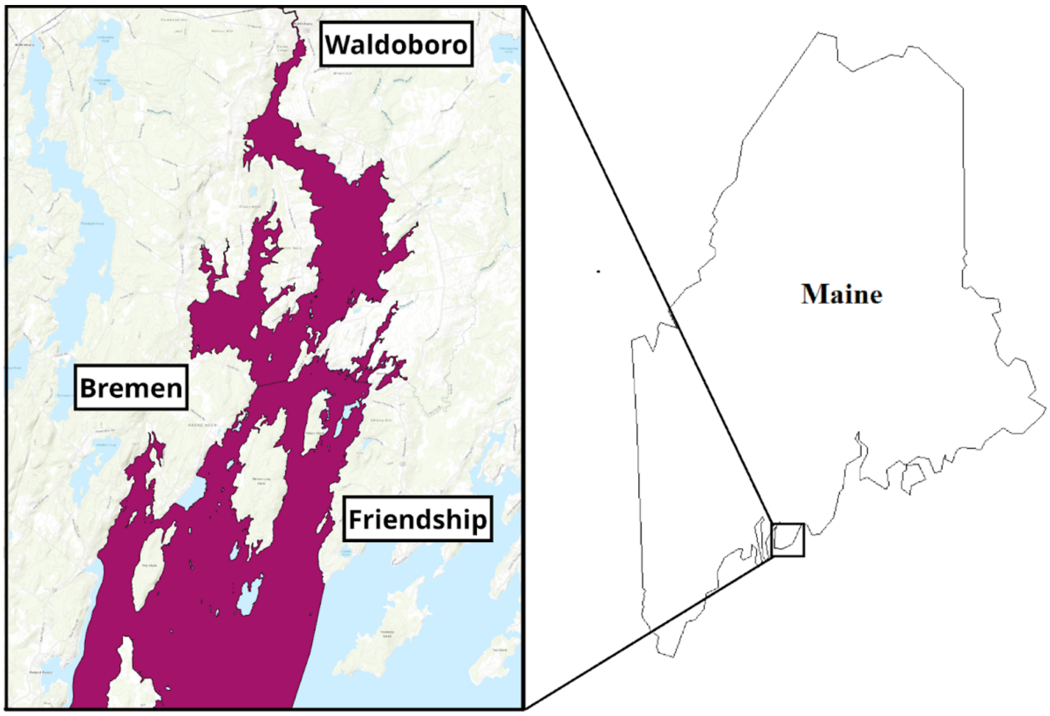

Figure 1 Medomak River Estuary and surrounding towns.

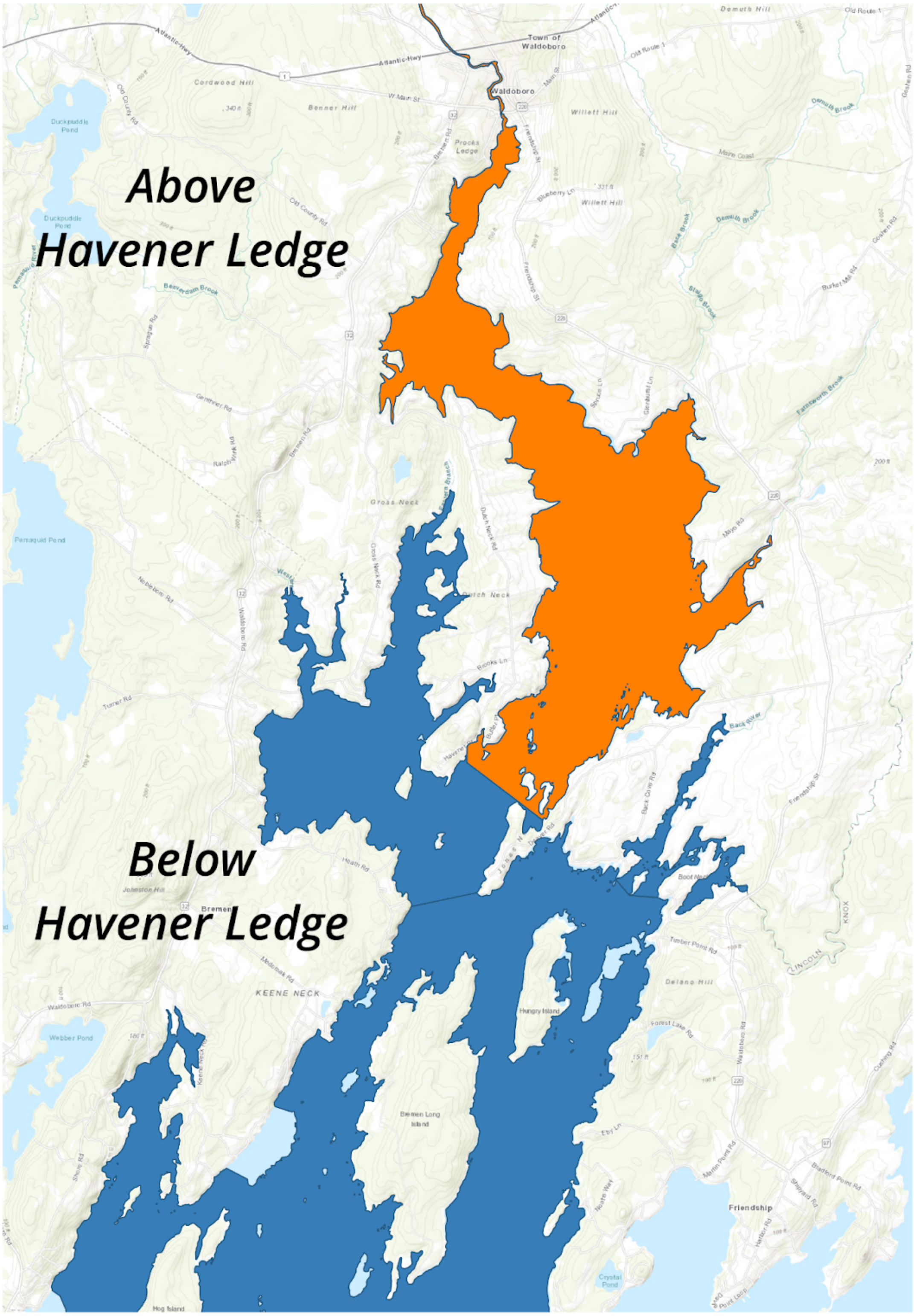

Figure 2 Major basins and areas in the Medomak River Estuary.

The Medomak River Estuary has moderate to high salinity (27-30 ppt) in the upper section of the river, and full-strength salinity (35 ppt) in the lower portion (Thornton & Mayer, 2015). Late summer water temperatures in the upper Medomak reach 68-77 °F (20-25 °C), while the lower river reaches 59-68°F (15-20 °C) (Thornton & Mayer, 2015). This makes the Medomak River a very good location for growing some species of shellfish, including softshell clams (*Mya arenaria*), American oysters (*Crassostrea virginica*), and quahogs (*Mercenaria mercenaria*) (D. Brady, personal communication).

The Medomak River is composed of a variety of different marine habitats. These habitats have not been studied in detail, but they include salt marshes, eelgrass beds, and extensive mudflats (Hillyer, 2019; Mills et al., 2020). The Medomak River is home to a wide variety of marine species, including worms, lobster, horseshoe crabs, fish, and shellfish. These have not been documented in detail, but see Chaves, 1997 and McMahon, 1999 for detailed descriptions of habitats and species in the neighboring Damariscotta River. In this study, participants mentioned commercial species including softshell clams, razor clams, quahogs, lobster, worms, scallops, and elvers. Clams and lobsters were discussed most frequently. Participants also discussed non-commercial species including striped bass, mackerel, wild birds, seals, and eelgrass. In total, 83 unique species were mentioned by study participants, highlighting the wide diversity of animal life in the Medomak River.

Commercial fishing is common in the Medomak River. It is commercially fished for softshell clams and frequently reports the most clam landings of any town in Maine (Hillyer, 2019). Other commercially fished species include quahogs, razor clams, lobster, menhaden (pogy), scallops, elvers, and seaweed. Previously, people fished for sea urchins and blue mussels. The Medomak has fewer than 10 aquaculture farms, which grow American oysters and kelp (*Aquaculture Map: Maine Department of Marine Resources*, 2021). Commercial fishing contributes considerably to the local economy. In 2020, the value of non-confidential landings of quahogs, softshell clams, razor clams, and lobster from ports in Waldoboro and Bremen totaled $2,911,322 (Maine Department of Marine Resources, 2020).

The Medomak River is heavily used for commercial fishing but does not experience heavy recreational use. It is a popular tourism and recreation destination, and these activities are increasing. Some activities like kayaking are becoming increasingly popular, especially in the upper sections of the river, and hiking and wildlife viewing from the conserved lands on the shores is popular as well. The Medomak is home to several Maine Island Trail Islands that have boat-accessible campsites. Maine Audubon owns property on Keene Neck and Hog Island and hosts many summer camps and seasonal visitors. Recreational motor boating occurs throughout the river and sailing is popular in the lower sections of the river. The Medomak River does not experience large amounts of tourism-related activity.

Methods

Study Participants

A total of 21 people participated in the study, which took place between October 2020 and January 2021. Participants included harbor masters, shellfish harvesters, aquaculture farmers, conservationists, lobster fishermen, other marine-dependent business owners, and residents who live and recreate on the rivers. All individuals needed to have been active and have experience on the river within the last three years to participate. Our study focused on activities like recreational boating or aquaculture (which we refer to as "general use") and commercial shellfish harvesting (which we refer to as "shellfish").

We had 14 participants complete the general use component of the study and 7 complete the shellfish component of the study. All shellfish survey participants were commercial shellfish harvesters. See Table 3 for a breakdown of participant information.

Study type	# Participants	Male	Female	Average age	Average years of experience
USE	14	8	6	56	31
SHELLFISH	7	7	0	54	25

Table 1 Participant demographic information for the Medomak River.

Data Integration

Both interviews and maps were used to collect data for this study. Used together, maps and interviews become a powerful tool and are methods that simultaneously feed into each other. For example, maps - like those shown in Figures 2 and 3 - help to ground interviews in a place and facilitate discussion of specific geographic locations. Interviews provide opportunities to ask clarifying questions about maps and create space for open ended questions that help researchers learn about things that may not have been initially considered in the study. Our plan is to integrate the local knowledge data we have collected with existing environmental data. Overall, maps and interviews are important tools to document local knowledge and can be used to study change in the Medomak River Estuary by framing spatial and temporal shifts in shellfish resources, species composition, and human uses of the estuary. For a detailed description of the methods we used, please see Appendix I.

