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Green Economics: Assessing The Feasibility Of A New England Green Crab (Carcinus Maenas) Fishery Through Fishermen Perspectives

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Abstract

The European green crab (*Carcinus maenas*) is a well-adapted invasive species that has flourished throughout coastal New England. Its arrival has caused numerous negative environmental and socioeconomic impacts, including the decline of the Maine soft shell clam (*Mya arenaria*) fishery. Increases in north Atlantic sea surface temperatures have simultaneously propelled the proliferation of *C. maenas* and caused northward shifts in the geographic ranges of commercially relevant species, including the American lobster (*Homarus americanus*). *C. maenas* represents an underutilized species that *H. americanus* and *M. arenaria* fishers can target to supplement any lost income if *C. maenas* markets are economically viable. The research explores the development of the *C. maenas* fishery, describes any barriers to the industry and dissects the economic feasibility of markets based on minimum price points and current landings data. Maine-based fishers were interviewed regarding their views on the current industry and the principle obstacles facing the industry. Past and current landings data was analyzed to determine trends in economic value. The biggest barrier to further industry development is the price per pound of hard-shell crabs. The market value of current landings is far below the threshold of what is considered acceptable to fishers, but the price point is rising. For the fishery to expand, consumer demand must be created. Stakeholders should target farmers markets and chain grocers to further market product. This study was conducted with a limited sample size and analyzed just the perspectives of one sector of the seafood supply chain. Future studies should operate on a larger scale and evaluate the viewpoints of wholesalers and consumers.

1. Project Objectives and Significance

The European green crab (*Carcinus maenas*) is a destructive invasive species that has established populations along the north Atlantic coast of North America (Tan and Beal, 2015). Spurred by warming sea surface temperatures (which have caused declines in southern New England American lobster abundance), *C. maenas* populations have increased greatly, and led to declines in Maine soft shell clam (*Mya arenaria*) populations (Congleton et al., 2016). Research has discovered controlled trapping for *C. maenas* does not decrease population sizes, but a commercial fishery could provide supplemental income to fishers suffering from the effects of climate change (Beal, 2014). However, few markets for *C. maenas* exist in North America and those that do are severely underdeveloped. This research seeks to evaluate the current North Atlantic *C. maenas* fishery by exploring its economic potential and viability. It also utilizes the perspectives of fishers to identify barriers to development and expansion and makes recommendations on what the future framework of a successful New England *C. maenas* fishery could look like.

2. Background

Over the last several decades, the planet has seen worldwide shifts in species ranges, phenology and abundances due to a combination of climate change and overpopulation (Barnosky et al., 2016). High carbon emissions have threatened to negatively impact ocean ecosystems, decreasing pH levels by 0.05 in the last two decades while significantly increasing ocean water temperatures. In the last 200 years, the atmosphere has warmed by 1° C, and at the current rate by 2070 the global temperature will reach higher than it has been since humans have existed (Barnosky et al., 2016). In fact, if current trends do not change, projected temperature rises by 2100 range from 3.1 to 4.25° C (Peters et al., 2013).

In the Atlantic, ocean warming has outpaced the majority of bodies of water in the world, and the Gulf of Maine (GOM) has warmed faster than 99% of the planet's oceans (Pershing et al., 2015). This temperature increase has caused a northward shift in the geographic ranges of several commercially relevant species. The warming of waters has increased the suitability of the North Atlantic for some species, such as the black sea bass (*Centropristis striata*), which has expanded its native range into the Gulf of Maine (McMahan et al, 2020). Other species, including the American lobster (*Homarus americanus*) have started to vacate southern New England in search of cooler waters further north (Wahle et al., 2015). One species that has both expanded its range and increased its population size during the rise in sea surface temperatures (SST) is the invasive European green crab (*Carcinus maenas*). *C. maenas* are extremely abundant along coastal New England and could represent a new target for fishermen, but their economic potential is unclear.

2.1 The European Green Crab (*Carcinus maenas)*

The European green crab (*Carcinus maenas*) is a decapod crustacean from the family Portunidae. *C. maenas* is native to northern Africa and Europe, and more specifically ranges from Norway and the British Isles south to Mauritania (Best et al., 2017). Also referred to as the European shore crab, they are the most common decapod crustacean in Europe. A routine occupant of the littoral zone, *C. maenas* cannot tolerate shores with high wave action, and prefer sheltered, rocky shores (Young and Elliot, 2019).

