The Natural History of the Milky Ribbon Worm: As Told by Maine Clam Diggers

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Abstract

This thesis provides a natural history-based background for the ecology of the milky ribbon worm *Cerebratulus lacteus* by utilizing the knowledge possessed by Maine clammers. Over recent years, the impact of the milky ribbon worm, a predatory worm that preys on soft-shell clams along the intertidal zones of the Gulf of Maine, has rapidly increased. There have not been many ecologically based studies on the milky ribbon worm, providing a rare opportunity to revert to the roots of ecology and gather the natural histories of this organism. Natural history has an important role in contemporary ecology as it provides the baseline knowledge of organisms, processes, and ecosystems that can then be used to develop future scientific research questions. Participatory research is a way to incorporate local ecological knowledge into scientific studies, that otherwise may not have been accessible by more contemporary, scientific means. This thesis uses participatory research methodologies to interview clammers about their experiences with the milky ribbon worm. Based on information gathered through these interviews, this study recommends further research on the milky ribbon worm be focused on the preferred sediment structures and textures of their habitat, the softening of mudflats in coastal Maine, the impact of increasing temperature on milky ribbon worms, the mechanisms by which milky ribbon worms find their prey, and milky ribbon worm behaviors that may provide opportunities for catching large numbers at one time.

Introduction

The purpose of this thesis was to develop an ecological understanding of the milky ribbon worm, based on natural histories, by utilizing the knowledge possessed by Maine clammers. A predatory worm that feeds mainly on bivalve mollusks, the species is having a major negative impact on the clamming industry in Maine. My end goal was to identify avenues for future studies exploring the ecology and impact of the milky ribbon worm. This study began with an ecological problem that has tangible impacts on the lives of people along the coast of Maine. Rather than operating in the manner of many contemporary studies in the natural sciences, where a question is developed and researched separate from the interconnections of ecology and human culture, this project, from its inception, through the research, and finally to the end product, has been deeply invested in the interaction between human communities and their local environments. However, it is also different from some stakeholder-focused research studies in that rather than being a direct study of the interactions of humans within a natural system, it is utilizing those interactions in order to glean additional information about the natural system. In short, it is a natural history study using the observational knowledge accumulated by stakeholders over the years and sometimes decades, in order to draw conclusions about how this ecological system operates. It is an exploration of the value of knowledge developed by people who live and breathe these ecological systems and depends on them for their livelihoods. The intention is for the methodologies and results utilized in this study to inform on and add story, narrative, and vision to future quantitatively based studies.

In the first chapter of this thesis I will discuss the contemporary use of natural history in ecology by examining the natural history roots of modern ecology, the importance of local ecological knowledge, and the use of participatory research techniques in ecology. The second chapter will begin with an overview of the existing literature surrounding the ecology of the milky ribbon worm, followed by the compellation of the interviews I conducted with Maine clam diggers. Finally, I will discuss the implications and future research questions that result from these histories. The hope is that this thesis will be used by future researchers to further our knowledge about the milky ribbon worm and lead to mitigation practices that will benefit the stakeholders in this system as well as add to the scientific knowledge base.

Chapter I – The Current Relevance of Natural Histories and Local Ecological Knowledge

I. Introduction – What is Natural History?

The term “natural history” often conjures images of dusty display cases full of hundreds of taxidermy birds, both current and extinct, massive dinosaur bones in entrance halls, miniature dioramas of foreign ecosystems, and slightly off-putting and problematic wax figures of peoples who lives long ago. In short, the image that comes to mind is a museum; a stagnant building, telling the stories of animals and peoples from far away and long ago. These days it is rare for someone to associate “natural history” with contemporary sciences; changing, exciting, groundbreaking, and current. The current concept of science is that it’s something that most often happens in a lab or in the field, as structured, scientifically devised research studies. While those methodologies are valid and integral parts of the contemporary pursuit of scientific knowledge, before the turn of the 20^{th} century, the natural history approach dominated the natural science fields (Benson 2000).

Natural history dates back long before the inception of “ecology” (Pastor 2018). It can be argued that ancient cave paintings of ice-age mammals are examples of natural history, as they were human’s descriptions of organisms they observed (Pastor 2018). When the term “natural history” was first coined by Pliny the Elder in the first century AD in his great work *Historia Naturalis,* the meaning of “history” was closer to that of “description” or “story” rather than referring to something that occurred in the past (Frazer 2014, McKeon et al. 2020). By that definition, natural history is a description of the natural world; the knowledge obtained by observing organisms in their natural habitats (Benson 2000, Frazer 2014, Tewksbury et al. 2014, Pastor 2018). Natural history is responsible for a huge portion of human understanding of the world we live in, from our understanding of evolution, to food chains and ecosystem interactions. The naming, classifying, and describing of organisms is one of the major rolls natural history has played in the furthering of scientific endeavors (Benson 2000, McKeon et al. 2020, Pastor 2018). Natural history forms the base knowledge on which ecology is built (Benson 2000, McKeon et al. 2020, Pastor 2018). Ecology was even described in 1927 by Charles Elton, a University of Cambridge zoologist, as "scientific natural history" (Pastor 2018, Worster 1977).

Despite the wealth of knowledge we have gained from natural history over the decades and centuries, it is rare to find contemporary mainstream scientific studies utilizing natural history techniques. At universities, there are fewer and fewer natural history courses offered and rarely is it required to take one for your degree, even for a degree is in the natural sciences (Frazer 2014). This is partially due to the fact that we have already accumulated the natural histories of many organisms and partially due to the movement of fields like ecology to hypothesis-based research, rather than research that is strictly observational (McKeon et al. 2020, Pastor 2018). That is not to say that the importance of natural history's contributions to scientific knowledge are unrecognized. In fact, there have been recent efforts to renew some focus on natural histories (McKeon et al. 2020, Pastor 2018). This can be seen in the 2017 addition of *The Scientific Naturalist* series to the scientific Journal *Ecology* (McKeon et al. 2020, Pastor 2018). This series showcases the natural histories of animals, plants, fungi, and microorganisms, describing their morphologies, behaviors, life cycles, and role in the ecosystem (Ecology 2020).

Natural history is a science based on observations of natural systems, and this observational knowledge often resides with communities of people who live, work, and sustain livelihoods from and within ecosystems. We refer to those who gain knowledge about the natural world through observations, those who do natural history, as naturalists. Contemporary uses of natural histories often involve working with communities to understand the ecosystems they live in and how they are changing, especially in the light of global climate change (McKeon et al.

2020). Though there are rare opportunities that arise where humans have not yet laid out the natural history of an organism, that is the case with the milky ribbon worm.

In order to frame the uses of natural history in contemporary ecology, I will explore the modern history of ecology, the importance of the use of local ecological knowledge (LEK) in scientific research, and the possible methodologies for incorporating local and stakeholder knowledge into science using participatory research techniques. These three themes together provide a framework through which natural history can and should be used in contemporary ecology and how it will be used in the framework and rational for my study of the milky ribbon worm.

II. History of Ecology

It is clear that over time, ecological understanding, methodologies, and approaches have moved beyond the field of natural history. However, it is important to understand that much of our ecological knowledge stems from groundwork done in the natural history style. Whether it is the first descriptions of species, or the first observations resulting in the "discovery" of ecological processes like evolution, natural history has played and can still play a vital role in furthering ecological understandings. Natural history accounts provide us with a holistic and intricate view of a system, its participants, and their relationships, providing perspectives more contemporary methodologies sometimes miss. From that additional understanding combined with existing knowledge we can then ask more quantitative research questions. Both of these methodological approaches and the ecological understandings they provide are necessary to produce complete ecological knowledge of a system.

Though the term was not coined until the 1860s, when it was first used by Ernst Heackel, the practices and research we now define as "ecology" have existed in some shape or form for centuries (Kingsland 2005). Aristotle observed and dissected animals for his research for writing his books *The History of Animals* and *Parts of Animals* in the third century BCE (Pastor 2018). In the 13th century AD Fredrick II wrote one of the first books dedicated to ornithology (Pastor 2018). Though neither of these men called what they did "ecology," their pursuit of knowledge of the natural world aligned with contemporary notions of ecology.

The word ecology stems from the Greek roots "oikos" and "logos". "Oikos" refers to the household or home and was later expanded to encompass political administrations (Faber and Manstetten 2010). More than a description of the physical location of a house, "oikos" refers to those who create and inhabit the home, encompassing the family, their flocks and fields, and the surrounding spaces that sustain them (Faber and Manstetten 2010). "Logos" loosely translated means law. So, together, ecology (oikos logos) refers to the laws controlling that which sustains the household. In other words, ecology is the study of the abundance and distribution of organisms and their interactions with the "oikos", their environment, all following the "logos" or laws of the system.