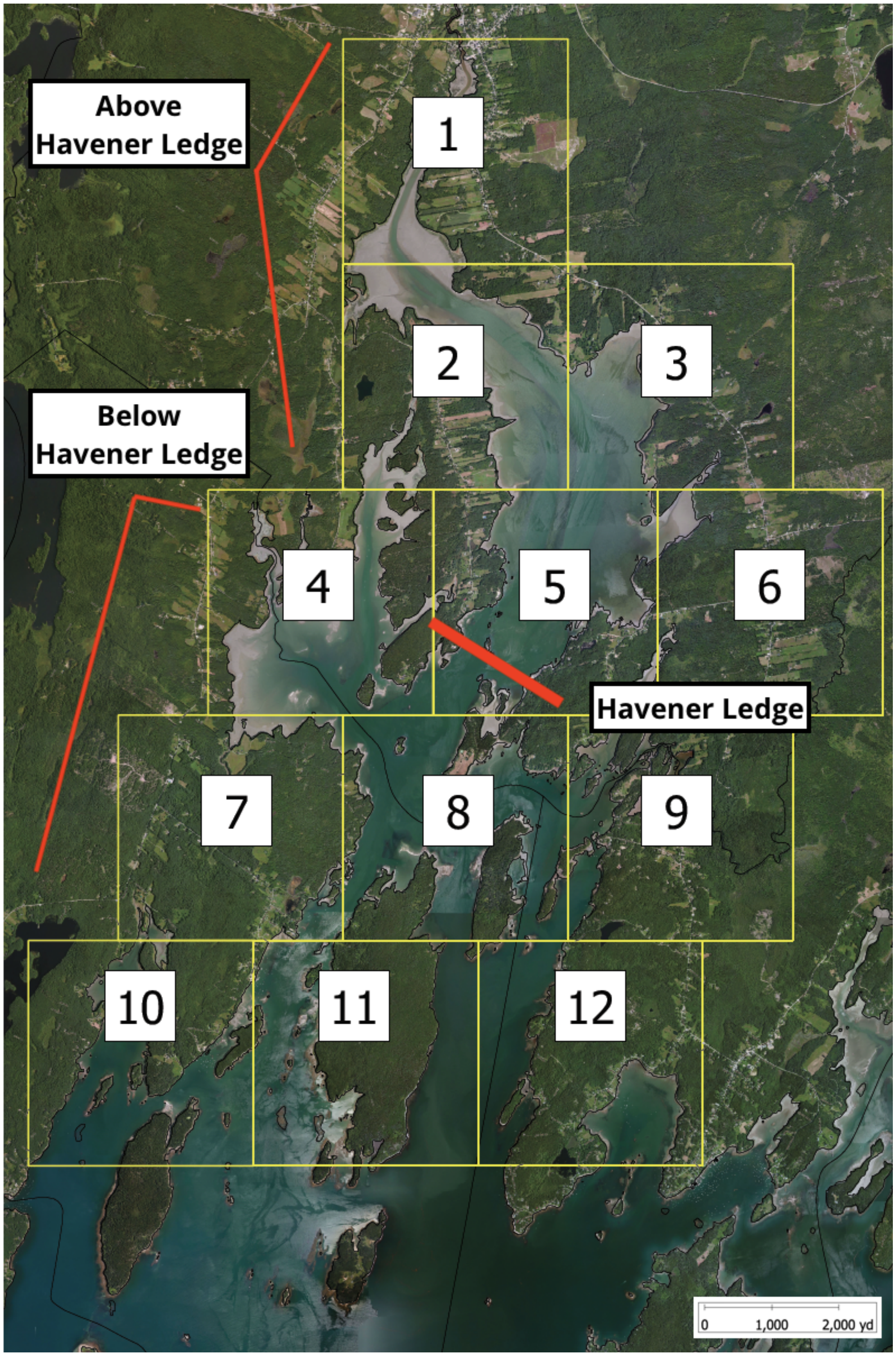

Figure 3 Upper and Lower sections of the Medomak River Estuary. Havener Ledge divides the Medomak into two sections (as delineated by the red lines) with distinct characteristics. The numbered squares (1-12) denote the sections of the river where participants were asked to share their knowledge.

Results

Overview of Activities

The Medomak River Estuary is a unique estuary ecosystem that is home to a diversity of commercially important marine species and vibrant wildlife. It is also an ecosystem that supports a great range of human uses, from recreational activities to commercial industries and marine livelihoods. According to study participants, river activity and use are widely distributed across the river, with some increased activity near Hog Island and Oar Island (Figure 5). Below we describe the types of activities identified through the local knowledge mapping study.

Commercial Fishing

The Medomak hosts several commercial fisheries that help to support local coastal economies. According to participant interviews, the three most cited fisheries include the lobster fishery (*Homarus americanus*), shellfish fishery, that targets softshell clams (*Mya arenaria*), and the Atlantic menhaden (or pogey, *Brevoortia tyrannus*) fishery. Other species that are targeted commercially include worms (*Glycera dibranchiata and Nereis diversicolor*), scallops (*Placopecten magellanicus*), other bait fish, and elvers (*Anguilla rostrata*). There is also commercial rockweed (*Ascophyllum nodosum*) harvesting and an offshore tuna (*Thunnus*) fishery, whose vessels return to the Medomak.

Study participants observed commercial shellfishing both above and below Havener Ledge, throughout the whole river (Figure 3). Other commercial fishing, like lobstering, was seen throughout the whole river, including both above and below Havener Ledge. Bait fishing was also noted throughout the whole river.

According to Maine Department of Marine Resources landings data for 2019-2020, menhaden has the highest landings in the Medomak, followed by lobster, softshell clam, quahogs, and elvers (Table 4). From 2019-2020, the number of harvesters for menhaden was 14, ranging from 51-59 for lobsters, 146-191 for softshell clams, 8-64 for quahogs, and 62-68 for elvers. Lobster was the highest value fishery at an average of $2,550,798.25/year between 2019-2020, followed by elvers at $887,703.02/year, and softshell clams at $667,563.89/year.

Year	Species	Avg Annual Live Lb. Weight	Avg Annual Value	Range of Annual Harvesters
2019-2020	Atlantic Menhaden	763,444	$ 203,543.19	14
2019-2020	American Lobster	591,494	$ 2,550,798.25	51-59
2019-2020	Softshell Clam	274,582	$ 667,563.89	146-191
2019-2020	Quahog / Hard Clam	69,756	$ 138,991.81	8-64
2019-2020	Elver	740	$ 997,703.02	62-68

Table 2 *Average landings and values for fisheries in the Medomak River Estuary from 2019-2020. Averages were taken to account for fluctuations between years. The ports of Waldoboro and Bremen were included in these totals. Data from the Maine DMR Landings webpage portal (https://mainedmr.shinyapps.io/Landings_Portal/).*

Aquaculture

In the Medomak, as of spring 2021, there is one active aquaculture lease totaling approximately 4 acres (Table 5). This lease is managed by one farm. There are 2 total active limited purpose aquaculture or LPA sites on the river currently. Study participants noted that aquaculture was only observed below Havener Ledge.

Number of Farms (A/P/S/E)	Number Aquaculture Leases (S and E)	Total Lease Acreage	Total LPA Sites (A)	# Of People Employed (*estimated average for 2020-2021*)
1	1	~ 4	2	5-10

Table 3 *Data were pulled from the State of Maine webpage on May 25, 2021, when the data had been last updated on April 30, 2021. Active (A) and Pending (P) sites were included in the totals. Each unique lease holder name was counted as an individual farm for these totals. Both Standard (S) and Experimental (E) leases were included in lease number total and total lease acreage. Data from the Maine DMR ArcGIS webpage. Data source: Maine DMR ArcGIS (https://maine.hub.arcgis.com/datasets/mainedmr-aquaculture-aq-leases/explore?location=43.969520%2C-69.377924%2C13.00).*

Recreational Boating & Fishing

The Medomak is a relatively placid waterway with moderate recreational boating and fishing use. The river is used for recreational boating including kayaking, sailing, motorboating, and other recreational vessels like jet skis (Table 5). Recreational fishing targets striped bass striped bass (stripers, *Morone saxatilis*), mackerel, and other species. The river is also commonly used for hunting, primarily of ducks and deer.

Study participants observed extensive recreational boating activities throughout the whole river, but most commonly below Havener Ledge (Figure 4). Kayaking was common throughout the whole river, while sailing was the most common boating activity below Havener Ledge. Recreational fishing activities were commonly observed below Havener Ledge but were also seen more generally throughout the whole river (Figure 4).

Tourism & Sightseeing

Tourist activities in the Medomak center around enjoying the river's wildlife and waterways. Specifically, participants mentioned observing wildlife and swimming as the primary tourist activities on the river (Table 5). Study participants noted that tourism activity was most common below Havener Ledge, and rarely observed elsewhere in the river (Figure 4).

Research

There is a long history of marine research activity in the Medomak, ranging from efforts led by professional research institutions to community scientists. The Medomak is home to several marine research, conservation, and management institutions, including the Hog Island Audubon Camp and the Medomak Valley Land Trust. Research activities range from water quality monitoring to the study of coastal bird populations. These institutions provide a range of river-related employment, from employees who work to support the functioning of the facilities on the banks of the estuary, to employees and students whose research centers on the estuary and other coastal and marine ecosystems.

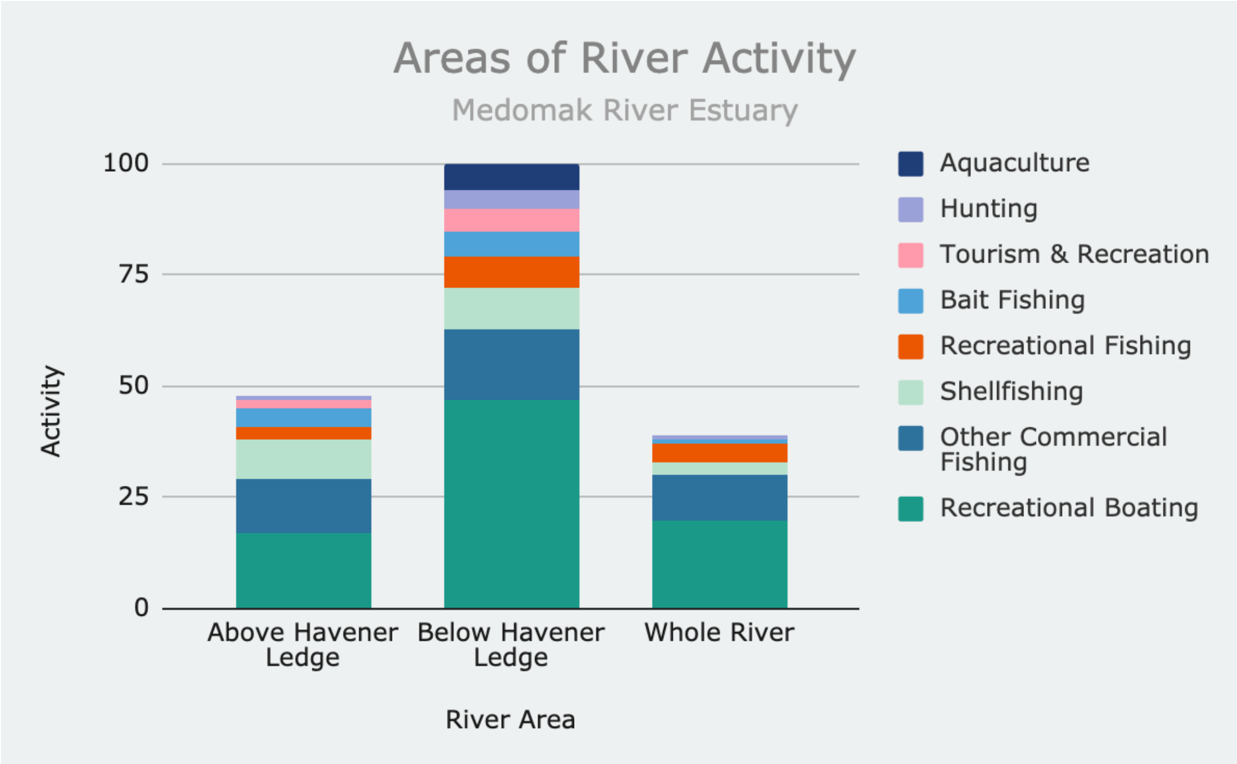

Figure 4 Count of the locations of different activities on the Medomak River mentioned by participants.