In the early 1800's, *C. maenas* was unwittingly transported across the Atlantic in the ballast water of merchant ships to the north Atlantic coast of North America. Since then, increased globalization has assisted with its introduction to every continent outside of Antarctica (Tan and Beal, 2015). In North America, *C. maenas* has flourished and populations ranges have expanded along either coast. The proliferation of *C. maenas* in the north Atlantic can be attributed to several distinct life traits, which include: a rapid growth rate, high fecundity, ability to tolerate a wide range of habitat conditions while aggressively competing for resources, and a lack of a natural biological control (Pasko and Goldberg, 2014).

2.1.1 Life History and Characteristics

C. maenas are an extremely versatile species and are well adapted to thrive in most climates due to their biological and reproductive strategies. They have a complex life-history that includes four planktonic zoeal stages and a megalopa stage (Dawirs et al., 1986). After the megalopa stage, in which they grow to 1.5 mm, individuals molt into a first-stage juvenile, and reside in sheltered benthic substrate (Zeng and Naylor, 1996). These substrates include gravel or cobble areas, including mussel beds with abundant seaweed cover, like the majority of coastal Maine. Adult crabs live for 5-7 years, molting an average of 18 times during their lifespan.

C. maenas are an *R*-selected species, meaning their population is governed by their biotic potential (ability to reproduce) (Rafferty, 2020). *R*-selected species reproduce at high rates, producing numerous small offspring, most of which do not survive to adulthood. Marine invertebrates, such as *C. maenas,* adapt reproductive strategies to local environments to optimize offspring survival and population stability (Best et al., 2017). These species generally have very short gestation periods as well as short lifespans. For example, in New England, *C. maenas*' clutch sizes range from 4,781-165,940 eggs, while their gestation period ranges from 32-64 days, depending on water temperature (Prince William Sound Regional Citizens Advisory Council, 2004).

C. maenas are both an eurythermal and euryhaline species, meaning they can tolerate a wide range of temperatures and salinities. High levels of the heat shock protein HSP70 help to protect against proteotoxic shock, allowing *C. maenas* to survive in habitats ranging from 0° C to 33-35° C (Young and Elliot, 2019). If exposed to air for an extended period, they can evaporatively cool their body by 2° C, and survive out of water for up to ten days. At high salinities, *C. maenas* are osmotic conformers, matching their body isotonically to the surrounding environment. However, when salinity hits a critical low point, they can regulate inner salinity levels. These hardy traits, combined with versatile reproductive strategies, have enabled *C. maenas* to adapt to changing ecosystems and climates throughout the globe, including in coastal New England. Population estimates are challenging due to the dynamic nature of the crabs, but in regions in which they are fully established (including the coastal north Atlantic), *C. maenas* are almost always considered "abundant" or "extremely abundant" (Young and Elliot, 2019).

2.1.2 Predation and Competition

C. maenas are opportunistic omnivores, and feed on a diverse variety of species. Juveniles consume mostly detritus but become more carnivorous as they age.
Throughout their worldwide range, *C. maenas* have been reported to feed on animals from at least 158 genera. However, in New England, *C. maenas* prey primarily on commercially relevant bivalves such as soft-shell clams (*Mya arenaria*), blue mussels (*Mytilus edulis*) and the eastern oyster (*Crassostrea virginica*), and occasionally consume newly settled juvenile lobsters and other *C. maenas* (Young and Elliot, 2019).

Though *C. maenas* is preyed upon by numerous species (including tautog, striped bass and various shorebirds), there are few effective biological controls in the north Atlantic, and this has allowed populations to multiply virtually unchecked in New England. However, there are examples of possible biological controls further south that need to be accounted for. For example, in southern New England, the establishment of the invasive Asian shore crab (*Hemigrapsus sanguineus*) has resulted in a decline of *C. maenas* populations in rocky, intertidal shores (Lohrer and Whitlatch, 2002). Likewise, in the mid-Atlantic, competition from the larger blue crab (*Callinectes sapidus*) has limited *C. maenas'* southward expansion into the Chesapeake Bay (DeRivera et al, 2005). Recently, it has become more common to witness *C. sapidus* in the GOM, notably further north than its historical range of Cape Cod, Massachusetts. It is likely this new distribution of *C. sapidus* is due to warming waters via climate change. If warming trends continue, *C. sapidus* populations could possibly become established in the GOM. Once established, these populations could potentially outcompete and prey on *C. maenas* populations and act as a natural biological control (Johnson, 2015).