Though he is credited with coining the term, Haeckel apparently had no intention of creating a new discipline of science when he used the word "ecology" to described the systems and questions Darwin and other naturalists, those who pursued knowledge though observations of the natural world, of the time were exploring, specifically Darwin's theories of evolution (Kingsland 2005). Rather than a discipline, it seems ecology began as a way to describe types of knowledge and approaches to scientific problems, mainly rooted in biology (Kingsland 2005). Haeckel's argument was that evolutionary biology as explored by Darwin, and the systems and problems inherent in its exploration, are all founded in this ecological knowledge and are worth further exploration (Kingsland 2005). It is this exploration that would later be known as "ecology".

However, the kind of knowledge Haeckel eventually described with the word "ecology" was being explored well before the 19th century. These early modern "ecologists" heavily resembled the "naturalists" of our contemporary world. They studied their surroundings as complex systems full of stories and relationships. Gilbert White of Selborne, England, born in 1720, in many ways brought the study of natural history to the attention of mainstream thinkers of the time with his work *The Natural History of Selborne* published in 1789 (Worster 1977). Published four years before White's death, this work was comprised of a collection of letters and essays on the wildlife and vegetation of the environment he walked in everyday for decades (Worster 1977). He wrote of the species he witnessed and, importantly, their interactions with each other and their surroundings (Worster 1977). Not only is White credited with developing the first comprehensive ecological description of the Selborne area, but he also wrote about several thereto undescribed species of bird (Worster 1977). In the years following his death the tradition of natural history essays continued and many prominent scientists made pilgrimages to Selborne to pay tribute to and seek inspiration from Gilbert White's legacy (Worster 1977). Among these scientists was Charles Darwin who, though he is credited with some of the most important ecological systemic descriptions of all time and is commonly described as a "scientist" in modern day, referred to himself as a naturalist, a term we now seldom associate with true science (Worster 1977, Bury 2006).

Living in the same time period but in mainland Europe, the Swedish scientist Carl Linnaeus published his impactful essay "The Oeconomy of Nature" which also provided a description of the ecological viewpoint well before Haeckel coined the term (Kingsland 2005, Worster 1977). This work began to outline the arrangement organisms and systems that are part of modern ecology, discussing the “roles” organisms fall into, a theory now known as “niches” (Kingsland 2005, Worster 1977). “Oeconomy,” or “economy,” is an apt way to describe the understanding of environmental relationships at the time. To scientists and writers like Linnaeus and later, Hermann Reinheimer, relationships between organisms were like trade agreements, with costs and benefits for each party, and specializations developed over time (Worster 1977). These roles and relationships were further explored by the works of Charles Darwin, most notably the theory of evolution and natural selection, one of the catalysts to Haeckel’s own examination of ecology (Kingsland 2005, Egerton 2011). Darwin used natural history to describe species and their interactions, which would bridge Linnaeus’ “economy of nature” with biological sciences, creating the backbone for ecology (Egerton 1983, Egerton 2011, Kingsland 2005)

Sharon E Kingland described the transition of ecology from a perspective to a biological discipline in her 2005 book *The Evolution of American Ecology, 1890-2000.* She argues for the connection of the Americans' scientific need to set themselves apart from and find their niche within the European dominated world of the physical and natural sciences at the time, with the development of ecology as a discipline (Kingsland 2005). Ecology continued to develop as a discipline throughout the latter half of the 19th and through the 20th century, demonstrating a movement away from the holistic natural history approach of Darwin and White, towards more quantitative methodologies (Egerton 1985, Kingsland 2005, Worster 1977). This shift was driven by changing ecological perspectives, the development of new technologies and understandings of natural and chemical processes, and the diminishing number of undescribed species, creating the belief that natural history accounts were, for the most part, obsolete (Egerton 1985, Kingsland 2005, Worster 1977). This shift was characterized in some ways by the ability to test ecological principles described through observation by Darwin and other naturalists in the lab. For example, a 1934 Russian study by scientist George F. Gause utilized modern techniques to test Darwin's theory of evolution with yeasts in test tubes (Worster 1977). Through this study, Gause "confirmed" that Darwin's observation-based (natural history) theories of competition and evolution were ecological laws (Worster 1977). He published his findings in his book *The Struggle for Existence,* a term coined by Darwin himself to describe his theories of competition-driven evolution (Darwin 1989, Worster 1977).

An important figure in the evolving field of ecology was A. G. Tansley, who worked in the 1930s to remove all organismal philosophy from ecology (Worster 1977). He rejected the idea that nature should be envisioned as one organism, instead he and his contemporaries studied ecology by examining environmental systems down to their most basic units to understand the physical entities of nature and their mechanics (Worster 1977). He focused on processes and ecosystems (Bocking 2012). Tansley also worked to incorporate resource management and conservation into ecological studies (Bocking 2012). This represents more than just a change in the view of nature; a shift from a holistic "zoomed out" perspective to an analytical, specific, deconstructed one (Egerton 1985, Kingsland 2005, Worster 1977). It also represents the shifting technologies and understandings of the time; scientific technologies that allowed for a new kind of analysis, with a focus on figures, data, and objectivity, to be built off the groundwork of past naturalists.

The relationship between Gause and Darwin's works on evolution provides an excellent example for the contemporary relationship between natural history and ecology. Charles Darwin developed his theories of competition and evolution through observations of a natural system (Darwin 1989). From this natural history base, Gause developed research questions and designed a study (Worster 1977). Without Darwin's descriptions of the system and processes at play, grounded in natural history methodologies, Gause would not have been able to conduct his quantitative lab research and would not have been able to "prove" Darwin's theories (Worster 1977). This demonstrates an important contemporary application of natural history in ecology. Natural history studies, whether they be descriptions of organisms or ecosystems, can highlight avenues and opportunities for further research.

III. Local Knowledge in Ecology

Ecological knowledge is not just developed by scientist, but also through the lived experiences of local people. Scientists develop ecological knowledge through research based on the scientific method (Bélisle et al. 2018). Local peoples develop their ecological knowledge through their lived experiences from day to day in the ecosystems that sustains them (Bélisle et al. 2018). Over recent years, attention has increasingly been paid to the incorporation of this knowledge into scientific ecological studies (Bélisle et al. 2018, Berkström et al. 2019, Robbins 2018). Referred to as local ecological knowledge (LEK), this concept encompasses both traditional and indigenous knowledge, and is often incredibly detailed as people rely on it for their survival (Robbins 2018). The incorporation of this knowledge into more classically quantitative ecological studies can provide holistic insights into the system than would otherwise have likely been unavailable to scientists (Bélisle et al. 2018, Robbins 2018). Ecological researcher Henry Huntington described the connection between beavers--fresh water inhabiting mammals, and Beluga whale--salt water mammals, made by an Inuit elder in Alaska (Robbins

2018). A 2017 Finish study published in *Science* described the adaptation of climate change indicators to include the knowledge of Skolt Sami people about insect behavior and population in order to provide better real time information about changes in ecosystems as a result of global warming (Robbins 2018) The described the progress northward of the scarbaeid beetle, native to more southern regions, allowing scientist to use the beetle as a proxy for the warming climate (Robbins 2018).

The changing climate specifically has increased interest in the incorporation of LEK into scientific research (Robbins 2018). Remote sensing and other monitoring methods can tell us part of what is happening to a system, but the people who experience these changes that can tell us about the results and consequences (Robbins 2018). In addition to furthering climate change research, LEK can be of great help in areas of the world where long-term environmental data is lacking, as can be the case in developing countries (Berkström et al. 2019). LEK has been shown to increase the success of management decisions when incorporated into research designed to improve management and conservation practices in fisheries (Berkström et al. 2019). Many types of ecological modeling have also increased their incorporation of LEK in recent years (Bélisle et al. 2018). The increased attention to the importance of "scientific" ecological knowledge working in tandem with LEK can be seen in an increased number of studies utilizing both included in international conventions such as the United Nations *Convention on Biological Diversity* and the *Paris Agreement* on climate change. It is important to acknowledge the place of local knowledge in ecological studies and to understand how this knowledge can be used.