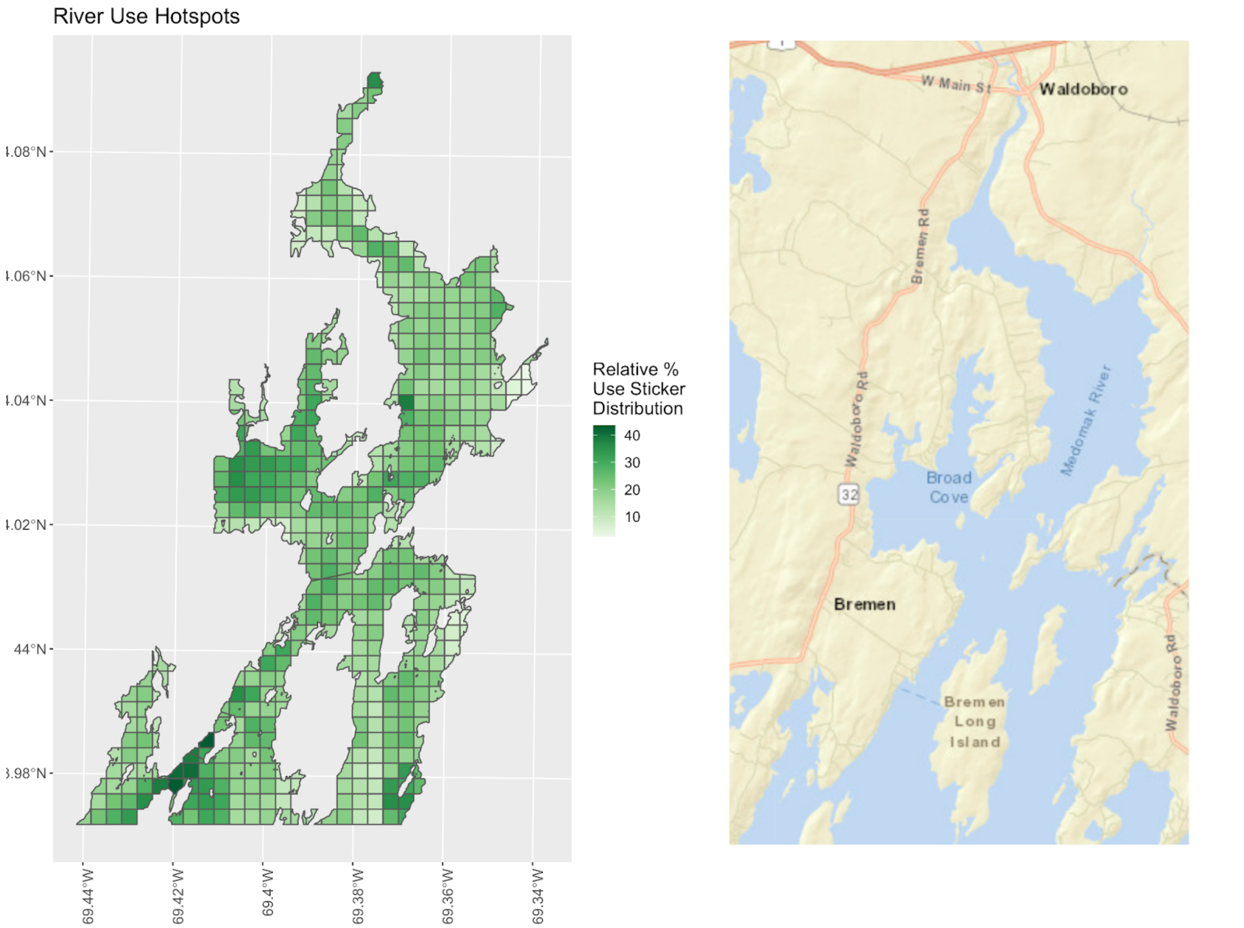

Figure 5: The map on the left shows the distribution of the intensity of human activities in the estuary. We describe how we generated these data in Appendix I. The map on the right is for reference.

Overview of Shellfish Resources in the Medomak River Estuary

Maine's intertidal shellfish populations help to support coastal livelihoods and have historically been Maine's second or third most valuable commercial marine fishery (Webber et al., 2021)). In 2020, 6.5 million pounds of softshell clams were landed with a value of $15.7 million in Maine, making it the second highest earning fishery in the state (Maine DMR, 2021b). Regardless, the shellfish fishery is changing and facing new challenges. Warming waters, increases in predator populations, and decreasing waterfront access are factors that are affecting the shellfish resource and fishery (Beal et al., 2018, 2020; Pershing et al., 2015). Therefore, improved knowledge about the state of the shellfish resource in the Medomak River Estuary and potential challenges facing the industry is essential for sustainable use and stewardship.

Commercially Targeted Shellfish Species

According to participant interviews with harvesters (n=7), commercial shellfish harvesters in the Medomak primarily target softshell clams (*Mya arenaria*) and razor clams (*Ensis directus*). These species can be found from the low to the high intertidal zone and live in various habitats, ranging from softer mud to harder sand and gravel (Table 6).

Species	**Habitat**	**Distribution**
Softshell Clam	Soft mud to hard mud, clay, sandy, shelly, rocky areas.	Mid to upper intertidal zone.
Quahog	Harder mud, sand, or gravel areas.	NA
Razor Clam	Soft mud to shelly, rocky mud.	NA

Table 4 Habitat and distribution information for shellfish species in the Medomak based on interview data (n=7).

Shellfish Predators & Threats to the Shellfish Fishery

Participants observed the following potential shellfish predators in the Medomak: green crabs (*Carcinus maenas*), ribbon worms (milky ribbon worm, *Cerebratulus lacteus*), boring snails (*Euspira heros*), and ducks and geese. Study participants also identified a number of potential threats to the shellfish fishery in the Medomak. Participants pointed to flat closures resulting from poor water quality and pollution and predation pressure as the two most pressing threats to the shellfish fishery.

Shellfish Abundance, Distribution & Diversity

Overall, study participants observed that the Medomak, on average, has areas of low and medium clam abundance (Figure 6). Areas with the greatest clam abundance were concentrated around the section of the river near Broad Cove, Sampson Cove, Long Cove, Clam Island, and various flats near Waldoboro. It should be noted that most of the study participants were Bremen and Waldoboro license holders, and therefore are most familiar with softshell clam abundance within the bounds of these two municipalities. Study participants observed low shellfish species richness, with only one species (commonly, softshell clam) being identified as present in most harvesting areas (Figure 7).

Estuary Changes & Trends

The Medomak has experienced changes through time that have altered its physical habitat and characteristics, species composition, and human uses. The interview portion of this study offered important information about how this system is changing and the intensity and direction of these changes (see Figure 8 for a summary of these results).

In the Medomak, warming waters and seasons was the greatest net increase observed by participants, followed by coastal development, kayaking/paddle boarding, and motorboating activity. Participants also observed both increases and decreases in green crab populations and river access and navigability, leading to a net change score of zero for both categories. The softshell clam fishery, both in fishery activity and harvestable soft-shell clam populations, was the greatest net decrease, according to participants. This was followed by a decrease in other commercial fishing activities.

Study Caveats & Limitations

It should be noted that the study participants were most familiar with, on average, six out of the 12 total river sections (Figure 3). Therefore, observations about activity are not fully comprehensive for the entire river. Only 10% or respondents were only familiar with the area above Havener Ledge. Instead, 45% of participants were familiar with the area below Havener Ledge and 45% of participants were familiar with areas spanning both above and below Havener Ledge. As a result, there may be a slight observation bias towards activities occurring below Havener Ledge.

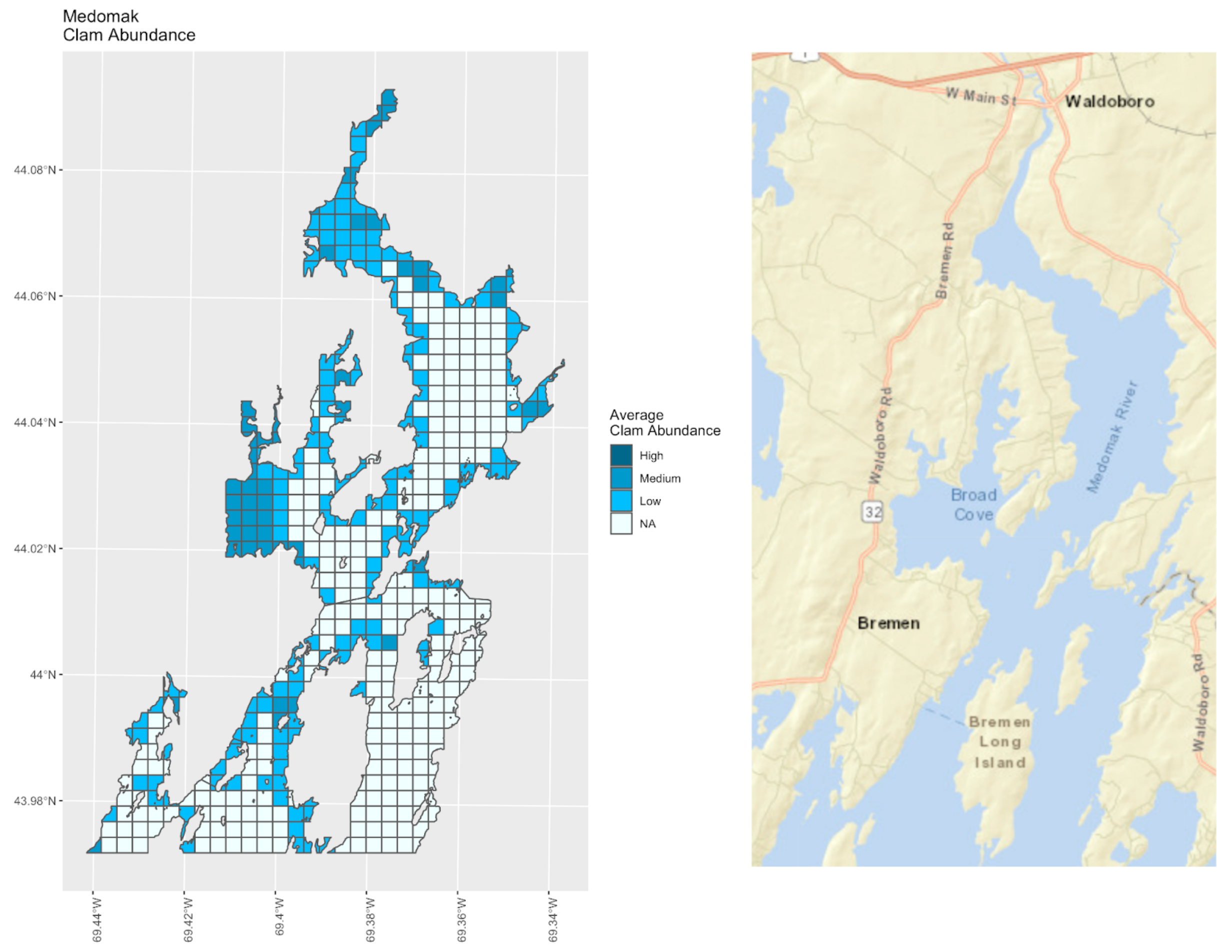

Figure 6 The map on the left synthesizes local knowledge of current clam abundance. Participants (n=7) identified areas with high, medium, and low softshell clam abundance. For detailed methods, see Appendix I. The map on the right is for reference.

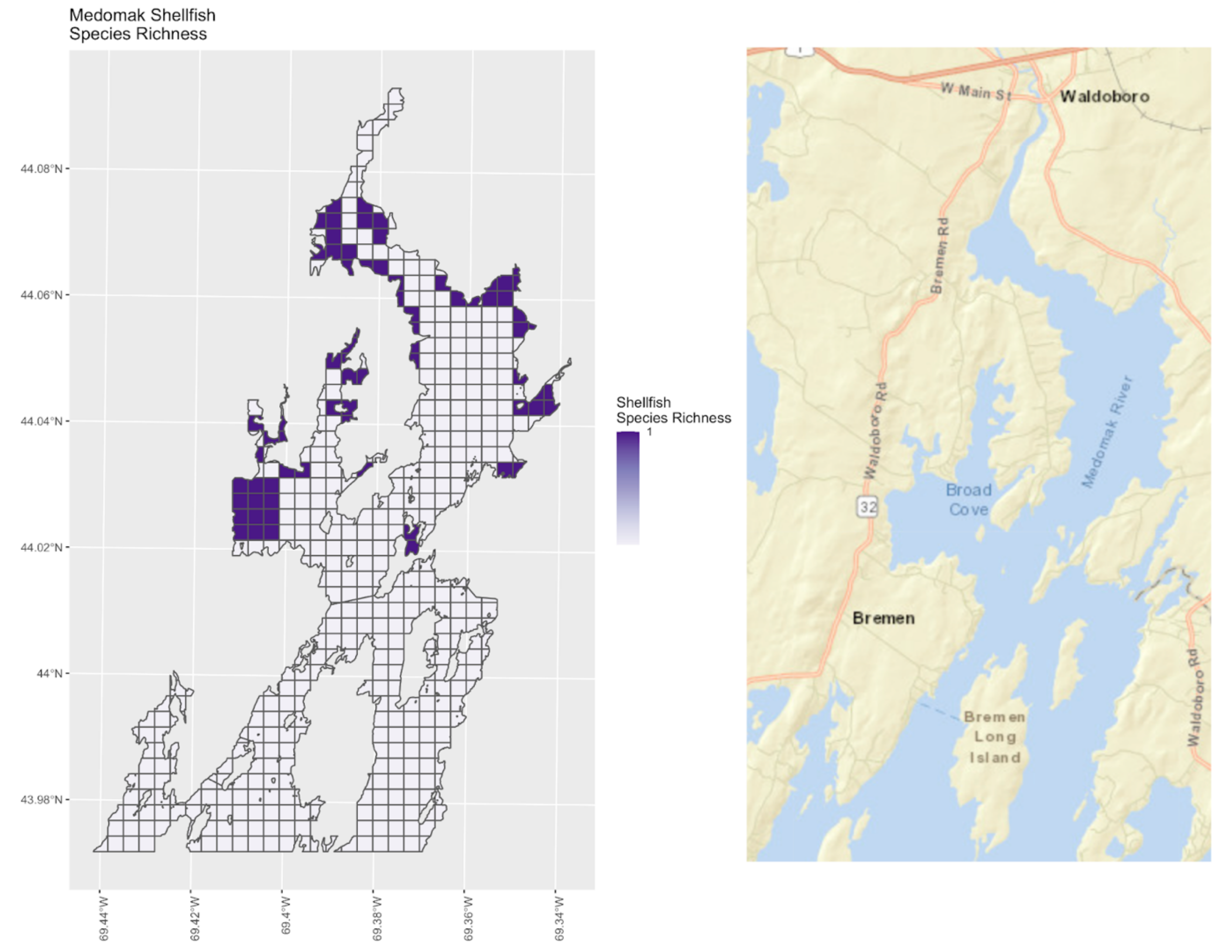

Figure 7 The map above (left) shows the shellfish species richness, or number of shellfish species, observed by study participants. Species included softshell clams, wild oysters, razor clams, and quahogs. Only shellfish species that were observed by three or more participants for a particular grid were included in this map. For example, a shellfish species richness score of 3 means that three shellfish species were observed by three or more people in a particular area.