2.2 Invasion History

There were three separate invasions responsible for *C. maenas'* spread throughout the world, all of which were brought about by an increase in shipping due to worldwide globalization (Best et al., 2017). These invasions occurred in three major episodes: the early 1800's, mid 1800's, and late 1900's.

2.2.1 The First Invasion: ~1817

C. maenas was first introduced to the mid-Atlantic coast of North America in 1817, likely from the ballasts and wormholes of wooden ships. (Tan and Beal, 2015; Young et al., 2017). It was initially sighted in the Long Island area, and later reported in Cape Cod, Massachusetts in 1872, followed by southern Maine in the early 1900s. By 1951, *C. maenas* had spread to Washington County, Maine and into southeastern Canada (Scattergood, 1952; Carlton and Cohen, 2003). *C. maenas*' rapid northeastward advance can be attributed to coastal fisheries, as Scattergood (1952) explains:

> "Undoubtedly, man's activities are partially responsible for the remarkable spread of Carcinides (sic). The lobster and sardine fisheries probably provide the principal means by which crabs may be transported from one area to another. Since the crabs can live for several days out of water, it is relatively easy for the crabs to be carried in lobster smacks, lobster carrying trucks, lobster-fishing boats, sardine carriers, and sardine-fishing boats. I have seen live crabs in crates of live lobsters and have noticed them aboard sardine carriers and fishing boats."

In 1989, *C. maenas* was observed in San Fransisco Bay, marking the first time it had been sighted on the North American west coast. They were likely transported as larvae in ballast water, but it is possible adults were present in algae that was used to pack New England lobsters (Carlton and Cohen, 1995; Cohen et al., 1995). They rapidly spread both northward and southward, and currently range from Morro Bay, California to Vancouver Island, British Columbia. It is hypothesized ocean currents during the El Nino winter of 1997-1998 transported larvae crabs northward to Washington State (Carlton and Cohen, 2003).

2.2.2 The Second Invasion: ~1857

In the mid-1800's, *C. maenas* was identified in multiple countries in South America, Australia and Hawaii. *C. maenas*' adaptability (they can live for over 90 days without food and survive for 60 days out of water if sheltered under seaweed) coupled with increased globalization was likely responsible for the second invasive episode (Carlton and Cohen, 2003). In the mid-1800's, several events occurred that could have influenced the dispersal of *C. maenas*. The introduction of Clipper ships to the world increased the speed and efficiency at which merchants could trade. Additionally, the California gold rush (1850's) and the opening of the Suez Canal (1869) altered global trade routes and increased regions to which *C. maenas* could be introduced (Carlton and Cohen, 2003). At the turn of the century, the industrial world became more technologically advanced and created more vectors through which invasions could occur. These vessels for transport include: Ship boring and fouling assemblages, solid ballast, fouled seawater pipes and sea chests, semisubmersible exploratory drilling platforms, ballast water, seaweed transported with commercial fisheries products, education research and private releases for fisheries purposes (Carlton and Cohen, 2003).

2.2.3 The Third Invasion: ~1990

In the late 1900's, the North Atlantic *C. maenas* population was supplemented by a more northern genotype in Nova Scotia, Canada (Cartlon and Cohen, 2003). The new genotype, which was introduced through a Nova Scotian harbor from increased vessel trafficking and shipping, interbred with the established *C. maenas* population as it expanded southward. Originating from far North Europe, the distinct *C. maenas* subspecies proved to be more resilient to colder temperatures and far more aggressive than its southern counterpart. It is likely that hybridization and introgression between the two *C. maenas* ecotypes first occurred in the early 2000's and continues to transpire today through a combination of natural dispersal and anthropogenic transport (Jeffery et al., 2017). This posed a new threat to native species and habitats since hybrid generations may be more tolerant to harsher winters and could spread *C. maenas*' range even further north. For example, *C. maenas* was reported in northern Newfoundland in 2003, and have since established populations in Placentia Bay, as well (Kanwit et al., 2014).

2.3 *C. maenas* vs The Climate

While *C. maenas*'s initial transport around the globe can be attributed to globalization, their emergence as an established species in the North Atlantic has been spurred by increased SST's. Despite *C. maenas*'s introduction to Maine in the early 1900's, their population did not explode until the 1950's (Ropes, 1968). This expansion was stimulated by an increased temperature anomaly in the GOM. However, during the 1980's temperatures started to increase again and have been on the rise since (Saba et al., 2016) (Figure 1).