IV. Participatory Research

As discussed above, there is a wealth of knowledge that is held by people in communities around the world, and much of this information can and should be acknowledged and utilized by scientific researchers. The incorporation of participatory research in the sciences has been given increasing attention over recent decades and is one way to utilize local ecological knowledge (Barreteau, Bots, and Daniell 2010, Peter, Diekötter, and Kremer 2019, Rowe and Frewer 2000). Participatory research is an approach to problem-oriented scientific research (research designed to explore the nature of a problem so as to develop solutions) in which the input, views, opinions, and knowledge of local stakeholders are incorporated into the research (Hirsch et al. 2010). In their 1995 paper on the subject, Cornwall and Jewkes write, "The key difference between participatory and other kinds of research methodologies lies in the location of power in the various stages of the research process." Participatory science can be used to incorporate social, ethical, and political knowledge that pure scientific approaches cannot create on their own (Hirsch et al. 2010, Cornwall and Jewkes 1995). Additionally, these methodologies can lead to the closing of gaps between policies, scientific research, and the public by incorporating stakeholder knowledge and feedback into decision making (Hirsch et al. 2010). It can also promote the consideration of complexities and interconnections within systems that may be apparent to stakeholders with local knowledge but may escape researchers (Hirsch et al. 2010). Participatory science incorporates local knowledge and uses solutions tailored to these local contexts (Berghöfer, Wittmer, and Rauschmayer 2008). The diversity of knowledge stemming from participatory research allows for a degree of flexibility in implementations as well as providing greater context for the problems being examined (Barreteau, Bots, and Daniell 2010, Hirsch et al. 2010)

Participatory science is becoming increasingly prominent in policy-making research as well as studies surrounding natural resource management (Barreteau, Bots, and Daniell 2010, Hirsch et al. 2010, Rowe and Frewer 2000, Cornwall and Jewkes 1995, Peter, Diekötter, and

Kremer 2019). Participatory science, because of its emphasis on the importance of multiple perspectives and involving stakeholders in the design and implementation of policies, can be an important part of adaptive management practices, which involve the improvement of management policies and practices by examining the outcomes of already implemented strategies (Hirsch et al. 2010). Much of the increase in attention to the importance of including stakeholders in research stems from the need for greater accountability and responsiveness of governmental, scientific, and industrial agencies to public needs, perceptions, and feedback, especially when said research will be used to inform policies and management practices (Rowe and Frewer 2000). Some important advocates for this kind of public involvement in the environmental sciences include the U.S. Department of Energy and the U.S. Environmental Protection Agency (Rowe and Frewer 2000). In contemporary policy-making there are even some kinds of environmental legislation that require the input of the public before instituting policy changes (Rowe and Frewer 2000).

A variety of methodologies are utilized when incorporating stakeholders in scientific and policy-oriented research, and these often incorporate different levels of involvement (Barreteau, Bots, and Daniell 2010, Hirsch et al. 2010, Rowe and Frewer 2000). The lowest level of participant involvement in research and policy decision making is in the basic communication of information from scientists or researchers to the public (Rowe and Frewer 2000). This level also includes the use of information about stakeholders, though not necessarily from them, in research (Barreteau, Bots, and Daniell 2010). This is a top down approach with a relatively one-way flow of information in which the ownership for the process lays entirely with the researcher, though they are taking into account stakeholder contexts (Barreteau, Bots, and Daniell 2010, Rowe and Frewer 2000). The next level of public involvement is the “consultation” level where stakeholders provide information based on their opinions and lived experiences within the system in question (Barreteau, Bots, and Daniell 2010). A level up from consultation places stakeholders on a more equal footing with researchers; knowledge is exchanged back and forth, rather than in one direction (Barreteau, Bots, and Daniell 2010). Barreteau, Bots, and Daniell's 2010 paper is dedicated to providing a framework for clarifying this kind of research. They delineate the highest level of participant involvement as the "collegiate level" of participant involvement, based on Prost and Hagmann's participation models. This level is characterized by actors working together as partners, where ownership of the process is shared equally, and decisions are made through consensus. This level makes little to no distinction between researcher or policy maker and stakeholders, and is also called the "codesign" level (Barreteau, Bots, and Daniell 2010).

Within each of these levels of participant integration there are still multiple variations of methodologies. These range from interviews and structured conversation with stakeholders, to organized group activities. Hirsch et al. (2010) describes approaches. Several of the techniques they describe involve the creation of a cognitive map or model, often in the form of a visualization activity where community members identify the central issue and its primary and secondary causes. They then outline the feedback loops and potential points of intervention. A less direct way of achieving this same result is through focus groups or interviews with stakeholders in which questions are asked to provide researchers with the information they need in order to develop these maps for themselves (Hirsch et al. 2010). Other strategies include nominal group techniques where a group of participants brainstorm individually and write their ideas on cards which are collected and then rated by the group in order of importance or urgency (Hirsch et al. 2010).

Many of these techniques and strategies are designed for problem-oriented research, often with the purpose of creating policy or management changes. There is, however, another avenue of participatory sciences that is focused on gathering information to increase scientific knowledge rather than being geared directly to policy or management purposes. These kinds of participant research studies often come in the form of citizen science. Citizen science allows researchers to gather large amounts data without needing to be in the field themselves (Peter, Diekötter, and Kremer 2019). These studies are often engineered to gather data concerning animal populations, animal movements, and biodiversity data through citizen monitoring, identifying, and recording (Peter, Diekötter, and Kremer 2019). There are many websites where citizens can sign up to record their observations. The Audubon Society is one such organization that holds bird counts and other research endeavors to take advantage of their members around the country (Staff 2020). This kind of science does not only provide researchers with high volumes of data, but has also been shown to shift behaviors and attitudes of those who participate, to teach them new skills, and to increase their interest in the subject (Peter, Diekötter, and Kremer 2019).

Despite all these benefits of participatory science, reference to participatory research in scientific studies often negatively impacts the reputation of the results of said study (Barreteau, Bots, and Daniell 2010). Some "traditional" views of research methodologies imply that solely scientists and experts should be in charge of decision-making and the information utilized to make these decisions (Rowe and Frewer 2000). There are concerns that environmental policies based on public perceptions of risk will not adequately reflect the true risk of the situation (Rowe and Frewer 2000). Scientific concerns of concepts such as uncertainty may not be understood by stakeholders who lack the background and reasoning abilities of experts (Rowe and Frewer

2000). Additionally, the issue of public biases and the lack of objectivity implicit when basing research on the public's views, opinions, and lives have also been cited as reasons to question participatory research results (Rowe and Frewer 2000). However, said limitations of knowledge, lack of objectivity, and poor understanding of risk can also be present in more traditional scientific research methods (Rowe and Frewer 2000).

Most scientific research begins with a research question or problem, then research is conducted in order to begin to identify avenues through which to solve the problem, and this usually results in further research questions (Barreteau, Bots, and Daniell 2010). Incorporating stakeholder knowledge into this process, from the identifying of the research question to the development of solutions, not only can give vital context as well as community support to a project but can also provide researchers with information they otherwise would not have access to. In the field of natural science, when it comes to describing a species about which scientists know little, the knowledge held by the community members who interact with the organism and its ecosystem should not be ignored. This knowledge can and should be tapped into by researchers using one of more of the participatory research methodologies described above. It is important when conducting studies like this to be sensitive to the public good, and to be explicit about the role of the public and how their knowledge will be used (Barreteau, Bots, and Daniell 2010).

The stakeholder participation-based research I conducted in order to gather the natural histories of the milky ribbon worm is different from many of the methodologies described above because the end goal wasn't to gather pubic opinions about or for a policy or management decision, at least not at this preliminary point in the research. The purpose of this research is to add to the existing natural history of the milky ribbon worm and to develop research questions for future studies. These future studies will be more likely to directly result in management decisions, and, in that case, stakeholders in the system should again be involved in that future research. The methodologies I utilized in this study most closely resemble the “consultation” level of involvement described by Barreteau, Bots, and Daniell (2010). My study was interview based, gathering the knowledge of clammers about the ecosystem and the organism in question. While the flow of information was primarily in one direction, from stakeholders to me, I utilize information about their lived experiences in a system, provided directly by them, rather than using demographic information gathered about them. My hope is that future studies that revolve around the milky ribbon worm will continue to take advantage of participatory research methodologies.

V. Conclusion

Though the field of ecology in its contemporary manifestation is no longer solely based on observations and descriptions, there are still important applications for natural history studies. Utilizing the ecological knowledge of local and indigenous peoples to conduct a natural history style study can provide scientists with vital understandings of systems. These studies can result in the illuminating of future research questions as well as identifying avenues for policy and management decisions. The next chapter will describe such a study; one where a natural history narrative was developed using the existing knowledge held by stakeholders in order to develop a hitherto non-existent ecological baseline understanding that was then used to identify paths for future, more quantitatively based scientific research.

Chapter II – Milky Ribbon Worm

I. Introduction

One of Maine's largest coastal economies is its fisheries, with thousands of people up and down the coast of Maine reliant on fisheries and aquaculture to support themselves and their families (Mcclenachan, Scyphers, and H. 2019). The top six fisheries in Maine (lobster, elver, herring, soft-shell clam, urchin, and scallop), combined were estimated to be worth over $548 million by the state of Maine in 2017 (Resources). Aquaculture in Maine contributes $137.6 million in economic output and employs 1,078 Mainers (Cole, Langston, and Davis 2017). There is an inherent pride and ownership in being a fisherman, clammer, or member of another water-based industry in Maine, and many Mainers' lives are deeply connected to coastal ecologies.