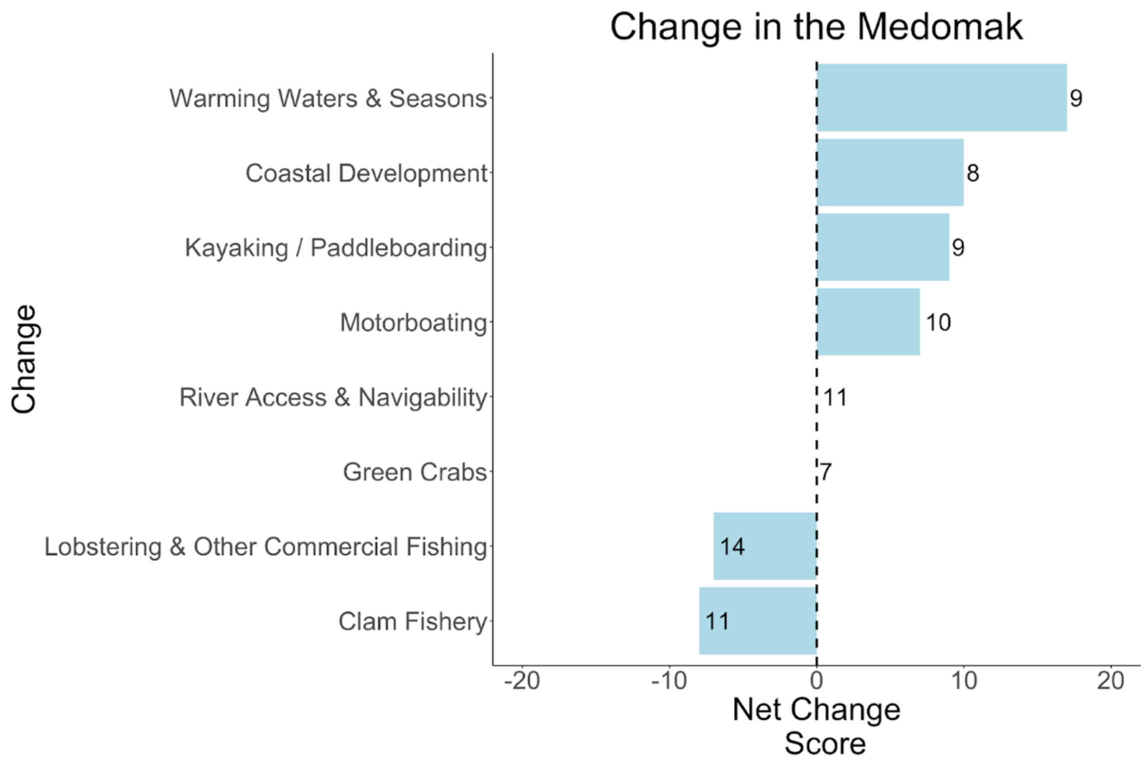

Figure 8 Changes identified by study participants (n=28). The bars show the magnitude (longer bars indicate more significant change) and direction of net change (increase=right of 0; decrease=left of 0) documented by the local knowledge study. For example, if an increase in kayaking was mentioned three times and a decrease in kayaking was mentioned once, the bar would have a value of positive two, taking the sum of these positive and negative values. The number at the end of each bar shows the total number of participants who identified each change and contributed to the net value shown. Each participant contributed one or more mentions to the total net change scores.

Conclusions

This study provided a snapshot of the human activities and how they interact with the ecology of the Medomak River Estuary. We also documented, thanks to deep local knowledge, how the social and ecological features are changing through time. We found that this estuary supports a variety of commercial and recreational activities, many of which overlap spatially. We also documented that the upper river is a hub for boating, aquaculture, and wild shellfish harvesting (Figures 5-7).

We interpret our findings with caution and believe that they will be strengthened with additional study in collaboration with harvesters and others in future years. Study participants were most familiar with, on average, six out of the 12 total river sections (Figure 3). Moreover, 45% of participants were most familiar with the area below Havener Ledge and only completed sections 1-3 and 5-6, while another 45% were familiar with areas spanning both above and below Havener Ledge. Only 10% of participants focused exclusively on the area above Havener Ledge (Figure 3). As a result, there may be an observation bias towards activities occurring below Havener Ledge. Additional observations throughout the estuary and particularly above Havener Ledge are warranted.

This study highlights how important local knowledge is to understanding complex coastal marine ecosystems like the Medomak. Study participants observed both fast and slow changes in the estuary, including changes in the abundance of harvested populations, like the softshell clam, and shifts in the type and intensity of human use activities, like kayaking and motorboating. Local knowledge, generated and shared by the individuals who know the estuary best, can contribute to understanding of what is happening in the estuary at temporally and spatially fine scales, the scale at which people are interacting with this dynamic ecosystem.

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APPENDIX G: LONG-TERM MONITORING SITE SELECTION

G.1 Site selection

Long-term monitoring sites for the community science project were selected using the local knowledge mapping study data. All possible areas were in the upper Damariscotta River estuary, Maine, north of Glidden Ledges. Areas with the highest reported shellfish diversity (i.e., areas with the greatest sum count of quahog, oyster, softshell clam, and razor clam stickers placed by participants) were selected as possible sites. Next, accessible sites were selected from the previous list. Sites were determined to be 'accessible' if they had walk-in access and available parking for 1-2 cars. Ideally accessible sites also did not cross over privately owned property. Finally, sites were further narrowed based on whether they were closed to harvesting, open to harvesting, or seasonally open to harvesting. The research team selected three sites with each level of harvesting access (open/closed/seasonal) to have sites that spanned the breadth of harvesting effort. The final sites selected are shown in the figure below (Figure E.1).

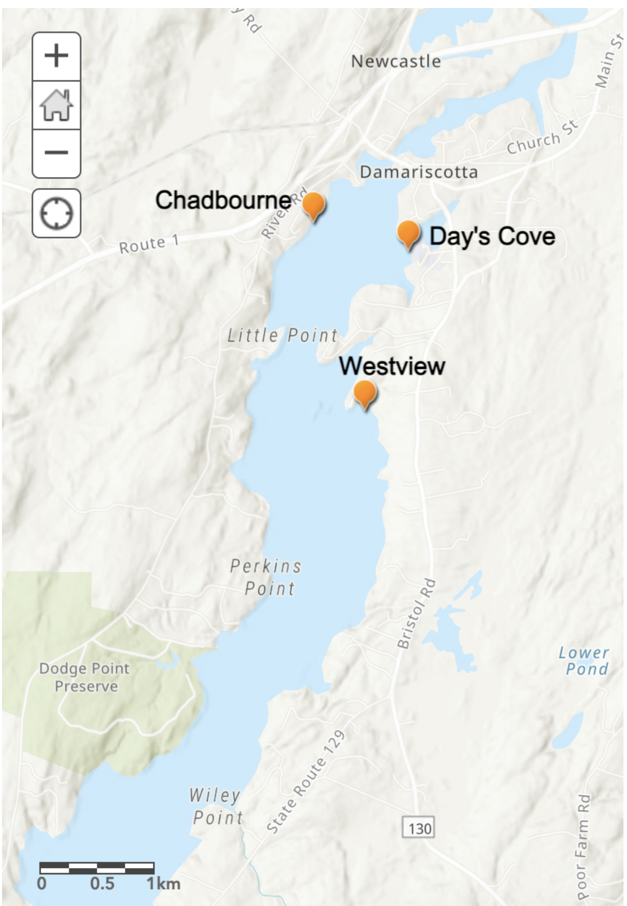

Figure G.1 Long-term monitoring sites in the upper Damariscotta River estuary. Sites selected using local knowledge data.

G.2 Site information

DAYS COVE

Waypoint: N 44° 01.618' W .069° 32.023'

Site Characteristics: Sheltered cove and straight shore. Closed to commercial harvesting.

Access: Days Cove is located in Damariscotta, ME along Bristol Road/State Route 129. Heading southward on Bristol Road you will pass Days Cove Lane on the left (western side of Bristol Road) and then cross a small bridge. Park in the small gravel lot on the western side of Bristol Road. Days Cove is to the west of this lot and continues northeast.

Figure G.2 Day's Cove site. Day's Cove site map showing clam abundance (high, medium and low) based on local knowledge mapping data. Maximum reported abundance shown.

WESTVIEW
Waypoint: N 44° 00.816' W 069° 12.356'

Site Characteristics: Sheltered cove. Closed seasonally, typically in summer months due to poor water quality.

Access: Westview/Sugar Loaf is located in Damariscotta, ME off of West View Road. Park on the road near the end of West View Road. Go through the turn around at the end of the road, continue back up the road a bit and park at the dirt turn off on the right side, just past 98 West View Road. Walk back down the road to the turn around loop. There is a wooden staircase down to the flats to the left of the loop at the end of the road.

Figure G.3 Westview site. Westview site map showing clam abundance (high, medium and low) based on local knowledge mapping data. Maximum reported abundance shown.

CHADBOURNE
Waypoint: N 44° 00.816' W 069° 12.356'

Site Characteristics: Straight shore. Open to harvesting year-round, barring extreme rainfall events and subsequent closure.

Access: Chadbourn is located in Newcastle, ME just off of Pleasant Street. Navigate towards 3 Pleasant Street. The road begins as 'Liberty Street' and then becomes 'Pleasant Street'. Drive to the end of the street and down a small driveway at the very end of the street until you see a dirt loop. Park in the loop and follow the path on the river side of the loop that leads down to the water. The site is just south of the dock (to the right of the dock) at the end of the path.

Figure G.4 Chadbourne site. Chadbourne site map showing clam abundance (high, medium and low) based on local knowledge mapping data. Maximum reported abundance shown.

APPENDIX H: DAMARISCOTTA COMMUNITY SCIENCE HANDBOOK

COMMUNITY SCIENCE IN THE DAMARISCOTTA RIVER ESTUARY: AN EDUCATIONAL EXPLORATION OF SHELLFISH ECOLOGY & HARVESTER LOCAL KNOWLEDGE

Working Draft | August 2021

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The Darling Marine Center recognizes that it is located in South Bristol along the Damariscotta River in the homeland of the Wabanaki Tribal Nations, where issues of water and territorial rights, and encroachment upon sacred sites, are ongoing. The historic Walinakiak Abenaki Tribe and other tribal peoples of the Pemaquid Peninsula area are connected to the modern, consolidated Abenaki Tribal Nation in Quebec and other Wabanaki Tribal Nations—the Passamaquoddy, Penobscot, Maliseet, and Micmac—through kinship, alliances, and diplomacy. The Darling Marine Center recognizes that the Wabanaki Tribal Nations are distinct, sovereign, legal and political entities with their own powers of self-governance and self-determination.