There is a direct correlation between warmer SST, mild winters and an increased *C. maenas* population. A SST drop below 1°C puts *C. maenas* outside of their physiochemical limits of survival. They become immobilized at -1°C, and high mortality rates occur at -3°C (Congleton et al., 2016). With waters warming by 0.23° C annually in the GOM, winters have become milder and shorter, with icing over harbors becoming less common where freezing previously occurred (Fernandez et al., 2015). Naturally, the mortality rate is lower than it used to be during the winter, resulting in more juvenile crabs surviving through winters. Current *C. maenas* populations are strongest along the mid and southwestern coasts of Maine, where SST's are among the highest in the GOM (McClenachan et al., 2015). This rise in population has caused negative environmental and socioeconomic impacts.

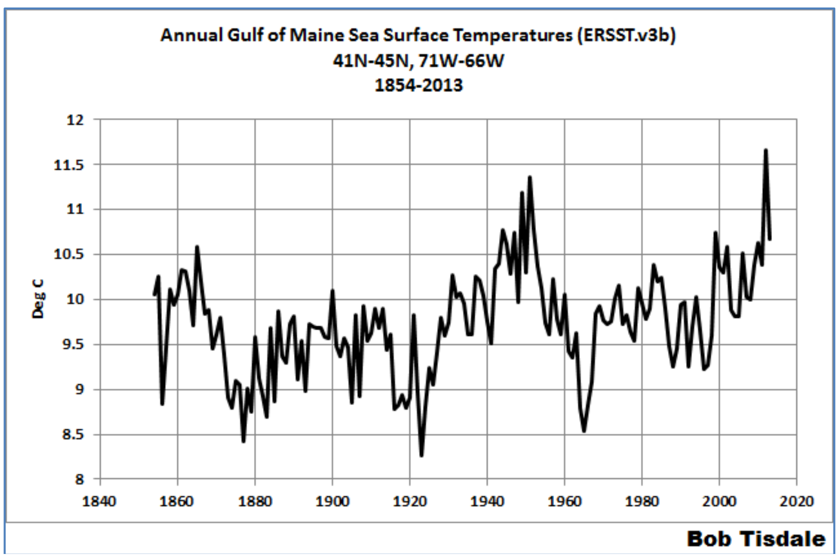

Fig 1. Annual increase in GOM SST from 1850 to 2020. Graph adapted from Tisdale, (2014).

2.4 Environmental Impacts

2.4.1 Eelgrass Bed Impacts

C. maenas have been labeled "ecosystem engineers" due to their ability to alter marine habitats and trophic levels (Tan and Beal, 2015). *C. maenas*'s impacts to soft-bottom intertidal areas are both environmentally and socio-economically damaging (Garbary et al., 2013; Matheson et al., 2016). Within intertidal ecosystems, *C. maenas* uses mussel beds, shell debris, ephemeral algae mats and aquatic vegetation (especially eelgrass) as shelter. Eelgrass (*Zostera marina*) beds are crucial to ecosystems and act as nurseries and shelter for commercially relevant fish and invertebrates, including Atlantic cod, southern flounder and bay scallops (Garbary et al., 2013). Additionally, they reduce turbidity, remove dissolved carbon and nitrogen, increase pH and act as support against erosion for saltwater estuaries (Kanwit et al., 2014). These ecosystem services place the annual value of *Z. marina* beds at $20,700 USD per hectare (Cole and Moksnes, 2016). As a result, a loss of eelgrass beds could prove devastating to local fishing communities.

C. maenas foraging behavior alters endemic benthic community structure and interactions, such as support for higher trophic levels and fisheries production (Davis and Burdick, 1998). A study conducted in Newfoundland implemented a Before-After-Control-Impact survey to assess biodiversity in Placentia and Bonavista Bays, and researchers found a tenfold decrease in fish biomass from seine samples from sites with and without the presence of *C. maenas* (Matheson et al., 2016). A sharp decline in the abundance of three-spined sticklebacks, an important prey for cod and other piscivorous fish, was also observed. This steep decline of biodiversity is alarming as it could lead to cascading effects such as "mesopredator release", and completely alter the balance of estuarine ecosystems. Several commercially important species also use these habitats as nursing grounds, and losses in abundance of juvenile fish can negatively impact coastal fishing communities. It is for this reason the country of Canada listed eelgrass as an "ecologically significant species". While this trend is certainly concerning, eelgrass beds are resilient and can make a full recovery just six years after damage occurs, which highlights the importance to find effective mitigation techniques for *C. maenas*.