These industries that sustain the life blood of coastal Maine are facing challenges left and right. Increased licensing regulations designed to support an ecological and economic fishery have over the past several decades lead to a decrease in fishers flexibility, creating economic pressures that ultimately work against ecological interests (Stoll, Beitl, and Wilson 2016). Climate change is resulting in rapidly warming waters which are changing coastal ecosystems; threatening some species while supporting others (Beal et al. 2016). These changes make the future of Maine fisheries so uncertain that organizations are pushing for investment into aquaculture as an economic, ecologic, and cultural alternative to Maine's wild fisheries (Grant). However, there is still work that can and should be done now to understand these changes and challenges in order to identify avenues for mitigation and adaptation.

Among Maine's most valuable marine economic sectors is the molluscan shellfish fishery (Athearn 2008). This fishery includes clams (soft-shell and quahogs), mussels, oysters, and scallops. In Maine, this industry directly employs over 1,500 people and contributes to around $56.0 million to the economy annually (Athearn 2008, Association). This is a significant portion of the income from Maine fisheries and also contributes about $29.9 million every year directly to Maine residents (Athearn 2008). The rest of the $56.0 million in economic contributions come from the labor income from sales of soft-shell clams (*Mya arenaria*) and other important commercially sold shellfish (Athearn 2008).

The soft-shell clam industry has existed in Maine's intertidal zones for more than a century, and is one of the most important of the molluscan shellfish fisheries (Beal et al. 2016). The soft-shell clam fishery was the second in economic value in Maine only to the lobster industry in 2015 and, based on 2019 landing data is currently in third place behind lobster and elver (McClenachan, O'Connor, and Reynolds 2015, Resources 2019). This means that, as well as being culturally valuable as a way of life passed down through generations, the clamming industry is financially vital for the livelihoods of many Mainers.

Over recent years there have been new pressures on this industry, including significant pressures at the ecological level. Warming coastal waters has countless impacts on the ecology along Maine's coasts. The waters of the Gulf of Maine had warming rates between 2004 and 2013 that were some of the highest in the world (Beal et al. 2016). With these warming waters come a slew of other consequences including but not limited to increased predation on clams (Carter and Moon 2020). Over the past four decades the number of clams harvested for sale (referred to as clam landings) in Maine has decreased by 75% (Beal et al. 2016). Though over recent years landings have stayed in the 900s to 600s tons range, this is significantly lower than the 1000-2000 tons range of the 1970s, 80s, and into the 90s (Resources 2019). This decrease in clam landings is thought to be, at least in part, linked to increased predation on crustaceans (Beal et al. 2016). Though there are hypotheses, there is not yet a direct answer for what force or forces are causing this increase in predation. Two of the species to which these changes in clam predation in Maine have been attributed to are the green crab (*Carcinus maenas)* and the milky ribbon worm (*Cerebratulus lacteus*) (Carter and Moon 2020, Lord and Williams 2017, Resources , Beal et al. 2016). Over the last two decades there has been an increasing amount of predation by green crabs, especially in areas of rapidly warming water (Beal et al. 2016). There have been many studies over the years focused on the green crab and, as an invasive species (originating in Europe), generally more attention has been paid to its eradication. There have been even been some efforts to commercialize green crabs for food at some high-end restaurants.

The milky ribbon worm is a less studied animal compared to the green crab and our knowledge of its general ecology, biology and impact is limited (Thiel and Kruse 2001). Milky ribbon worms are an endemic species to Atlantic North America and are part of the phylum Nemertea, worms characterized by the presence of a proboscis which they use to feed (William 1985). We know that milky ribbon worms are a threat to soft-shell clams along the Atlantic coast as far north as Canada and are also found as far south as Florida (Carter and Moon 2020, Bourque, Miron, and Landry 2001). This threat seems to have been recognized as far back as the 80s, but in recent years its impact has grown significantly (Bourque, Miron, and Landry 2001). It is thought that the milky ribbon worm uses chemical cues, released by soft-shell clams and other crustaceans, to identify, track, hunt, and finally attack its prey (Thiel and Kruse 2001). Once they have identified their prey, in this case often soft-shell clams, they inject them with a neurotoxin by inserting their proboscis into the pedal opening or siphons of the clam and repeatedly puncture its tissue (Göransson et al. 2019, Thiel and Kruse 2001, William 1985). These toxins immobilize their prey, allowing the worm to feed, sucking the clam out of its shell without damaging the shell itself (Thiel and Kruse 2001). Many of the most extensive studies on the milky ribbon worm have been examining these neurotoxins, often for the purposes of identifying potential pharmaceutical uses (William 1985, Göransson et al. 2019).

Studies have shown that milky ribbon worms are highly selective when it comes to their prey food (Bourque, Miron, and Landry 2001, Thiel and Kruse 2001). In Maine, they tend to prefer soft-shell clams over other bivalves and can be incredibly destructive to whole beds of these clams (Bourque, Miron, and Landry 2001, Thiel and Kruse 2001). However, based on this study they do not seem to discriminate between their prey organisms by size (Bourque, Miron, and Landry 2001). However, Downeast Institute suggests that milky ribbon worms may wait to attack clams until they are about an inch in length, though does not seem to be peer reviewed literature to support this (Institute). It is thought that one of the reasons these worms are so distributive to clam beds is because they may exist in a constant state of hunger, meaning they feed constantly as long as their prey is present, thus wiping out whole beds of clams (Thiel and Kruse 2001). Studies have demonstrated that in areas where milky ribbon worms are present, clam mortality can reach 100% whereas in areas without milky ribbon worms clam mortality was 0% (Bourque, Miron, and Landry 2001). Milky ribbon worms seem to also be unattractive prey for many other predators (Bourque, Miron, and Landry 2001). In a 2001 study, remains of milky ribbon worms were found in the stomachs of only .84% of fish examined in the laboratory, and only .09% of fish stomachs examined in the field (McDermott 2001). They were found in the stomachs of a total of 27 fish species, though not in high quantities in any (McDermott 2001). It is thought that one of the reasons milky ribbon worms do not make attractive prey for other predators is that along with the neurotoxin they deploy for hunting purposes, they also have defense toxins to deter predators (Göransson et al. 2019). There has been some success with using milky ribbon worms as bait for sports fishing and it is thought that fish will go after the bated worm, and then are unable to spit the ribbon worms out upon realizing they are toxic because of the hook (McDermott 2001).

It is clear that there are many unanswered questions surround the ecology and impact of the milky ribbon worm. In order to better identify means for minimizing the negative impacts of the milky ribbon worm on clam populations and on the clamming industry, a more in-depth understanding of their ecology, their impact, and the reason for their increased prevalence must be reached. The goal of this study is to use the existing knowledge of stakeholders in this system, mainly clammers, to develop a clearer picture of ribbon worm ecology, as well to hypothesize the reasons for their increasing impact on the ecosystem. Additionally, a main goal of this work is to identify avenues and important research questions to inform future scientific studies on the milky ribbon worm.

II. Methodology

The methodologies of this study were defined in part by the limitations of the existing research-derived knowledge surrounding the milky ribbon worm. This provided us with the opportunity to revert to methods of study that have not often been utilized in the contemporary sciences; mainly, utilizing the existing knowledge held by stakeholders to fill in the gaps in the scientific database. This study relies on the local knowledge of people whose livelihoods depend on the ecosystem in question. Natural histories are the descriptions of organisms, their environments, and interactions. They are the narratives that form ecological understandings. It is uncommon these days to encounter a species for which these narratives have not yet been recounted. It is especially uncommon to for an organism as physically large as the milky ribbon worm, to be lacking in these recorded histories.

In order to develop research questions for future scientific studies surrounding an organism, there first must be a basic understanding of its relationships with its environment. As of yet, the milky ribbon worm doesn't have these recorded histories. However, that is not to say that they do not exist in other, non-academic forms. Maine clammers have been working in these environments for generations. Many of them spend 2-6 hours almost every day, almost every week, every year for decades digging clams along the coast of Maine. There is no scientific observation-based study we could design that would produce the kinds of knowledge, starting with our ignorance of the systems, that these people already have. One of the predominant reasons that this kind of information could not be initially gathered by a team of scientists observing the system is because the gaps in our knowledge of the ecology of the milky ribbon worm are so significant that we don't even have a concrete understanding of the research questions we need to ask in order to design a study to increase this knowledge. So, in this study I set out to collect these histories, these descriptions, and to provide a natural history derived ecological baseline understanding of the milky ribbon worm, its preferred habitats, lifecycle, the extent of its impacted damage, and to make predictions about the possible causes of this increase in their abundance and distribution to the Maine clamming industry over recent years. The end goal is to develop research questions and avenues to be explored in future studies.