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Photo Credit: Sarah Risley

Shellfish Ecological Survey:
A Method for Assessing Shellfish Ecology in Muddy and Rocky Intertidal Habitats

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SUMMARY:
Updated information on the abundance, distribution, and diversity of shellfish species is incredibly important to effective stewardship of the shellfish resource. This protocol was developed to document population data on commercially important shellfish species in Maine. Surveys are intended to be performed in areas that are important to shellfish harvesters, either as active or historic harvesting grounds, and will ideally be conducted on a consistent annual basis in order to help inform shellfish management decisions. This survey also collects data on the shellfish ecosystem, including information on worms, crabs, and other species who share habitats with shellfish.

INTRODUCTION:
Maine's intertidal shellfish populations support coastal livelihoods and have historically been Maine's second or third most valuable commercial marine fishery (Webber et al., 2021). In 2020 alone, 6.5 million pounds of softshell clams were landed with a value of $15.7 million in Maine, making it the second highest earning fishery in the state (DMR, 2021). Regardless, the shellfish fishery is changing and facing new challenges. Warming waters, increases in predator populations, and decreasing waterfront access are factors that are affecting the shellfish resource and fishery (B. Beal et al., 2018a; B. F. Beal, Coffin, et al., 2020b; Pershing et al., 2015). Therefore, improved knowledge about the state of the shellfish resource in the Damariscotta River Estuary and potential challenges facing the industry is essential for sustainable use and stewardship.

This protocol seeks to combine local ecological knowledge, held by shellfish harvesters, with environmental data on the spatiotemporal population dynamics of Maine's commercially important shellfish species. These environmental and local ecological knowledge data collection methods are meant to promote long-term monitoring by high school students, led by University of Darling Marine Researchers in partnership with high school educators. This protocol is designed to be integrated into high school coursework and can occur in either the fall or the spring semesters of the school year.

Species of commercial importance that are included in this protocol are soft-shell clams (*Mya arenaria*), quahogs (*Mercenaria mercenaria*), American oysters (*Crassostrea virginia*), European oysters (*Ostrea edulis*), blue mussels (*Mytilus edulis*), razor clams (*Ensis directus*), and surf clams (*Spisula solidissima*). Worm species—including blood worms (*Glycera dibranchiata*) and sand worms (*Nereis virens*)—as well as crab species—including green crabs (*Carcinus maenas*), jonah crabs (*Cancer borealis)*, and rock crabs (*Cancer irroratus*)—are also included in this protocol in an effort to take an ecological approach by quantifying the abundance of other intertidal inhabitants that influence and interact with shellfish species. Although all of these species are included in the protocol, the survey can be adapted to focus on particular species of interest or additional intertidal species.

This protocol is designed to target locations that are of current or historic importance to shellfish harvesters and show signs of being shellfish habitat (e.g. clam holes or shells) (Gillespie & Bourne, 2000). The protocol documents important habitat information, including sediment type, percent algal cover, percent rock surface, and siphon hole count in order to understand the relationship between these habitat characteristics and shellfish distribution, abundance, and diversity. The scale at which monitoring occurs can be flexible but should always be consistent from year to year.

PROTOCOL:

1. **Materials:**
   - 40-50 m fiberglass transect tape
   - 1 PVC $0.25m^2$ quadrat (0.5mx0.5m, made of ½” PVC)
   - Clam rake
   - 1 Mesh sieve (for spat samples, 0.25” aperture)
   - Vernier calipers
   - Gallon plastic bags (for spat samples)
   - Clip board
   - Pencils and permanent markers
   - Datasheets (see Appendix 4-5)
   - Field Guides (see Appendix 2)
   - 1-2 wooden stakes (for marking transect areas)
   - Waterproof gloves
   - **Optional*
     - Jet sled (to transport spat samples)
     - Thermometer (if collecting environmental data)
     - Refractometer (if collecting environmental data)

2. **Identifying Shellfish Areas**

2.1. ***Local Ecological Knowledge Surveys***

Shellfish harvesters and Shellfish Committees possess a deep knowledge of the location, species, and abundance of current and historic shellfish populations. Therefore, asking harvesters where they dig and what species they harvest in those areas is an essential first step to this survey protocol. Local ecological knowledge surveys (Appendix 1) should be conducted with harvesters on an annual basis to document important context information and determine the locations of surveys within monitoring sites. This way, field survey participants can ensure that shellfish data is being collected in areas important to harvesters and the shellfish resource.

2.2. ***Walk-Over Surveys***

If for any reason input from shellfish harvesters or the Shellfish Committee is unable to be obtained, a short walk-over survey may be conducted at monitoring sites. This can be done by selectively digging at the site and looking for signs of shellfish species, including shells and siphon holes, or identifying areas with sediments known to be preferred by the shellfish species of interest (e.g. sand, mud, and gravel mixture areas for soft-shell clams). Mark these areas on a printed map of the site, using the maps from the local ecological knowledge surveys (Appendix 1).

3. Determining Tidal Zones

Information on tidal zones boundaries for monitoring sites is helpful for both identifying shellfish habitat areas and exploring relationships between shellfish population abundance and tidal zone distribution. Therefore, although not required, it is helpful to determine tidal zones for each monitoring site.

Tidal delineation can be done three ways:

3.1. Using wooden stakes, mark the high tide mark and the low tide marks on or as close as possible to a 0.0 ft tide. Then visually divide the flat by thirds to identify the high, mid, and low tidal zones.

3.2. Use a GPS or cell phone to mark waypoints/pins every 10-25 m along the high and low tide lines in the site on or as close as possible to a 0.0 ft tide. Then divide the map into three zones in QGIS/GIS to identify the tidal zones.

3.3. Use aerial photography that was taken on, or as close as possible, to a 0.0 ft low tide to estimate tidal zones by dividing the flat area into low, mid, and high tidal zones.

4. Conducting the Survey

Shellfish in the Damariscotta River Estuary live in diverse habitats that range from soft mud and sand to large, seaweed-covered rocks. Because these habitats are so diverse, the shellfish survey is divided into two distinct approaches: a mudflat survey and a rocky survey.

Mudflat Habitat Survey*:* If shellfish harvesters or the walk-over survey indicate that areas below the rock line where the mudflat begins are the most important and are the locations where they actively harvest commercially important shellfish species, then a mudflat survey should be conducted. This survey covers the mid tidal mudflat area just below the rock line of a shore or cove and extends as far down as the subtidal line that is only accessible on negative tides. In the Damariscotta, this survey will generally target quahogs, soft-shell clams, and razor clams. The sediment can be sandy, muddy, gravelly, and may contain small to medium-sized rocks.

Rocky Habitat Survey: If shellfish harvesters of the walk-over survey indicate that areas within the rock line above the mudflats are the most important and are the locations where they actively harvest commercially important shellfish species, then a rocky survey should be conducted. This survey covers the mid-tidal rocky area to the high tide mark. In the Damariscotta, this survey will generally target oysters and quahogs. These areas should have at least 50% rock surface and/or 50% algae cover.

5. *Mudflat Habitat Survey Protocol*

5.1. Before arriving at the site, fill out the datasheet with tide information, moon phase, participants, etc.

- **5.1.1.** *If collecting spat*: Pre-label gallon plastic bags using a permanent marker with the transect and plot number prior to arriving at the site. These bags will be used to collect that spat surface sample for each plot.

5.2. Arrive at the site at least one hour before low tide. Give yourself enough time to park and walk into the site. Locate your survey area using a site map (paper or digital) and other indicators that this is the targeted shellfish area, such as siphon holes or sediment type.

5.3. Prior to beginning the survey, assign roles to each team member. The number of team members determines the number of roles:

- **5.3.1.** *If there are four:* **Digger=** Uses the clam rake to dig out each plot, **Sorter=** Combs through mud—given to them from the digger—for shellfish, **Measurer=** measures each specimen from the sorter, **Recorder=** Records all species and measurements in the datasheet.
- **5.3.2.** *If there are three:* **Digger=** Uses the clam rake to dig out each plot, **Sorter/Measurer=** Combs through mud—given to them from the digger—for shellfish and measures each specimen, **Recorder=** Records all species and measurements in the datasheet.
  - **5.3.2.1.** For groups of four or three, the role of the digger should rotate after each plot. This is to ensure that no one gets too tired, and the searching is thorough each time.
- **5.3.3.** *If there are two:* **Digger/Sorter=** Uses the clam rake to dig out each plot and combs through mud for shellfish, **Measurer/Recorder=** Measures and records all species and measurements in the datasheet.

5.4. Begin by measuring out a 25 m transect within your survey area that is parallel to the low water line. Mark one end of your transect with a wooden stake and then walk out the transect tape until you have reached 25 m. This will delineate the boundaries of the shellfish area in which you will be surveying.

5.5. Start the survey at the end of the 25 m transect. Randomly toss the 0.25 m^2 quadrat within the predefined shellfish area. This is Plot 1. If the plot does not contain siphon holes, throw the quadrat again. Press the quadrat firmly into the sediment or use your hands to outline the plot in the sediment. Remove the quadrat. Record the algae species (if none=NA), the algal cover to the nearest 25% (25%, 50%, 75%, 100%), the sediment type, % rock surface, the number of siphon holes, and any other species visible within the plot.

5.5.1. Siphon holes are usually about the size of the circumference of a pencil. Worm holes are commonly seen near siphon holes but should not be confused with or counted as siphon holes. These holes will either be smaller, closer to the size of a pencil tip, or a similar size but surrounded by a mound of sand.

5.6. Next, if sampling for spat (clams < 10mm), use your hands to remove the top 1-2" of mud from one-half of the plot. Place the sample into your pre-labeled gallon size bag. <u>Samples from all plots will be processed after completing the full survey.</u> The samples can either be:

5.6.1. Sieved at the site using a 5-gallon bucket, sieve, and seawater. Use the jet sled to carry samples down to the waterline, place the sediment in the screen frame and sieve with water. Identify and measure all softshell clam spat.

5.6.2. Transported off the flat using a jet sled and sieved at another location with running seawater. Pour the samples into the screen frame and sieve with water. Identify and measure all softshell clam spat. Note: A collection permit is required to remove shellfish from the flats. All spat samples must be returned to the flats from which they were collected.

5.6.3. **NOTE**: Species other than softshell clams will be present in the samples. Use a hand lens to distinguish between species.

5.7. Now prepare to dig out your plot and look for shellfish. Prior to digging the plot, the digger will clean the sediment away from one edge of the plot to make it easier to dig.

5.8. Next, the digger will use the clam rake to dig the plot edge-to-edge, down to a depth of at least 8" or until no more clams are found. They will use the rake to cut the mud into thin slices (~1") and use their hands to remove the sediment from the plot, placing it to the side of the plot for the sorter.

5.8.1. Think of the plot like a grid and dig slice by slice, making sure to not take overly large sections. Make sure that the rake goes as far down as possible by alternating between carefully wiggling it and pushing it down.

5.8.2. If the slice you are digging contains, or is near a siphon hole, move the entry site of the rake so that you are not digging directly into the hole. Take even greater care pushing the rake into sections like these to try to minimize the number of clams punctured by the rake.

5.8.3. If you are digging in an area where you think there are clams, it is sometimes easier and safer to use your hands than to use the rake.

5.9. The sorter will search through the sediment and will identify all living shellfish specimens. They will set the shellfish specimens into the sieve to be measured. If there is a measurer, measure the shellfish as you dig. If there is not, measure all shellfish after the plot is complete. See Appendix 3 for guidelines on how to measure shellfish.

5.10. The recorder will mark the presence of any worms (Appendix 2C) or crabs (Appendix 2c) in the datasheet and will record the carapace width of any crabs found. The recorder will also mark down all shellfish species and their measurements. They will need length measurements for soft-shell clams, length and height measurements for oysters, and length and hinge measurements for quahogs (see: Appendix 3).

5.10.1. When you find a worm, even if you have found many before, you still need to take the time to distinguish if it is a bloodworm or a sandworm (Appendix 2C). If you find just a piece of a worm, odds are likely that you have already counted another piece of it, so this piece should not be counted. After you count a worm, throw it far away to make sure that it doesn't get recounted.

5.11. Once the plot is completely dug out and all specimens are recorded and measured, return all specimens to the plot, covering them up with mud.