Multiple studies have attributed declines in *Z. marina* beds to increased *C. maenas* activity (Garbary et al., 2013; Howard et al., 2019; Matheson et al., 2016). Garbary et al. (2013) discovered a 75% decrease in eelgrass in Nova Scotia, Canada due to *C. maenas* activity, while Howard et al. (2019) found *C. maenas* was responsible for a 71-83% decline in an eelgrass bed over a 4-week period in British Columbia, Canada. These studies both concluded the primary reason for destruction was the "fraying" of *Z. marina* blades (likely while crabs were digging for clams).

2.4.2 Soft shell clam predation

Another consequence associated with the arrival of *C. maenas* to New England is the damage they have caused to the Maine soft shell clam (*Mya arenaria)* fishery. The *M. arenaria* industry is the third largest fishery in Maine and makes up 4% of the annual seafood market. On average, *M. arenaria* brings about $21 million per year to Maine, though that number fluctuates with annual harvests (Davidsohn, 2018). For example, in 2004 the *M. arenaria* fishery contributed $16.61 million to the Maine economy (Congleton et al., 2016). Annual harvests, however, have been in a regular decline since the 1950's, which coincides with the initial increase of *C. maenas* populations in Maine (figure 2). Over the past 40 years, Maine's commercial production of *M. arenaria* has decreased by almost 75%, and clam landings in 2017 were the lowest in the last 80 years due to increased predation by *C. maenas* (Beal et al., 2018).

The likely cause for the decline in *M. arenaria* abundance is not from an increase in GOM SST, but from decreased winter mortality rates in the *C. maenas* population in response to the increased SST. Congleton et al. (2016) discovered *C. maenas* predation on *M. arenaria* is higher when the previous winter is milder due to decreased winter mortality resulting in larger populations of *C. maenas*. With larger *C. maenas* populations there is an obvious uptick in *M. arenaria* predation. As mild winters become increasingly frequent in the GOM, further declines in *M. arenaria* populations are expected.

C. maenas predation not only affects *M. arenaria* population sizes, it also alters their behavior. While foraging, *C. maenas* uses its claws, called chelipeds, to dig for newly settled juvenile and adult *M. arenaria*. They then crush the shells and extract the meat from the dead clam. Multiple studies have discovered that *M. arenaria* will burrow deeper to avoid *C. maenas* (Whitlow et al., 2003; Whitlow, 2010; Flynn and Smee, 2010). These studies demonstrated that *C. maenas* induced a greater burrowing response on *M. arenaria* than clams not exposed to them. In Yarmouth, ME in 2013, Heinig (2013) found clam size distribution in the Cousins River was heavily weighted to larger size categories, and many of the clams were unusually large. These clams were buried in depths of up to 18 inches. In all sample sites, very few small or intermediate sized clams were found. The absence of two-year classes throughout the sites is very concerning and could result in a loss in excess of $300,000 annually in the Cousins River alone (Kanwit et al., 2014).

A study conducted by Tan and Beal (2015) warned about the potential underestimation of *C. maenas* predation on *M. arenaria*. They compared populations of juvenile *M. arenaria* with predator deterrents to control groups without protection and determined crabs can prey on clams without leaving telltale signs of disturbance. By cutting mantle tissue and consuming tissue inside clams, *C. maenas* can consume clams without crushing the shells. This new evidence points to the possibility previous studies have underestimated *C. maenas*' influence on the *M. arenaria* industry.

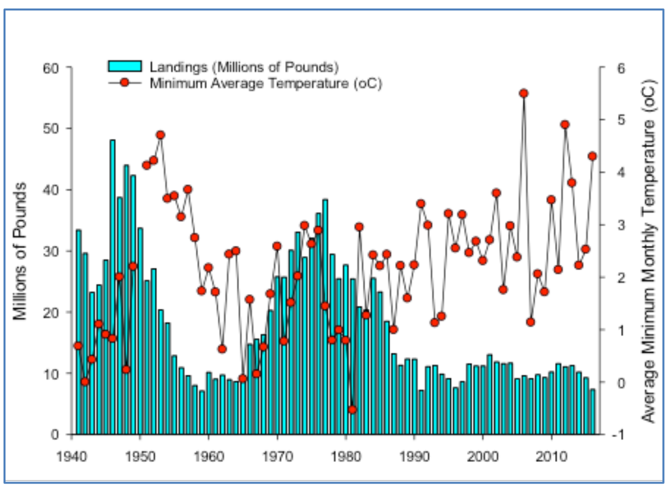

Figure 2. Annual *M. arenaria* landings compared to minimum average SSTs in the GOM. Data accounts for the years 1940-2017. Chart adapted from Beal et al., (2016).