To acquire this knowledge, I developed interview questions to engage clammers knowledge of the ecosystem, identified interviewees through work with community partners, conducted phone interviews with these stakeholders, and finally analyzed the interviews in order to develop an understanding of common themes and to pull together an ecological description of the milky ribbon worm.

Developing Interview Questions

To frame questions I would later ask my interviewees, I tried to focus on preventing questions from leading my interviewees to answers that I was looking for, and rather left them open-ended enough that their responses would hopefully be in the form of a narrative, describing their involvement in the ecosystem and observations over the years. The first few questions were intended to gather basic demographic information (Appendix I). This was mainly for the purpose of my own analysis as all my interviewees will remain completely anonymous and no information that could allude to their identify will be included in this study. One of the key questions in this section was to identify the town or area where they clam in order to facilitate the comparison across geographic space. The following questions focused on digging practices and moved on to explore their experiences with milky ribbon worms and environmental changes they'd observed overtime. These questions underwent several drafts and workshopped by several people in order to ensure they were accessible to interviewees and prompted the most open-ended and thorough responses to give us as complete an image of the system as possible.

Interviews

I was fortunate enough in this process to work with Jessica Joyce of Tidal Bay Consulting, LLC. She provided me with several initial clammers to contact who would be willing to speak to me. I was able to connect with five clammers in total, mostly in the Casco Bay area. All of my interviews were conducted over the phone. It was most helpful to check the tide charts before trying to contact my interviewees as most were out clamming at low tides. I spoke to clammers from Freeport, Scarborough, Georgetown, and Harpswell. All of interviews lasted between twenty and thirty-five minutes. Each interview was recorded for my own personal use for analysis. None of these recordings will be published or released for others to view, they were simply a tool to allow for a greater ease of analysis. While I ensured all of my interview questions were answered, most of them were answered in the style of a conversation, rather than by my going down the list of questions.

III. The Natural History of the Milky Ribbon Worm According to Maine Coastal Clammers

The following is the compilation of accounts surrounding the milky ribbon worm as told by coastal Maine clammers who have interacted with these worms and their environments on a daily basis for years and sometimes for decades. The purpose of this section is to compile the existing knowledge held by these stakeholders. The information provided in these pages should be taken as the subjective experiences and views of these stakeholders and valued as vital firsthand accounts of this system. It should be noted that all the clammers I interviewed were from the Casco Bay area, so their accounts, for the most part, are only commentary on those environments. While most diggers refer to the milky ribbon worms as “tapeworms”, for the purposes of my discussion I will continue to use the name milky ribbon worm.

Habitat

We know from previous research that milky ribbon worms inhabit tidal areas along the coast of the North America as far south as Florida and up into Canada. However, in order to explore their impact on the Maine clamming industry and identify potential mitigation practices it is important to understand where in these tidal areas these worms inhabit. If there are sediment types they prefer or avoid, or geomorphology differences between areas with and those without ribbon worms we might be able to easier study these organisms and develop mitigation protocols.

One contact worked with a graduate student from the University of New England a few years ago on a project attempting to identify the preferred sediment type of the milky ribbon worm. This study was focused in Scarborough, Maine. Unfortunately, the study did not yield any concrete answers. There was no statistically relevant difference in milky ribbon worm populations dependent on sediment type. However, based on this clammer's own firsthand knowledge digging the flats, he thinks that there is a correlation between milky ribbon worm prevalence and soft-shell clam prevalence. He also thinks that milky ribbon worms prefer soft clay mud over soupy muds, because it is more difficult for the ribbon worm to maintain their burrow tunnels in soupy mud, as well as over larger grain sized sands. "Soupy mud" is a phrase that was used by several of the clam diggers I spoke to and refers to the texture of some mud exposed at low tide when it is so soft that holes made by footprints or organisms quickly close up. In mud like this, the diggers say, it is easy to sink up to your knees and you have to be careful with your boots. Another contact thought the explanation for the worms' preference for softer muds over larger grained sands is because they are fragile organisms and have a difficult time burrowing through sands without breaking apart. Again, although this preference for softer, but not soupy, sediment was cited by each of my interviewees, each contact was quick to explain that, although this sediment type may be a preference, milky ribbon worms are found anywhere there are soft-shell clams, whether that's up close to the high tide mark in the larger grained sands, or out in the soupy mud of the low tidal zone.

There seems to be some disagreement about whether milky ribbon worms prefer direct coastal environments, such as tidal coves, or if they prefer tidal river environments. However, more of my interviewees believe the worms are more common on the coast and not as much up the rivers. One digger, however, was explicit that there are always statistical outliers and it still seems like milky ribbon worms tend to appear anywhere there are soft shell clams. One out of the five of my contacts said he encounters more ribbon worms in the tidal river he digs in. However, he also specified that he digs more in this river than in tidal coves, so the comparison may be inaccurate. Additionally, the same clammer described this river as one with a lot of inflow and not a lot of outflow, meaning that it is highly saline, which could be a reason for the high numbers of ribbon worms, although we cannot at this point make a statement about the salinity preferences of the ribbon worm. One clammer mentioned his experiences in Wiscasset where most of the clamming is in rivers. There, milky ribbon worms have not been much a problem so far, and there are some areas that still haven't seen any, leading this clammer to wonder about the impact of salinity on milky ribbon worms.

Some river intertidal zones where there have been a larger population of milky river worms expose very large areas of mud for many hours during low tide. There are some areas of coves and tidal rivers that, at low tide, only have fully exposed flats for two or three hours, and there are others with such high outflow that their flats are exposed for upwards of 6 hours at full tides. Some clammers think that the ribbon worms prefer these areas because the sun is able to warm the mud for longer and, according to anecdotal evidence from these Maine clammers, milky ribbon worms have greater success during warmer years and seasons.

General Behavior

The largest worm one contact had ever seen was a seven-foot-long worm he encountered in Scarborough. The same contact noted that one of the challenges with trying to remove milky ribbon worms from their habitat is that they are very fragile and, when stressed, they will split themselves into many smaller pieces. These pieces can stay alive on their own for a good amount of time, and the section that has the head can completely regenerate. Based on the accounts of several other clammers, this fragility seems in increase with low temperatures. In areas where the flats are exposed to the sun for many hours each day, warming them significantly, clammers I spoke to noted that the worms seem less fragile and move faster. They “shorten up” when it’s warm and feel fatter and stronger. When it’s cold they break apart very easily and move much more slowly. If they are on the surface of the mud when the temperature drops, they sometimes freeze there because they can’t more quickly enough to get back into the mud.

Rather than moving like snakes, slithering back and forth to move forward, one interviewee described milky ribbon worms as bunching their bodies up and then lengthen out, pulling them forward. This is how they move through and on top of the mud. Based on accounts from diggers they can also swim very well and have been observed swimming both during the day and at night. One contact described large numbers (he estimated maybe hundreds) of ribbon worms swimming around at night, just under the surface of the water, though no other contact had seen them swimming in the numbers this digger described.

Though most of my contacts argue that milky ribbon worms make really good prey for many predators because they look enticing swimming around, none cited seeing ribbon worms being eaten by any organism besides seagulls. Seagulls will eat the milky ribbon worms the clammers throw to them, however, my contacts said that even seagulls won’t eat too many. One digger described seagulls as pest birds who will eat anything, including any clams left on the mud’s surface while digging, but that after they’ve eaten a few ribbon worms thrown to them they’ll pick them up and drop them again. Though two of my contacts have used ribbon worms as striped bass bait, there were no accounts of seeing ribbon worms being preyed upon without human intervention.

Diet and Eating Behavior

It is clear from each of my interviews that the preferred food source for the milky ribbon worms is soft-shell clams. The diggers believe this is because soft shells are slower moving than razor clams, and they cannot fully close their shells to stop the milky ribbon worm from using their proboscis to penetrate their tissue, injecting it with a neurotoxin that kills it, like quahogs can. However, although soft shell clams are their preferred diet, the diggers I spoke to said that milky ribbon worms will attack and eat quahogs. One contact vividly described opening a quahog to find a ribbon worn curled up inside the shell, already haven eaten most of the quahogs tissue. He thought what must happen is that quahogs will snap closed with the milky ribbon worm still inside and the ribbon worm has to digest the clam in order to loosen the muscles holding the shell together so it can get out.