5.11.1. A completely dug out plot will be dug as far down as possible, or until clams are no longer being found. You will typically either hit clay or water will start pooling at the bottom.

5.12. Randomly toss the 0.25 m² quadrat again for Plot 2, so that you are progressing through the predefined shellfish area. Repeat the digging, sorting, and measuring process. Continue sampling until a total of 5 plots are completed.

5.12.1. As a reminder, for groups of four or three, the role of the digger should rotate after each plot. This is to ensure that no one gets too tired and the searching is thorough each time.

6. *Rocky Habitat Survey Protocol*

6.1. Before arriving at the site, fill out the datasheet with tide information, moon phase, participants, etc.

6.2. Arrive at the site at least one hour before low tide. Give yourself enough time to park and walk into the site.

6.3. Locate your survey area using a site map (paper or digital) and other indicators that this is the targeted shellfish area, such as rock surface or algal cover.

6.4. Prior to beginning the survey, assign roles to each team member. It is important that each team member sticks with their role so that the survey is consistent. The number of team members determines the number of roles:

6.4.1. *If there are four:* **Searcher=** Uses hands (with gloves) to search under algae, rock, and in mud for specimens, **Measurer 1 and Measurer 2=** Measures each specimen, **Recorder=** Records all species and measurements in the datasheet.

6.4.2. *If there are three:* **Searcher=** Uses hands (with gloves) to search under algae, rock, and in mud for specimens, **Measurer=** Measures each specimen, **Recorder=** Records all species and measurements in the datasheet.

6.4.3. *If there are two:* **Searcher=** Uses hands (with gloves) to search under algae, rock, and in mud for specimens, **Measurer/Recorder=** Measures each specimen and records all species and measurements in the datasheet.

6.5. Begin by measuring out a 25 m transect within your survey area that is parallel to the low water line. Mark one end of your transect with a wooden stake and then walk out the transect tape until you have reached 25 m. This will delineate the boundaries of the shellfish area in which you will be surveying.

6.6. Start the survey at the end of the 25 m transect. Randomly toss the 0.25 m^2 quadrat within the predefined shellfish area. This is Plot 1. If the plot does not contain at least 50% rock surface and/or 50% algae cover, throw the quadrat again. Record the algae species (if none=NA), the algal cover to the nearest 25% (25%, 50%, 75%, 100%), the sediment type, % rock surface, the number of siphon holes, and any other species visible within the plot.

6.6.1. Again, siphon holes are usually about the size of the circumference of a pencil. Worm holes are commonly seen near siphon holes but should not be confused with or counted as siphon holes. These holes will either be smaller, closer to the size of a pencil tip, or a similar size but surrounded by a mound of sand.

6.7. The searcher will then explore within the quadrat, section by section, looking under algae and rocks for any shellfish specimens. They will feel through the top layer of sediment for any unattached oysters or quahogs. If there are distinct siphon holes, they will spot dig where the hole is to try to find the soft-shell clam. They will give any unattached shellfish specimens to the measurer(s). They will point out any attached shellfish

specimens that need to be measured. See Appendix 3 for guidelines on how to measure shellfish.

- **6.7.1.** Think of the plot as if it is split into quarters and thoroughly search through one section at a time. Clear away as much seaweed as possible and check along the edges and corner before moving onto the next quarter section.

6.8. The recorder will mark the presence of any worms (Appendix 2C) or crabs (Appendix 2E) in the datasheet and will record the carapace width of any crabs found. The recorder will also mark down all shellfish species and their measurements. They will need length measurements for soft-shell clams, length and height measurements for oysters, and length and hinge measurements for quahogs (Appendix 3).

- **6.8.1.** Again, when you find a worm, even if you have found many before, you still need to take the time to distinguish if it is a bloodworm or a sandworm (Appendix 2C). If you find just a piece of a worm, odds are likely that you have already counted another piece of it, so this piece should not be counted. After you count a worm, throw it far away to make sure that it doesn't get recounted.

6.9. Once the plot is completely searched and all specimens are recorded and measured, return all specimens to the plot, covering them up with sediment or algae.

6.10. Randomly toss the 0.25 m² quadrat again for Plot 2, so that you are progressing through the predefined shellfish area. Repeat the searching and measuring process. Continue sampling until a total of 5 plots are completed.

7. Data Entry & Analysis:

- Scan and upload paper data sheets to the shared Google drive folder.
  - Scanning can be done through the notes app on an iPhone.
- Enter data into the Shellfish Ecological Survey Excel sheet.
  - Enter site information first,
  - Enter worm and crab information next,
  - Enter shellfish information (plot and surface sample spat data) last.
    - Make sure that each worm, crab, and shellfish found gets its own line in the spreadsheet.

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The protocol below is courtesy of Dr. Marissa McMahan and Manomet. Green crabs are voracious predators that affect many important bivalve shellfish species[8,9]. Therefore, learning about the spatial distribution and abundance of green crabs in the Damariscotta River Estuary offers insights into how, where, and to two degree these predators may be affecting shellfish populations.

A method for assessing intertidal populations of the invasive European green crab

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SUMMARY:
Understanding spatiotemporal patterns in green crab population dynamics is essential for predicting and managing the ecological and economic impacts of this harmful invasive species. This protocol was developed in an effort to create a standardized method for assessing green crab populations in the rocky intertidal zone of the Northwest Atlantic.

INTRODUCTION:
Biological invasions can potentially disrupt species interactions and ecological processes, and may have far reaching ecological[1,2,3] and economic consequences[4]. The ability to successfully predict, mitigate, and adapt to invasions strongly depends on characterizing spatiotemporal population dynamics[5]. While a range of tools exist (e.g., population genetics, stable isotopes) and are emerging (e.g., eDNA) for tracking invasive species, traditional in-situ monitoring techniques continue to be widely utilized for assessing invasive species distribution and abundance.

The European green crab (*Carcinus maenas*) is an invasive species that was first detected in North America in 1817 and has successfully invaded ecosystems worldwide[6,7]. Green crabs have a multitude of negative impacts on local ecosystems, including reducing native bivalve populations through predation[8,9], competing with native crustaceans for food and shelter[10,11,12] and destruction of eel grass habitat and subsequent changes to fish community structure[12,13,14]. Compounding these issues is the link between increasing green crab abundance and increasing ocean temperature[15,16], which has had severe ecological and socio-economic consequences in areas such as the Gulf of Maine, where warming is occurring faster than 99% of the world's other oceans[17].

On the eastern seaboard of North America, green crabs range from Virginia to Newfoundland. They are most commonly found on wave-protected shorelines, estuaries, and embayments in depths ranging from the high tide level to 5-6 m[18]. Their presence in the intertidal zone makes them an ideal marine species for shoreline surveys. There are many organizations, researchers, citizen scientist groups, and educators currently conducting green crab population monitoring. However, the lack of a standardized protocol makes it difficult to compare datasets and to ultimately understand green crab populations on both a local and regional scale.

This protocol is designed to quantify spatiotemporal population dynamics of green crabs in the rocky intertidal zone in New England and Atlantic Canada. Ideally, the development of a standardized, inexpensive, and easily adaptable survey will promote long-term monitoring efforts by a wide range of users, including researchers, citizen scientists, educators, and students. The scale at which monitoring occurs can be flexible but should always be consistent from year to year. For example, this protocol was developed in Maine and is conducted on a monthly basis from April-November each year. Sampling does not occur from December-March because intertidal crab populations become scarce in the winter months, and accessing the shoreline can be dangerous in cold, icy conditions. Investigators in southern New England will likely have a wider seasonal sampling window due to more mild winter conditions, and investigators in Atlantic Canada will likely have a narrower sampling window. Some users, such as school groups, may be confined to sampling once or twice per year, in which case they should always sample during the same time periods, and at the same sites, so data can be compared across sites and years.

Although green crabs are the target species of interest in this protocol, data is also collected for native Jonah and rock crabs (*Cancer borealis and Cancer irroratus*), as well as the invasive Asian shore crab (*Hemigrapsus sanguineus*). These are crab species commonly found in the rocky intertidal zone in northern New England, and trends in their population distribution and abundance have ecological and economic significance. The survey can be adapted to include other species of interest that may occur in the areas where it is utilized (e.g., mud crabs may be a species of interest in southern New England).

PROTOCOL:

1. **Materials:**
   - 40 m fiberglass transect tape
   - 1 m^2 quadrat (made from 1/2" PVC)
   - Vernier calipers
   - Clip board
   - Pencils
   - Data sheets (see Appendix 7)
   - 5 gal bucket
   - Waterproof gloves

   *Optional:
     - Color protocol (Appendix 6)
     - 1/2" Rebar
     - Thermometer
     - Refractometer

2. **Site selection and description**

2.1) Locate a wave-sheltered rocky intertidal site with cobble and algal canopy habitat. The first site visit should be scheduled during an average low tide (i.e., tidal height as close to 0.0 m as possible), as determined from the NOAA Tide Predications website (https://tidesandcurrents.noaa.gov/tide_predictions.html?gid=1401), and should be set aside specifically for site description activities as there will likely not be time for conducting an actual survey on the same day. Plan to arrive at the survey site at least 1 hr before low tide.

2.2) Determine the area of the shoreline where the survey will be conducted by running a transect tape vertically from the low intertidal zone (i.e., the splash zone on an average 0 m low tide) to the high intertidal zone (i.e., the black microalgal zone that is typically dry at high tide) as close to the scheduled low tide time as possible. Divide the resulting distance into three equal sections (high, middle, and low). This is a relatively simple method of determining tidal range that can be deployed by a wide range of users (i.e., it does not require specialized equipment or rigorous methodology). The survey is conducted in the low section and parallel to the shoreline. Establish permanent markers delineating the low intertidal zone parallel to the shoreline using rebar or natural permanent landmarks such as immovable boulders, ledge, dock pilings, etc. The use of permanent markers allows the investigator to avoid having to delineate the shoreline using a transect tape on every visit.

2.3) Record the location of the study site using a global positioning system (GPS) unit, or a device such as a smart phone that has GPS capability (e.g., many compass apps are free to download or are already pre-programmed on smart phones). Record written site coordinates in degrees, minutes, and seconds (DMS) format (e.g., 43°48'14.2"N, 69°44'50.5"W) on a site description data sheet. The site description data sheet should also include directions to the site, instructions for parking and accessing the shoreline, and a description of how the low intertidal is delineated (i.e., natural landmarks, permanent markers, etc.). Any other special considerations unique to the site should also be noted.

3. **Conducting survey**

3.1) Prior to arriving at the survey site, the following information should be recorded on the Intertidal Survey data sheet (see Appendix 1 for example): site name, sampling date, participants, time and height of low tide at the location/date you will be sampling (determined using the NOAA Tide Predications website, or an app such as Tides), and lunar phase (determined using a lunar calendar such as www.moongiant.com).

3.2) Surveys occur within a two hour window of time straddling one hour before and one hour after mean low water, as this is the window in which the low intertidal zone is exposed. Plan to arrive at the survey site early enough to park, get to the survey area, unpack, and start the survey 1 hr prior to low tide. Upon arriving at the shoreline area where you will be sampling, unpack and setup gear including the 1 m2 quadrat, clipboard with Intertidal Survey data sheet and color protocol (if using), calipers, and a small bucket. Water temperature and salinity measurements are optional but should be taken prior to the start of the survey using a thermometer and refractometer in the water directly adjacent to the survey area.

3.3) To begin the survey, randomly toss the 1 m^2 quadrat within the predefined low intertidal zone area that runs parallel to the shoreline (a transect tape is not needed to conduct the survey because the sample area has already been defined). Record a visual estimate of the percent of both moveable rock and algae canopy cover (e.g., *Ascophyllum* or *Fucus spp.*) within the quadrat to the nearest quarter percent (i.e., 0, 25, 50, 75, or 100%). Rocky intertidal habitat is often patchy and can contain areas of sand, mud, ledge, or other habitats where green crabs are not found. To avoid skewing density estimates by sampling unsuitable habitat, only quadrats with greater than 50% movable rock, or greater than 50% algal canopy, are sampled.

3.4) Within each quadrat, lift moveable rocks or cobble and carefully move aside algae to look for crabs. Be sure to replace all rocks and algae as you found them. Collect all of the crabs you find and store them in a bucket until the entire quadrat has been searched.