2.5 *C. maenas* Management in Maine

In response to the negative environmental and socioeconomic impacts caused by *C. maenas* to the State of Maine's fisheries, then-Maine governor Paul LePage established the Governor's Task Force on the Invasive European Green Crab in February 2014. The task force oversaw the devising of a management plan for the State of Maine regarding *C. maenas* (Kanwit et al., 2014). The executive order reads:

> "AN ORDER ESTABLISHING THE GOVERNOR'S TASK FORCE ON THE INVASIVE EUROPEAN GREEN CRAB"
>
> WHEREAS, the European green crab population has rapidly expanded in Maine's coastal waters in recent years; and
>
> WHEREAS, the European green crab is a voracious predator known to be causing resource depletion of bivalve shellfish species such as the blue mussel and soft-shelled clam; and
>
> WHEREAS, the European green crab has destroyed eelgrass and fringe marsh habitat throughout the coast; and
>
> WHEREAS, the bivalve shellfish fishery is worth approximately $25 million to the state economy; and
>
> WHEREAS, the eelgrass and fringe marsh habitats are critically important to the health and productivity of Maine's marine resources; and
>
> WHEREAS, the impacts of European green crab predation are unknown with regard to other commercially important marine species; and
>
> NOW, THEREFORE, I, Paul R. LePage, Governor of the State of Maine, hereby order as follows:
>
> The Governor's Task Force on the invasive European green crab is hereby established."

Maine officials have stated they will not manage *C. maenas* as a fishery due to their status as an invasive species, and the top priority is eliminating them from the ecosystem (Kanwit et al., 2014). In September 2014, the Governor's Task Force report was published, which included data on documented *C. maenas* impacts and possible mitigation strategies. These mitigation strategies are discussed below.

2.6 Invasive Species Management

There are two main methods that are used to manage invasive species, but they depend on several factors within the population. These methods include biological and mechanical control. Biological control is the intentional manipulation of natural enemies by humans for the purpose of controlling pests (National Invasive Species Information Center, 2020). Often times though, this method can have unintended consequences (i.e., the cane toad in Australia).

In its native European range, *C. maenas* is held in check partially by the parasitical barnacle *Sacculina carcini*. After injecting itself into its hosts' larvae, *S. carcini* permeates into somatic tissue and "castrates" its victims. This prevents *C. maenas* from molting and eventually leads to mortality (Bateman et al., 2017). Scientists have considered introducing *S. carcini* into North American habitats to control invasive *C. maenas* populations, but this could negatively affect other species in the ecosystem. Researchers in a lab in California discovered *S. carcini* utilized Dungeness crabs (*Metacarcinus magister*) as a host. This could cause a massive collapse in *M. magister* populations and the fishery, which is worth over $150 million annually to the Pacific Coast of the United States (Oregon Dungeness Crab Commission, 2011).

A more realistic approach to mitigating *C. maenas* populations is mechanical control. Mechanical control techniques often use incentives to encourage the harvest of invasive species. Examples of control programs that utilize incentives include:

Bounty Program – A financial incentive program in which an individual is paid to collect a specified organism

Contract Operation – Provides payment to a service provider for the removal of an invasive species.

Commercial Market – The harvest of a species for sale to a specific market

Recreational Harvest – Enhances or encourages recreational fishing, hunting, or trapping of an invasive species. These actions include outreach and modifying regulations (Pasko and Goldberg, 2019)

2.6.1 Recreational Trapping of *C. maenas*

Multiple studies have unsuccessfully explored the utilization of recreational trapping to reduce *C. maenas* populations. On the southwest coast of the United States, researchers were warned trapping with the intention of eradication could trigger a phenomenon known as "the hydra effect" (Grosholz et al, 2021).

Named after the mythological creature that, when decapitated, grew back two heads, the hydra effect can be summarized as "population increases in response to mortality". The study involving *C. maenas* occurred in several lagoons in central California where, due to the recent (~1990) introduction (and lack of establishment) of *C. maenas* to the region, researchers thought eradication might still be attainable. Over a four-year period, the *C. maenas* population in Seadrift Lagoon was reduced by over 90% (125,000 individuals to 10,000 individuals) from intensive trapping efforts. However, the following year the population exploded to over 300,000 individuals, a 30-fold increase. Researchers concluded the population increase was directly related to trapping efforts, and triggered stage-specific overcompensation in juvenile crabs.