Another interviewee described how he found out that milky ribbon worms will eat blood worms (bait worms). He had a few blood worms in a bucket he was taking out with him and, though he usually throws the milky ribbon worms to the seagulls, this time when he pulled one out of the mud, he put it in the bucket with the blood worms. When he was heading off the flats the blood worms were gone, and only the milky ribbon worm was swimming in the bottom of the bucket. The only logical explanation, he felt, was that the milky ribbon worm had eaten the blood worms. This, as well as the anecdotal evidence of milky ribbon worms eating quahogs, suggests that, although soft-shell clams seem to make up the majority of the worm’s diets and are their preferred food source, milky ribbon worms will eat other organisms as well.

According to the diggers I spoke to, the way milky ribbon worms kill and eat their prey is one of the contributing factors to their widespread catastrophic impact. They say that within days a group of milky ribbon worms can decimate an entire bed of clams. From anecdotal accounts is seems like a ribbon worm will find a bed of clams and go through and inject multiple clams with its toxin. The diggers say this is what kills the clams. According to one of my interviewees, the worm will then wait until the clams begin to decay before going back through and eating them. Another digger described how the worm starts by eating the stomach of the clam and will leave the band, snout, and muscles. Several diggers said that because there is tissue left in the shell after the worm is done eating, the clam will rot. A few diggers described the negative results of rotting clams left in the flats. They say that when the clams turn rancid, the rest of the clams in the bed, even if they were not "stung" by the milky ribbon worm, will die because of the rotting clams around them. Though most of the diggers who cited this impact were not sure why rotting clams would kill other clams, one said that it was the smell, or whatever made the rotting clams smell, that kills the other. They said that in these areas the mud turns black and sour. You can see ooze coming up from the holes where the dead and rotting clams are.

Most of my contacts believed that soft shells must send off a chemical signal or a smell when they get to a certain size, which would explain how an untouched bed of clams can go untouched for over a year as they grow, and then within weeks be completely decimated. There is a general agreement that once clams grow to about an inch and a half, which takes between one and two years, the ribbon worms will move in and begin attacking clams. One of my contacts described to me how he can tell when he first gets to an area if there are going to be milky ribbon worms, even before he begins to dig and sees any firsthand. He says that the flats look different in areas where the ribbon worms are. Either you'll see large areas where the mud has turned black and you'll know that there will be dozens of dead and rotting clams, or you'll see an area that could be as large as 5-6 feet across that is elevated more than the surrounding mud. This area will have no clams in it and will be infested with milky ribbon worms.

Changes in the Environment

A common thread through all of my interviews was the acknowledgement that the world is getting warmer, both the atmosphere and the waters. Many of my contacts have been clamming, fishing, or both for more than 20 years now, and over the years have accumulated good deal of firsthand environmental knowledge. They describe disappearing species, new growth of algae and vegetations they never used to see, and the emergence of "new" animal species too, like the milky ribbon worm and the green crab.

Also noted is the changing tides and water levels. Of the diggers who mentioned tides, each said that tides seem to be getting more extreme as the years go on and water levels are rising. The coast is eroding at rates that alarmed many of the stakeholders with whom I spoke. One described building new sea walls in the same area every few years as the water rises and the bank is pushed farther and farther back. Three of the five diggers I spoke to directly sited global climate change as a main contributor to both the rise in sea level and the increasing temperatures.

Another environmental change most of my interviewees described, though none were completely certain of its cause, is the changing of tidal sediment structure and texture. It seems that the mud that is exposed at low tide is getting softer. One clammer described stories the older diggers tell about being able to drive out onto the mud in the summers at low tide and drive out again as the tide came in. In these same areas that were described to him the mud is now so soft that you sink to your mid-calf or up to your knee. Several possibilities for the causes of this softening were described by the diggers I spoke to. A few diggers said that they know that not only are coastal waters warming, but that the chemistry of the ocean is changing as well. They though that this change in chemistry could be resulting in softer the mud. Another possibility a digger told me is that the mud is softening because of consistent turning over of the mud by clammers. He predicted that the more they disturb the mud and turn it over, almost as if they are a human rototill, the softer the mud will become. Finally, one digger who has been digging in the same cove for 20 years said that there is an industrial plant that dumps sediment into the ocean off the coast. He thinks the finer particles from this industry are being brought into the cove where he digs, adding finer particles to the mud and making them softer.

Impact

There were conflicting accounts regarding the severity of the milky ribbon worm impact and problem. Some of my interviewees have been hit hard by milky ribbon worms and have begun to feel their livelihoods suffer accordingly. One digger described losing around $1300 in one season because he had seeded an area for soft shells (seeding is a practice to “planting” baby clams in an area until they grow to the legal commercial harvest size of 2 inches across). He seeded these beds and periodically went back to check on them, checking their size, keeping an eye out for predators, and turning over the mud. There were no ribbon worms until the clams were about 1.5 inches long. He went back one day when they were almost harvestable size (2 inches) and he could see the line where the milky ribbon worms had appeared and begun to decimate his bed. He lost every single clam in that bed, and all the investment that went into it. This same digger doesn’t know if he’ll be able to continue in the soft-shell industry. He doesn’t want to give up on them, but if he keeps experiencing losses like that, he’ll have no choice. Another digger said that in his area there used to be over 20 fulltime diggers, and now there are only a handful. Many have left the industry for factory jobs because the numbers of soft shells are so low right now it takes too long and is too difficult to make a profit. He himself has turned to oyster farming as a supplement to clam digging. He said a big reason for the dwindling soft-shell numbers is the ribbon worm.

Other diggers I spoke to note that the number and impact of milky ribbon worms has certainly increased over recent years and they are a really big problem, but that they haven't had to change their practices in order mitigate losses from the worms. These seemed to be the diggers who do not seed for soft shells and, thus, have a relatively low initial investment cost and so are less likely to lose a lot of money to ribbon worms. One digger said that green crabs were much more of an issue a few years back than the milky ribbon worms have ever been and that seagulls will always be the most problematic clam predator. Another digger has been counting the number of milky ribbon worms he sees in the field for a few weeks since hearing of my project and says that in his area, where he is mostly digging in tidal rivers, he sees 10-15 worms a day, which is actually fewer than he saw 10 or so years ago. He attributes this decline in their population to his and his fellow diggers in the area's diligent removal of all milky ribbon worms they encounter while they dig.

Although the severity of the impact is up for debate, all of my contacts agreed that a little over 20 years ago there were few to no milky ribbon worms. No one had ever seen or heard of them and, since then, they have become increasingly prevalent in the Casco Bay area. The diggers I spoke to had several theories as to why their numbers seem to be increasing. A dominant theory is connected to the warming air and waters. As previously stated, diggers find that milky ribbon worms prefer warm water and weather and become weak and will die if it gets too cold. Because of this, it seems that warm waters are good for the worms. Some diggers also drew a connection between temperature, soft-shell growth rates, and the worms. Soft shells can grow faster and reach maturity more quickly in warmer waters. However, these diggers think that there is a connection between soft-shell clam size and the presence of milky ribbon worms. They think that ribbon worms only appear when the clam reaches about 1.5 inches in length. Because of this, some think that the faster the clams grow, the faster the ribbon worms find and destroy entire beds. One of my contacts specifically mentioned the winter of 2012 as a very mild winter and said that there was a huge boom in the number of milky ribbon worms he was seeing the following spring and summer. He also said he suffered more losses due to the ribbon worms that year. This could be one of the reasons why, despite the fact that warmer waters should benefit soft shells, their populations are dropping. However, this decrease in population could, as mentioned by one of my interviewees, simply be linked to normal cycles in soft-shell populations. This contact mentioned that quahogs seem to be making a comeback after having a low population size for many years. He said that in the past soft-shell populations and quahog populations have been inversely related to each other.

Several of my interviewees also cited the softening mud as a potential contributor to the increase of milky ribbon worms along the coast of Maine. Most of the diggers think that soft mud is preferred by milky ribbon worms and that the softening of the mud may be a reason ribbon worms are better able to inflict often catastrophic damage on large areas of clams.

Potential and Current Mitigation Practices

Several of my contacts said that they and many of the other diggers in their areas (mostly in the Casco Bay area) either throw milky ribbon worms to the seagulls when they find them, or they put them in buckets and bring them out with them. This seems to have worked well in some areas and, if organized and increased, could continue to have an impact in ribbon worm mitigation. It seems, however, that even seagulls don’t find milky ribbon worms to be particularly appealing food. They'll eat them for a bit then they'll stop eating them and just drop them. Normally seagulls will eat whatever you throw them until, according to one of my contacts, they vomit or die.

One contact described a mesh box he sewed with 2mm mesh that he filled with clams and buried in the mud. At the end of the season there were milky ribbon worms all around this area and had killed and eaten many of the soft shells surrounding the box, but none in the box were touched and no worm had managed to get it. However, there are a few issues with this strategy. First, it doesn't seem to be practical on a physical and labor scale or on a financial one to put all clams for harvest in these boxes. Additionally, as my contact pointed out, from a brief experiment like this it is hard to tell how accurate the results were. For instance, if there had been no other soft-shells in the area besides the ones in the box, would the milky ribbon worms have worked harder to get inside?