3.5) For each crab, identify and record the species (to save space, species codes are used on the Intertidal Survey sheet (Appendix 1) and measure the carapace width (CW) to the nearest 1 mm using Vernier calipers. Additional characteristics recorded for all crab species include sex, number of claws, number of legs, shell condition (i.e., hard- or soft-shell as determined by whether the shell resists (hard) or gives (soft) when finger pressure is applied), and the presence (i.e., ovigerous) or absence of extruded eggs for females. Sex and shell condition are often difficult to determine for crabs measuring less than 10 mm. To avoid this common measurement error, 'NA' (not available) is recorded for these categories for crabs ≤ 10 mm.

3.6) Color is an optional characteristic that can be recorded for green crabs, but not other crab species, using the color protocol developed by Young and Elliot[17] (Appendix 2). Investigators should print a copy of this protocol and bring it with them if they choose to collect color data. The pre-molt shell condition is also an optional characteristic that can be recorded for green crabs if the investigator is comfortable identifying external pre-molt indicators (see Appendix 3 for example). Pre-molt green crabs are within 3 weeks of molting and are of particular interest to the emerging soft-shell green crab fishery[19,20,McMahan unpublished data]. Color and pre-molt condition are not determined for green crabs ≤ 10 mm ('NA' is recorded).

3.7) Return all crabs to the habitat within the quadrat once all measurements and characteristics have been recorded.

3.8) Continue randomly tossing the quadrat within the predefined low intertidal area until you have sampled a total of 10 m^2. Continually move forward along the low intertidal area of shoreline to ensure that resampling does not occur.

4. Data management and analysis

4.1) Post-survey, all raw data sheets should be checked for errors and legibility, copied, scanned, and archived. The copy is used for data entry into an excel spreadsheet (see Appendix 4 for example) and then also archived. Scanned data sheets are stored electronically.

4.2) Data analysis can be simple or complex, depending on the needs of the investigator. Density is perhaps one of the easiest and most useful calculations. Site density is calculated by dividing the total number of crabs by the total number of quadrats sampled. Other useful metrics to calculate include, but are not limited to, sex ratio, cumulative size frequency, injury rate, shell condition ratio, and overall species encounter rates (e.g., % of native vs. invasive crabs).

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The protocol below is courtesy of Dr. Brian Beal, Sara Randall, and the Downeast Institute. Studying softshell clam recruitment and green crab predation is important to understand current and future shellfish population in the Damariscotta River estuary.

Downeast Institute Soft-Shell Clam Monitoring Network Methods

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ADAPTED FROM: Soft-Shell Clam Recruitment Monitoring Network Technical Report: 2020 Spring Baseline Clam Survey Results

Reference: Beal, B.F. and S.F. Randall. 2020. Soft-Shell Clam Recruitment Monitoring Network Technical Report #1: 2020 Spring Baseline Clam Survey Results. Downeast Institute, Beals, ME. 39 pgs.

SUMMARY:
For more than three decades, commercial landings of soft-shell clams in Maine have been declining, and this has occurred at the same time that sea surface temperatures (SSTs) in the Gulf of Maine have been increasing. While many factors contribute to the productivity of intertidal flats along the Maine coast, seawater temperature is a critical driver that influences everything from spawning and reproduction to predation (by both native and invasive species), as well as sediment chemistry which affects the ability of clams of all sizes to produce their protective shells. Clam landings are used as a proxy for clam production, but do not tell the entire story because of annual, regional, and seasonal differences in fishing effort. Fisheries-independent data sources, however, do exist. During the past two decades, with help from students, clammers, and municipal officials, the Downeast Institute (DEI) and the University of

Maine at Machias (UMM) have taken thousands of sediment cores from clam flats from Kittery to Lubec To measure clam densities as well as their sizes. Results of those sampling efforts align with the 30-year downward trend in commercial clam landings. Additionally, DEI and UMM scientists have conducted hundreds of field experiments at various locations along the coast. Results of these trials generally indicate that fewer clams are reaching commercial sizes now than in the past (i.e., research published in Beal et al., 2018; Beal et al., 2016). The Soft-Shell Clam Recruitment Monitoring Network was created to standardize fisheries-independent data collection, and to begin building a long-term database. By deploying identical monitoring units at intertidal sites spanning the coast, we can begin to quantify differences in clam recruitment and survival at local, regional, and statewide scales. This effort may inform new measures to better manage soft-shell clam resources during a period of warming seawater and help reverse the 40-year trend of declining landings.

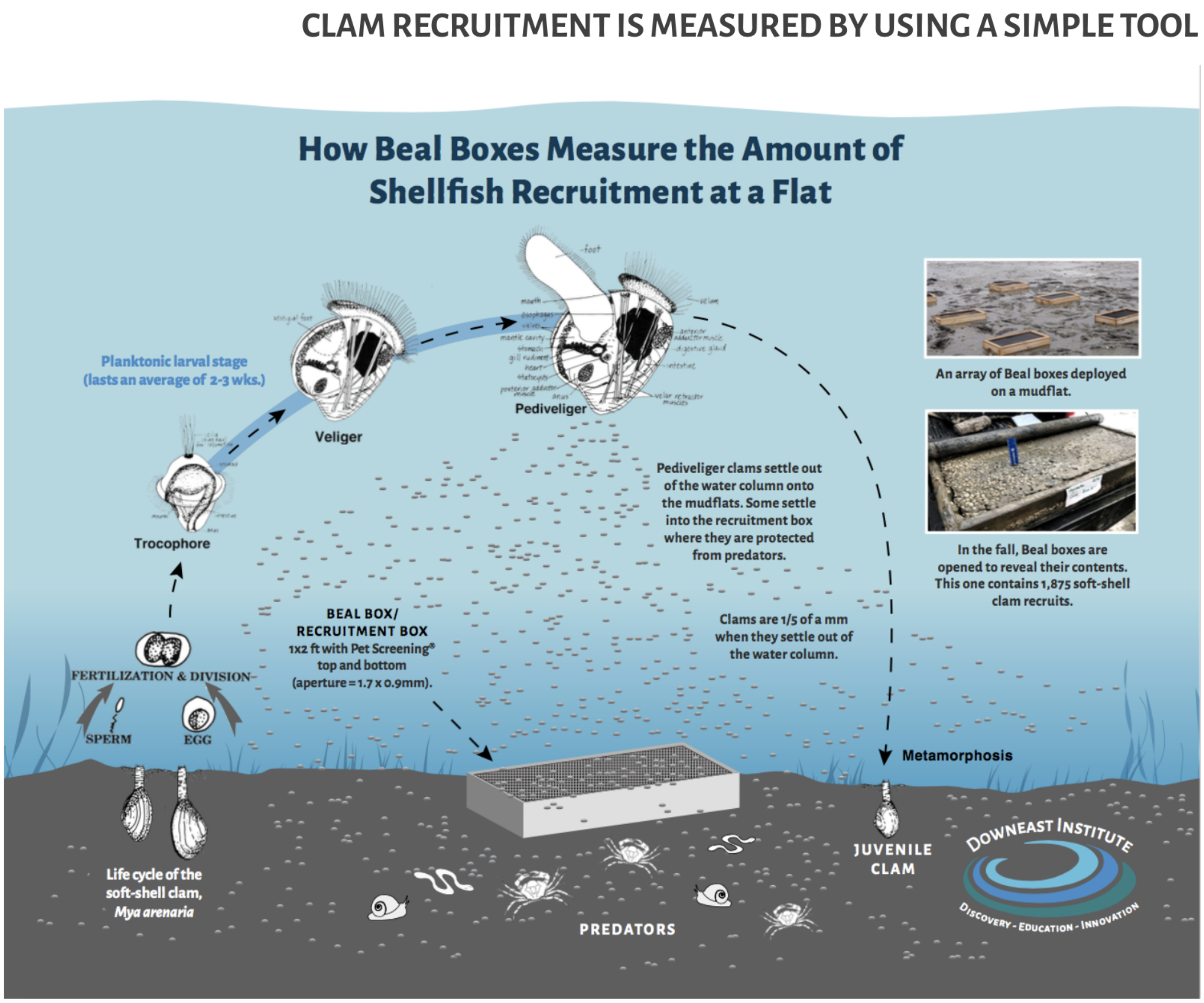
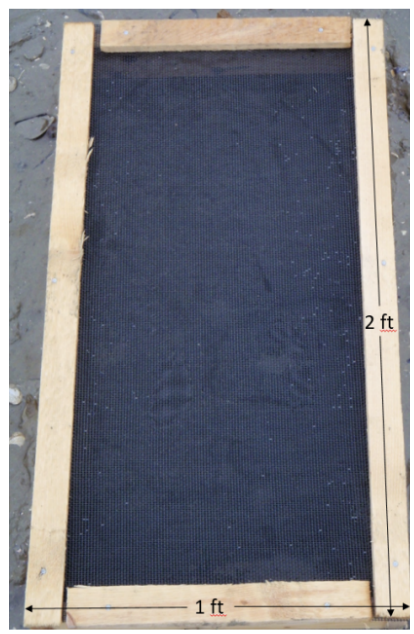


Image from https://downeastinstitute.org/research/soft-shell-clams/soft-shell-clam-recruitment-monitoring-network/

INTRODUCTION:
Measuring Clam Recruitment and Survival
In 2015, DEI scientists began using a new tool, the soft-shell clam recruitment box (Figure 1), to examine what recruitment looks like in a predator-protected environment compared to the unprotected environment of a mudflat. In April, prior to the clam spawning season, the scientists, along with clammers from the Maine Clammers Association, deployed 120 boxes in the Harraseeket River in Freeport, Maine (six boxes in each of 10 sites along both the east and west side of the river from near the mouth to the head) and sampled the boxes in November. Results of that study were published in the Journal of Shellfish Research (Beal et al., 2018), and can be found here: https://downeastinstitute.org/wp-content/uploads/2018/ 08/035.037. 0101.pdf.

Subsequently, DEI staff has worked with others who have used the boxes to determine soft-shell clam recruitment rates in a variety of coastal communities, including Cutler, Machiasport, Gouldsboro, Sullivan, Bar Harbor, Blue Hill, Penobscot, Deer Isle, Stonington, Islesboro, Searsport, Thomaston, South Thomaston, Bremen, Damariscotta, and Harpswell. DEI established a coastwide Soft-Shell Clam Recruitment Monitoring Network in early May 2020 to standardize the survey methods and expand the geographic footprint of this work. This network is funded for two years (February 2020-2022) through the Maine Sea Grant College Program. We are seeking other sources of funding to continue and expand the Network to build a comprehensive, long term data set that can be used to predict future trends in recruitment, similar in concept to the American Lobster Settlement Index (ALSI).

Recruitment boxes: Soft-shell clam recruitment box. A soft-shell clam recruitment box made of spruce strapping, 1-ft x 2-ft x 3 inches deep. The top and bottom are lined with heavy-duty window screening called PetScreen © made from vinyl-coated polyester that is 7x stronger than fiberglass and aluminum screening. Boxes are anchored to the mudflat surface by pounding a 20-inch wooden lath at each short end into the sediment to a depth of 17-inches. Galvanized trap nails are used to attach the lath to the box.



Soft-Shell Clam Recruitment Monitoring Network

The overarching goals of the Soft-Shell Clam Recruitment Monitoring Network are to: • Increase visibility and public awareness of a fishery that is threatened by a dramatically changing marine environment; • Create an extensive data set for shellfish managers to better understand factors that affect the fishery; and, • Encourage participation and learning by coastal residents including clammers, shellfish committee members, and other municipal officials as well as K-12 grade students, their teachers and parents.

The main goal of the coastwide network is to observe soft-shell clam recruitment in predator protected boxes from May to November and compare those results to core samples taken in November from the ambient mudflat surrounding the boxes. Differences in density or clam size between the cores and boxes likely is due to predation. Nine communities with vital commercial or recreational shellfish programs across the coast of Maine have partnered with DEI to create the Network. In an effort to obtain recruitment information from a representative sample of the coast, locations were equally divided between three regions of the Maine coast (southwest, midcoast, downeast) (Table 1; Fig. 5).