In Maine, the trapping of *C. maenas* to mitigate populations and increase *M. arenaria* abundance has been attempted without much success. From 2013 to 2017, researchers from the Downeast Institute (DEI) partnered with local *M. arenaria* fishers to determine how effective routine trapping and exclusion fencing is against *C. maenas* in Casco Bay, Maine (Beal, 2014). They arrived at two important conclusions: 1. It is not possible to mitigate *C. maenas* populations by trapping crabs along open areas of the coast. 2. It is possible, however, to deter *C. maenas* predatory activities on *M. arenaria* in small, routinely maintained areas, and enhance wild clam populations through the utilization of exclusionary fencing (Beal, 2014). Further DEI research highlighted the fact that it is a waste of time and resources to recreationally trap *C. maenas* if population reduction is the primary goal (Green Crab Research, n.d).

2.6.2 Commercial Harvest of *C. maenas*

For marine invasive species like that of *C. maenas*, the most successful control efforts are commercial market programs, and specifically incorporate the "If you can't beat em, eat em" motto (Conant, 2020). In the Mississippi River Basin, restaurants were incentivized to control invasive populations of Asian carp (including black carp, bighead carp and silver carp). Similarly, in 2010 NOAA established the *Eat Lionfish* campaign along the southeastern coast of the United States (Pasko and Goldberg, 2019). The program encouraged the consumption of the invasive lionfish (*Pterpois volitans*), a particularly aggressive predator. Combined with the incorporation of tournaments and a partnership with Whole Foods, the movement has succeeded in bringing attention to negative effects associated with *P. volitans*, as well as reducing their population density (Conant, 2020).

It is unclear if high enough fishing pressure could be generated to reduce *C. maenas* populations in the North Atlantic due to the nature of the species: they are highly mobile, disperse long distances and consist of highly established populations (Young and Elliot, 2019). Incentive programs (such as commercial fisheries) are only successful as the primary method of management if the number of individuals harvested exceeds the mortality rate for a breeding cycle (Pasko and Goldberg, 2019). With winter mortality rates decreasing due to mild winters, even higher fishing pressure is required for any success to occur. Instead, fishermen should view commercial markets as an opportunity to take advantage of an under-utilized species.

In fisheries management, an underutilized species is defined as a species whose stocks are under-fished or under-exploited while being fished below the maximum sustainable yield (MSY) (Farmery et al., 2020). There is no current MSY for *C. maenas* because it is managed as an invasive species and not as a fishery, which in the State of Maine are mutually exclusive. By law, invasive species are not managed by the state. For this reason, no data is gathered on invasive species, including population estimates. However, for species with limited data concerning population dynamics, "stocks can be considered as under-utilized where direct and indirect fishing effort is low, or absent, as a result of factors other than the stock being previously overfished" (Farmery et al., 2020). In the case of *C. maenas*, fishing effort is low not because it was previously overfished, but because fishermen lack the economic incentive to target them (van Putten et al., 2019).

The main reason there are few incentives for fishers to target *C. maenas* is the lack of markets and consumer demand in North America. The reasons for this deficiency in markets stems from a combination of limited *C. maenas* fishing experience, a gap in consumer education and the morphology of *C. maenas*. These barriers to industry are further explored in this study. However, there is an industry in Europe based around native *C. maenas* populations that may be adaptable to North Atlantic markets, of which the pros and cons are discussed below.

2.7 Existing Green Crab Markets

The following is a summary of existing or prospective *C. maenas* markets in North America and abroad.

2.7.1 Bait for recreational anglers (UK)

In the United Kingdom, a *C. maenas* fishery utilizes a technique called "crab-tiling" to harvest over 1 million *C. maenas* annually from southwestern UK estuaries. Fishermen place stable structures, such as roof shingles and car tires, in the intertidal substrate, which acts as shelter for *C. maenas*. Individuals that are in the pre-ecdysis stage (molting imminent) and have carapaces with widths greater than 40 mm are then collected and sold to the angling community. These select crabs, which make up about 10% of the population found under "tiles", are referred to as "peeler crabs", and make great bait for recreational fish species such as the European bass (*Dicentrachus labrus*). In the southwestern UK, there are about 77,000 tiles laid in mudflats, as the mild climate allows *C. maenas* to molt year-round (Sheehan et al., 2008). Crab-tiling is a largely unregulated and monetarily successful fishery.