Another mitigation strategy that one of my contacts brought up was to take advantage of the possibility that milky ribbon worms swim around at night. If source was right and they swim in great numbers just under the surface at night, it might be possible to use a very fine net to scoop them straight out of the water and then dispose of them.

A few of my contacts mentioned how good ribbon worms are for bait, particularly for stripers. One clammer told the story of his first ever encounter with a ribbon worm over 25 years ago, though he and many other clammers refer to them as tape worms. He had never seen or heard of one before, and then he took his young daughter and nephew digging one afternoon and then fishing. He dug up a ribbon worm and, not knowing what it was, put it in his bait bucket. He used it later for fishing stripers and said that he has huge success with it. He proposed the possibility of finding a market for ribbon worms, probably as bait. He thinks that the creation of a market green crabs has been a huge help in getting rid of them and would like to see that as well as a search for a market for ribbon worms, maybe as bait, continue.

Problems with Mitigation Tactics

There were several roadblocks surrounding the ability to control ribbon worm populations that were expressed to me in these interviews. One roadblock that was described was the difficulty of studying ribbon worms, as a mud dwelling organism that are only encountered while clamming or when they swim around, which seems to be predominantly at night. The diggers I spoke to weren't incredibly clear on the life cycles of milky ribbon worms so didn't know if there was a way to target breeding areas.

One contact pointed out that one of the most important things to quantify surrounding milky ribbon worms is their impact on the soft-shell clam population. However, in the opinion of one digger, the metrics and methodologies by which clam populations are measured can be inaccurate, making quantifying the true impact of milky ribbon worms nearly impossible. The random sampling from coves in order to calculate and track population size, he feels, is inadequate and can only really tell us that there are more clams in one small location, and not tell us anything about what might be happening to clam populations ten feet to the left of right of where was directly measured.

Some of my contacts discussed the issue that the mitigation tactics that seem to have the greatest potential for preventing the mass killing of soft-shell clams would also be very difficult, both financially and practically, to scale up to a level that would make a tangible difference. For instance, it would be financially infeasible and physically impractical to encage any clam you wanted to at some point harvest in a mesh box and bury it in the mud.

An additional complication seems to be that some of the practices that are thought to help control milky ribbon worm outbreaks may also aid in their ability to reach clams in the future. One digger believes that that turning the mud often in order to pull out ribbon worms, even before the clams are mature, may prevent them from decimating that bed initially, but, if diggers predictions are true and turning the mud leads to softening mud which is preferred by milky ribbon worms, in the long run this practice may lead to greater clam mortality.

IV. Implications and Research Questions

The information that has been gathered through these interviews and conversations with stakeholders throughout the course of this process are invaluable to us as a threshold of ecological understandings from people who spend nearly every day working in and around the system in question. As previously stated, it would be impossible for us to develop for ourselves the firsthand knowledge these diggers possess without spending hundreds upon hundreds of hours in the field. From this knowledge, we can identify avenues for further, more quantitatively based research. I have identified several opportunities for more research that could lead to a greater understanding of milky ribbon worm ecology and, thusly, to potential mitigation techniques. Each of these opportunities poses several potential research questions. (see Table 1. for summary).

Sediment

The first of these avenues for exploration centers around the preferred sediment habitat of milky ribbon worms. While there have been some preliminary studies done attempting to identify a preferred sediment texture and structure for milky ribbon worms, there have been no conclusive results. From my conversations with diggers, the general consensus is that ribbon worms prefer softer muds with more clay than sand. However, diggers though that ribbon worms don't do as well if the mud is too soft and won't hold its shape. It would be valuable for researchers and those trying to mitigate the effects of ribbon worms to test this hypothesis. As one of my interviewees discussed, there was a preliminary study done by the University of New England that was unable to identify the sediment structure and texture preferred by milky ribbon worms. However, previous studies focused more generally on the phylum nemertean suggest that that many nemertean species are found in soft-bottom sediments rather than hard bottom sediments (Theil and Kruse 2001, McDermott and Roe 1985).

Another part of this sediment-based research should examine the validity of the observation that mudflats in coastal Maine are softening. From a literature search I was unable to identify any peer reviewed literature confirming or denying that intertidal mudflats are softening. I was also unable to find historical sediment texture and structure data for locations along the Gulf of Maine, thus limiting my ability to compare the anecdotal evidence provided by the clam diggers to past records. Because of the lack of literature on the subject, the first step in a future study should be to explore whether or not the mudflats are softening. Next, should the hypothesis that the mudflats are softening be accepted, the possible causes for this softening should be examined. One digger predicted that the mudflats are softening because of clammers turning over the sediments like rototills, which may loosen and soften the sediment overtime. Sediment loosening and softening has to do with both the structure (heavily dependent on porosity) and texture (grain size) of the sediment (Singer and Munns 1996). While there is a gap in recent literature surrounding the impacts of clam digging on intertidal sediments in Maine, a 1986 study suggests that digging increases the amount of course grains in the mud by bringing coarser bottom sediments up and also decreases the fine grains in the sediment by increasing the suspension of these finer grades in the water column due to their disturbance (Anderson and Meyer 1986). Other studies, though examining different methods of shellfish harvesting are note Maine-specific, also suggest that the disturbance of marine sediments results in the re-suspension of fine grain particles and increases instability of the sediment (Aspden et al. 2004, Mercaldo-Allen and Goldberg 2011). This literature suggests that the "softening" of the mud that diggers are experiencing may more closely resemble the loosening of the structure and increasing instability of the sediment, rather than a texture change.

Another possible cause of changing intertidal sediments cited by my interviewees was climate change related factors, including changing ocean chemistry, sea level change, and shifting tides. Though not expressly identified by these diggers, changing weather and currents could also fit into this category. Studies have looked into the impacts of storm surges, ocean acidification, intensification of tides, and shifting currents (Dickson, Kelley, and Barnhardt 1994, Fagherazzi et al. 2017, Strong et al. 2014, Bentley and Schneider 2015). The sediments that make up most intertidal flats in the Gulf of Maine are derived from the erosion of local glacial sediments (Dickson, Kelley, and Barnhardt 1994). It is not just Maine's coastal waters that are becoming more acidic, but also its coastal sediments (Bentley and Schneider 2015). Increased storm surges, intense currents, higher tides, and sediment acidification (which also creates unsuitable environments for bivalves) are contributing to increasing rates of erosion of tidal sediments, while increased rates of evaporation have been demonstrated to increase sediment resistance to erosion (Bentley and Schneider 2015, Fagherazzi et al. 2017, Strong et al. 2014). Changes in rates of erosion could also be contributing to the changes in tidal sediment structures. More specific studies to coastal Maine that examine the balance between the climate change related forces that increase and decrease sedimentary erosion could be helpful in evaluating what changes are happening within the system and how they are impacting milky ribbon worm populations.

Temperature

Another avenue for future exploration is to evaluate the claim that milky ribbon worms thrive in warmer waters and climates. The evaluation of this claim could provide insight into the origin of the rapid increase in milky ribbon worm impact on soft-shell populations. While there are many species of Nemertea, not all prefer warm waters, some are adapted for cooler climates (Theil and Kruse 2001). However, there does seem to be general anecdotal agreement that the milky ribbon worm does prefer warmer conditions. One of my contacts specifically noted the winter of 2012 as being incredibly mild. He said that the following spring and summer he saw a large increase in the number of milky ribbon worms. 2012 was one of the warmers years on record in the North Atlantic (Mills et al.). The sea surface temperature anomaly in the Gulf of Maine for 2012 was 2˚C above 1982-2011 averages (Mills et al.). Based on the experiences of this clam digger as well as the data demonstrating 2012 as a major heat wave year, it seems that the anecdotal increase in ribbon worm populations could be linked to this increase in temperature. One of my contacts noted that he has found ribbon worms frozen on top of the mud when the temperature drops quickly. If in 2012 the temperatures were so mild there may not have been as many ribbon worm mortalities related to freezing.

All of my contacts noted that the increase in milky ribbon worms they have observed has occurred over the last 20 years. While temperatures in the Gulf of Maine after 1981 increased on average at a rate of 0.026˚C per year, after 2004 this rate of increase rose to 0.26˚C per year. This increase in the rate of warming of the Gulf of Maine when compared to the anecdotal evidence of the increase in milky ribbon worm populations over the last 20 years may suggest a correlation. Moving forward, it would beneficial to conduct more interviews with clammers and to identify years, like 2012, where they noticed high numbers of milky ribbon worms and to compare these to historical climate data including sea surface temperature data, ice in and ice out dates, and atmospheric data.