During the first two weeks of May 2020, within each community, recruitment boxes were placed in the lower mid-intertidal gradient at two flats. Standardizing placement at this tidal height on the flats allows for less ambiguous results. Deployment of the boxes and initial baseline clam density/clam size surveys occurred prior to clam spawning. Boxes were deployed during week one in each of the three southwest and one midcoast communities, while the remaining five communities began the project during week two. Because water temperatures trigger clam spawning, it is most likely for clams to spawn in midcoast and southern Maine prior to eastern Maine. In addition, we introduced a small-scale experiment at each flat to compare the effectiveness of two different types of recruitment boxes. In more dynamic intertidal environments (typically characterized by sandy or gravelly sediments) we have observed erosion occurring under boxes, which can create gaps between the bottom of the box and the mudflat surface. Because the settling clams are many times smaller than the aperture of the PetScreen® (1.7 mm), they may enter the box from the top and exit immediately through the bottom into the gap. From previous field studies, it appears that woven ground cover bottoms may retain settling clams better than the PetScreen® bottoms in these conditions. To test this, one-half of the boxes at each flat have both a PetScreen® top and bottom, while the remaining half have a PetScreen® top and a ground cover bottom. The ground cover is constructed of UV-stabilized woven polypropylene. 1

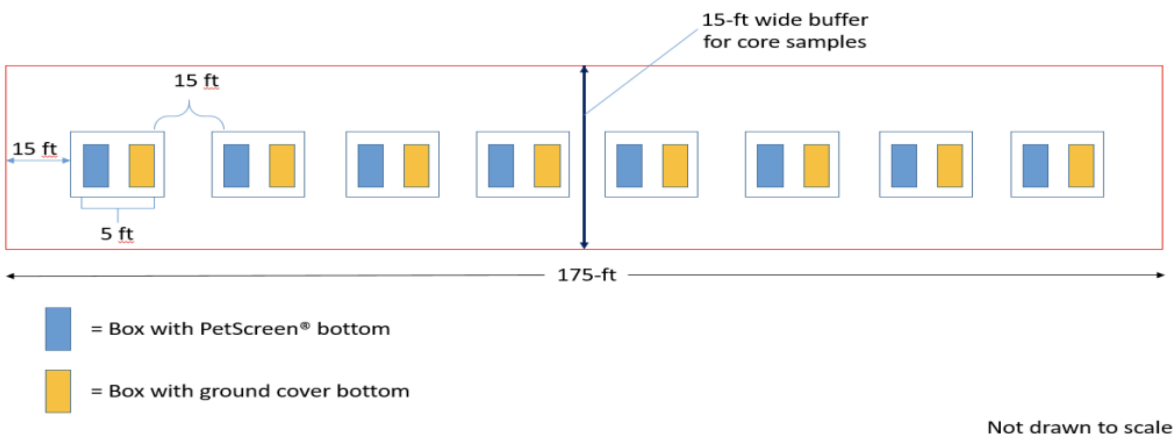
METHODS

Field Design

The experimental design we used is referred to as a “randomized complete block design” (Figure H.2). Blocks consist of two boxes approximately 3-ft apart: one with a screened bottom and the other with a ground cover bottom. Eight blocks (16 boxes) were installed at each flat with approximately 15-ft between each block.

In addition to soft-shell clams, recruitment boxes collect other organisms that can settle through the 1.7 mm mesh or that can crawl in through the mesh. Organisms that we have observed in the typical boxes (those with PetScreen® tops and bottoms) include other bivalves with planktonic larvae, such as: American oysters, European oysters, Baltic macomas, Blue mussels, False angel wings, Razor clams, Surf clams, Hard clams (quahogs), and False quahogs. We have also found several species of snails, such as: periwinkles, mud snails, and oyster drills. Other species we have encountered include bloodworms,sand worms, and sand shrimp. Finally, boxes do not completely deter predators, as we have found green crabs in some boxes. Green crabs can enter the boxes via settlement from the plankton (at sizes less than 1.5 mm in carapace width) or can crawl in through the aperture of the mesh shortly after they settle to the flats. Crabs that molt or shed can become entrapped in the recruitment box and prey on the clams and other organisms.

The Clam Recruitment Monitoring Network experiments don't require controls because findings from two previous field studies, conducted in 2016 and 2018, allowed us to reach some important conclusions. In these studies DEI scientists placed control boxes (i.e. wooden frames without any screening on top or bottom) on the mud and determined that the number of clams found in the controls did not differ significantly from the number of clams found in core samples taken from the adjacent mudflat. The 2018 field study also tested several additional types of controls. These included boxes with: 1) complete bottoms and tops with one-quarter of the PetScreen® removed; 2) complete bottoms and tops with three-quarters of the PetScreen® removed; 3) complete bottoms and no tops; and, 4) no bottoms and complete tops with PetScreen®. The average number of clams per square foot and average clam size were measured, and neither differed significantly between core samples taken from the control and those taken in the adjacent mudflat. These results verify that recruitment boxes do not attract clams but are simply static collectors that reflect recruitment conditions at the particular site.



Field layout: Field layout of recruitment boxes.

Deployment

Sixteen boxes were deployed in a line parallel to the water's edge just above the mean low tide (0.0 ft) level at each site. Boxes were placed according to the field layout (Figure 2) and anchored to the mudflat using stakes or lath (Figure 1). After recruitment boxes were installed at each flat, we took bottom core samples (N = 16) using a coring device that was 6-inches in diameter x 6-inches deep (approximately 0.02 ft2). Two samples were taken from each of the eight blocks (Figure H.2) at a distance several feet away from each box.

Boxes were deployed in the early summer, prior to clam spawning. Our study deployed boxes within the 'Midcoast' region data range, in early May (see table H.1).

Region	Community	Flat	Latitude	Longitude	Date
Southwest	Wells	Dolphin Lane	43.312598	-70.566041	05/02/2020
		Upper Landing	43.328310	-70.564968	05/02/2020
	Scarborough	Jones Creek	43.545055	-70.337574	05/05/2020
		Winnock Neck	43.563433	-70.332752	05/05/2020
	Brunswick	Harpswell Cove	43.851390	-70.337574	05/03/2020
		Thomas Point	43.889054	-69.891326	05/03/2020
Midcoast	Wiscasset	Cushman Cove	43.980916	-69.675589	05/06/2020
		Maine Yankee	43.949494	-69.698933	05/06/2020
	Bremen	Sam's Cove	43.987371	-69.424402	05/14/2020
		Broad Cove	44.029679	-69.410194	05/14/2020
	Islesboro	Little Broad Cove	44.307537	-68.899876	05/12/2020
		Ryder Cove	44.342229	-68.888036	05/12/2020
Downeast	Lamoine	Raccoon Cove	44.467405	-68.284742	05/13/2020
	Franklin	Hog Bay	44.574758	-68.223165	05/13/2020
	Beals	Squid Pond	44.504950	-67.602240	05/11/2020
		Perio Point	44.521038	-67.609106	05/11/2020
	Sipayik	Half Moon Cove	44.951776	-67.043796	05/15/2020
		Gleason Cove	44.967142	-67.054778	05/15/2020

Deployment dates Deployment dates of 2020 soft-shell clam recruitment boxes. Our study deployed boxes within the midcoast region date range: May 12-14, 2021.

Recruitment Box Collection and Processing

Recruitment boxes remained in the field until November 2021 when they were removed and the contents of each washed through a 1 mm sieve. All clams from each box were counted, and a representative sample of individuals measured to give an estimate of the distribution of sizes. In addition, the adjacent (unprotected) mudflat was sampled using the same 6-inch diameter x 6- inch deep coring device used in May. The number and size of clam recruits in the core samples were compared to what was found in the recruitment boxes. The difference in number per square foot and/or size distribution of clams between boxes and the core samples reflects the difference that this type of predator protection affords (aka the recruit "survival rate"). Knowing the survival rate gives Shellfish Committees information about why a flat is commercially productive or not.

REFERENCES

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2. Beal, B. F., Nault, D.- M., Annis,H., Thayer, P., Leighton, H., & B. Ellis. 2016. Comparative, large-scale field trials along the Maine coast to assess management options to enhance populations of the commercially important soft-shell clam, Mya arenaria L. Journal of Shellfish Research 35(4), 711–727.

APPENDIX I: COMMUNITY SCIENCE ANALYSIS TABLES

Table I.1 Summary statistics for all species of interest (SS=softshell clam, Q=quahog, GC=green crab) at the study sites (n=3). Data for Day's Cove was excluded from further analysis due to high algal cover on the boxes that impeded their functioning and impacted results.

Site	Treatment	Species	variable	n	mean	sd
Chadbourne	Core	GC	Count_m2	8	0.000	0.000
Chadbourne	Core	Q	Count_m2	8	0.000	0.000
Chadbourne	Core	SS	Count_m2	8	0.000	0.000
Chadbourne	Groundcloth	GC	Count_m2	8	1.655	3.065
Chadbourne	Groundcloth	Q	Count_m2	8	1.655	3.065
Chadbourne	Groundcloth	SS	Count_m2	8	3.310	3.539
Chadbourne	Petscreen	GC	Count_m2	8	0.828	2.341
Chadbourne	Petscreen	Q	Count_m2	8	3.310	3.539
Chadbourne	Petscreen	SS	Count_m2	8	19.861	16.598
Days_Cove	Core	GC	Count_m2	8	0.000	0.000
Days_Cove	Core	Q	Count_m2	8	0.000	0.000
Days_Cove	Core	SS	Count_m2	8	5.139	7.770
Days_Cove	Groundcloth	GC	Count_m2	8	0.000	0.000
Days_Cove	Groundcloth	Q	Count_m2	8	0.000	0.000
Days_Cove	Groundcloth	SS	Count_m2	8	0.000	0.000
Days_Cove	Petscreen	GC	Count_m2	8	0.000	0.000
Days_Cove	Petscreen	Q	Count_m2	8	0.000	0.000
Days_Cove	Petscreen	SS	Count_m2	8	0.000	0.000
Lowes_Cove	Core	GC	Count_m2	8	0.000	0.000
Lowes_Cove	Core	Q	Count_m2	8	0.000	0.000
Lowes_Cove	Core	SS	Count_m2	8	0.000	0.000
Lowes_Cove	Groundcloth	GC	Count_m2	8	19.861	13.241
Lowes_Cove	Groundcloth	Q	Count_m2	8	0.000	0.000
Lowes_Cove	Groundcloth	SS	Count_m2	8	1.655	4.681
Lowes_Cove	Petscreen	GC	Count_m2	8	19.033	20.766
Lowes_Cove	Petscreen	Q	Count_m2	8	0.000	0.000
Lowes_Cove	Petscreen	SS	Count_m2	8	4.138	11.703

Table I.2 Summary statistics for the softshell clam recruitment study (n=2 sites). Upper=Chadbourne site, Lower=Lowe's Cove site, SS=softshell clam.

Treatment	Species	site_gen	variable	n	mean	sd
Petscreen	SS	Lower	Count_m2	8	4.138	11.703
Petscreen	SS	Upper	Count_m2	8	19.861	16.598

Table I.3 Summary statistics for the shellfish ecological survey (n=3 sites). AO=American oyster, SS=softshell clam, Q=quahog. Data collected later July to early August 2021.

site	species	variable	n	mean	sd
Chadbourne	AO	count_m2	10	11.6	17.933
Chadbourne	Q	count_m2	10	1.2	1.932
Chadbourne	SS	count_m2	10	5.6	7.106
Days Cove	AO	count_m2	10	11.6	17.122
Days Cove	Q	count_m2	10	3.2	5.266
Days Cove	SS	count_m2	10	12.0	9.238
Westview	AO	count_m2	10	15.2	17.054
Westview	Q	count_m2	10	2.4	5.060
Westview	SS	count_m2	10	13.6	22.564

BIOGRAPHY OF THE AUTHOR

Sarah Corrine Risley was born in Rochester, New York on December 31, 1990. She was raised in Geneseo, New York and graduated from Geneseo Central School in 2009. She attended Skidmore College and graduated *Summa Cum Laude* in 2013 with a bachelor's degree in Environmental Studies. Sarah worked in the fields of education, agriculture, and food system justice for five years before deciding to return to the sciences. She moved to Maine to pursue an advanced degree in marine science and, after serving as a research assistant studying small-scale fisheries in the Dr. Joshua Stoll lab, entered the dual Marine Biology and Marine Policy program in the summer of 2019. Sarah is a candidate for the Master of Science Degrees in Marine Biology and Marine Policy from the University of Maine in May 2022.