Clam Size

Despite the conclusion drawn by a past study on milky ribbon worms feeding habits that they are not selective based on size of soft-shell clams when they feed (Bourque, Miron, and Landry 2001), the clam diggers I spoke to discussed that ribbon worms often do not appear in a bed of soft shells until they reach around 1.5 inches. This supports the Downeast Institutes theory that milky ribbon worms do prefer larger clams (Institute). This discrepancy between the peer reviewed study and the evidence from the Downeast Institute and the diggers I spoke with is worth pursuing as it may give us an indication about how ribbon worms identify their prey, which may lead to the development of mitigation practices. Some species of nemertean use chemosensing to find and actively pursue their prey into their dwellings where they attack (Theil and Kruse 2001). Evidence shows that *Lineus viridis,* a species in the same phylum as the milky ribbon worm, heavily relies on chemical cues to find prey and, in areas where these chemical signals spread over a large area, more of these nemertines appear (Thiel 1998). The question arises surrounding what chemical signals the milky ribbon worm identifies and follows while hunting soft-shell clams. Sources suggest that clams do give off chemical cues that can be picked up on by predators like crabs and Nemertea as well as picking up on the chemical cues given off by some of their predators (Flynn and Smee 2010, Hay 2009). However, there seems to be a gap in literature surrounding the development of these chemical cues by soft-shell clams. It would be valuable to identify if there is a time in the lifecycle of soft-shell clams, when they reach reproductive maturity or another point in their life cycle, when they begin to give off strong chemical cues that the milky ribbon worm and other predators follow. If these cues are size related, it may allow for the development of more mitigation practices.

Another possibility related to the chemical cues released by soft-shell clams is that the strength of these cues and the ability of milky ribbon worms to pick up on them is related to the population density of soft-shell clams, rather than directly to the size of the clams. The evidence provided by the Downeast Institute and my interviewees suggests that the preference is due to size, however, studies have shown that soft-shell clam populations reach their peak density at between 30-40 mm in shell length (Appeldoorn 1980, Gerasimova, Maximovich, and Filippova 2015). This range encompasses the 1.5 inches suggested as the preferred prey size of the milky ribbon worm by the Downeast Institute and my interviewees. I suggest the possibility that, in the case size may be a metric for population density. The higher the clam density, the stronger the chemical cues they release will be, drawing more ribbon worms. I think both of these possibilities, size and density, should be explored in order explore potential mitigation practices that could slow or dampen the chemical cues of soft-shell clams, preventing their detection by milky ribbon worms.

Nocturnal Swimming

Another avenue for further research is the evaluation of the claim of some clammers that they have witnessed milky ribbon worms swimming at night. One digger described seeing them swim in large numbers at night. If this is true, it might provide a potential mitigation technique. One digger expressed his interest, if it is discovered that there are times where milky ribbon worms swim in large groups, to go out at those times on his boat with a find net to catch as many as possible. Further research into this may provide us with informative behavioral data as well as a potentially effective mitigation technique.

In conclusion, the information gathered from these conversations with stakeholders has provided a baseline ecological knowledge for beginning to understand the potential mechanisms behind the increase in the impact of milky ribbon worms on soft shell clam populations. This information can now be used to inform research questions to be pursued using more quantitative techniques. My hope is that this study not only helps to provide a jumping off point for future studies focusing on the milky ribbon worm, but also brings attention to the importance of the knowledge that is held by stakeholders of various systems, not just the clamming industry of coastal Maine.

Table 1. Summary of participant observations, existing literature, and implications and recommendation for the primary ecological aspects taken from interviews

Primary Ecological Aspect	Participant Observation	Existing Literature	Implications/Recommendations
Sediment Preference	Milky ribbon worms prefer soft mud to harder, sandier sediments	No published studies surrounding milky ribbon worm sediment preference	Recommendation for further research into sediment preference
Changes in Sediment	Mudflats in the Gulf of Maine are softening	No published studies about softening mudflats Changing coastal sediments may relate to changing weather patterns and ocean chemistry	Softening mudflats may contribute to increased impact of milky ribbon worms Recommend further research into the nature of changing intertidal sediments
Climate Change	Milky ribbon worms prefer warm waters and climate	The Gulf of Maine is one of the fastest warmest bodies of water in the world	Warming waters and climate may contribute to the increased impact of milky ribbon worms Recommend further comparison of anecdotally high milky ribbon worm years and climate and sea surface temperature data
Clam Size	Milky ribbon worms start attacking a bed of clams when they reach about 1.5 inches in length	Laboratory based experimental study showed no preference in clam size Soft-shell clam density is at its highest when clams reach approximately 1.5 inches in length	The chemical signals milky ribbon worms follow to find soft-shell clams may be strongest when the clam reaches a certain size or when the bed reaches maximum clam density Further research recommended to identify drivers of chemical signal strength
Nocturnal Swimming	Milky ribbon worms have been seen swimming at night in large numbers	No existing literature on nocturnal swimming habits of milky ribbon worm	Nocturnal swimming close facilitate mass netting of milky ribbon worms and aid in mitigation

Conclusion

At the base of ecological knowledge is an understanding of the natural world, its components, systems, and processes developed through people's observations of their surroundings. The discipline of ecology developed as a way to describe the thoughts and explorations triggered by these observations. In short, ecology stemmed from and still has its roots deep within natural history. Though in contemporary times many species have already been described, there are still important uses for natural history style methodologies. One such application involves utilizing the ecological knowledge held by local communities around the world. This local ecological knowledge provides insight into the interconnectedness of the natural world that quantitative-based scientific studies sometimes miss. These observations are becoming increasingly important as we track the impacts of global climate change around the world. Local communities and indigenous populations are often exposed to indicators of changing environments before scientists are able to study them.

The local ecological knowledge of Maine clammers surrounding the milky ribbon worm provided a rare opportunity not only to collect the natural histories of an ecologically obscure organism, but also to gain a better understanding of the multitude of ecological impacts of the changing climate. Some of the most important ecological aspects of the milky ribbon worm that were identified by the clammers I interviewed seemed to support that this organism has a preference for warm water and climate, prefers soft mud to coarser sediment, only infiltrate beds of soft-shell clams when the clams reach approximately 1.5 inches in length, and swim in large numbers at night. Along with these valuable insights into the ecology of the milky ribbon worm, clammers described many changes in the environment they have observed over the last few decades, many of which could have direct impacts on the milky ribbon worm. Their observations on changing tides, the warming water and climate, changes in the biotic community in which they work, and the softening of the sediments of coastal mudflats may help emphasis or direct where further study is warranted.

This wealth of information and knowledge presents many opportunities for further research that could lead to the development of mitigation practices that could help save the soft-shell clamming industry. In a changing climate people around the world whose lives depend on their relationship with their ecosystems are experiencing threats to their livelihoods, whether they come from rising water, invasive species, or increased impacts of native predators (like the milky ribbon worm). The ability of scientists to study these changes and report to policy makers quickly enough to protect ecosystems and livelihoods is limited by time and manpower. My hope is that studies like mine, that acknowledge the limitations to conventional scientific research and celebrate and respect the knowledge of local peoples and stakeholders, will continue to gain prevalence and recognition in the larger scientific community.

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Appendix 1 – Interview Questions

Questions for Harvester:

Name:

Age:

Town:

How long have you been a harvester?

What type of shellfish do you dig for?

Where do you dig clams? (what kind of environment) What is the sediment like? Is it muddier or more sandy?

What kinds of organisms, besides the clams, do you encounter in the sediment? In the environment in general?

How do you choose a location? Do your sites change? From year to year? Seasonal?

What methods do you use to dig clams? Are you digging with hands? Rake? Why?

Tell me what your day on the flats looks like. What do you do? What are the kinds of things you look for?

Has this changed since you began to deal with the MRW? Have you had to change where you are clamming? If so, how? (eg. different sediment types, access, changes in shellfish populations?)

How long ago did you begin to notice the impact?

What does this impact look like?

Have you noticed anything in particular about the flats where you see more MRW or more effects of the MRW?

Where you find MRW, what is the sediment like? Muddy? Sandy? Smelly? Color?

What about the vegetation at the edge of these flats? Are there differences between those with and without MRW?

What about the clams in areas where there is noticeable predation by MRW? Are they bigger, smaller, fewer?

Have you noticed anything different with other organisms in areas impacted by the MRW? Are there more bait worms? Fewer? Green crabs? Other observations?

Have you noticed interactions between the MRW and other sediment dwelling organisms? Green crabs? Bait worms?

How do you minimize the effects of green crabs and MRW on your digging?

Have you noticed any changes in the environment that have happened at the same time as the increasing impact of the MRW?