2.7.2 Venetian Moeche

In Venice, Italy, there is a successful fishery that targets the Mediterranean green crab (*Carcinus aestuarii)* in its soft-shell phase. Once harvested, the crabs are lightly battered and fried and typically served with a glass of prosecco as a dish called Moeche. *C. aestuarii* are very similar to *C. maenas* and the two species could easily be substituted for one another in Moeche. Moeche can retail for more than €51.14/kg, equivalent to about

$27USD/lb. Despite the steep price, the Venetian Moeche industry is largely an artisanal fishery because it requires large time investments from fishers. Crabs are captured and stored in floating cages (like that of *H. americanus* crates) until they shed, and then are harvested and sold to restaurants (Sheehan et al., 2017; Poirier et al., 2016). The fishery is also seasonal (dependent on fall and spring molting seasons) but can be supplemented with the harvest of ripe (pregnant) female crabs.

2.7.3 Potential Establishment of *C. maenas* Fishery & Market Expansion

Both crab-tiling and Moeche utilize soft-shell crabs. In the mid-Atlantic, the soft-shell blue crab market for human consumption is a well-established and extremely successful industry (NOAA, n.d.). The creation of a soft-shell industry around human consumption makes the most sense from an economic viewpoint.

2.7.4 North American "Moeche" Model

The Massachusetts and Maine based nonprofit, Manomet, in conjunction with the New Hampshire Sea Grant, recently started a small-scale soft-shell *C. maenas* fishery in southern Maine. The fishery utilizes the existing "Moeche" model to get the highest commercial value for *C. maenas* in North America, and operates by selling dockside directly to interested restaurants, where fishermen can net $2-$3 USD per crab (size dependent). Participants – mostly lobstermen, clam diggers and oyster farmers – harvest and shed soft-shell *C. maenas* to supplement their primary incomes. Aside from a small time investment, harvest costs are low because most fishermen already own the necessary gear (M. McMahan, Personal Communication, 2020).

Of the possible commercial markets for *C. maenas*, an adapted "Moeche" fishery is the most promising from an economic point of view; harvested products have a much higher value than other forms of *C. maenas*. Once crabs are initially harvested, they are stored in lobster crates and sorted through to find any "peeler" crabs (where molting is imminent). The optimal SST for molting in Italy (where the established "Moeche" industry exists) is 17° C, which occurs on average in the month of June in Massachusetts and July in Maine.

However, there are several barriers preventing the further development of a soft-shell *C. maenas* fishery in New England. The process of harvesting soft-shell crabs requires steep time investments and a trained eye. It is rare to catch crabs in their soft-shell phase because they are not foraging during ecdysis (molting) and consequently are not attracted to bait in the traps. Instead, fishers catch *C. maenas* when they are considered "peeler" crabs, where molting is imminent (molting of peeler crabs generally occurs within 2 weeks). There are subtle signs fishers can use to identify peeler crabs from post-molt crabs, which include a "greying" or halo around the episternites and a darkening of the apex line (Poirier et al, 2016). These identification clues can be tough for fishermen to master, especially if they harvest a large volume of crabs. Even if fishers efficiently identify peeler crabs, over 75% of each harvest are post-molt crabs, and useless for the soft-shell market.

Therefore, the development of the soft-shell industry is reliant on the development of hard-shell *C. maenas* fisheries.

2.7.5 Utilization of hard-shell crab

There are several established crab fisheries in North America, all of which have significant hard-shell markets based around human consumption. These species, which include the Alaskan king crab, snow crab, Dungeness crab, blue crab, and Jonah crab, are all considerably larger than *C. maenas* (which ranges from 2.7 - 3.6 inches from carapace tip to tip in the North Atlantic). The small size of *C. maenas* presents an issue to the formation of a hard-shell market because the meat-to-shell ratio is poor, meaning processers must work harder to obtain usable meat. Since processors would have to buy larger volumes of *C. maenas* to get similar meat quantities of larger crab species, the dockside *C. maenas* price point is lower than necessary to incentivize the harvest of *C. maenas*. Adding value to hard-shell crabs by creating additional markets could potentially increase the overall price point of *C. maenas* and convince fishers to target them.

2.7.6 Adding value to hard-shell crabs

One value-add hard-shell *C. maenas* market is its utilization in stocks and sauces in restaurants. There is no set price per pound for this market, but it would likely have to be low because fish stocks are not a valuable commodity and could easily be replaced with cheaper species (B. Weiss, Personal Communication, 2021). An example of a value-add on product is empanadas derived from *C. maenas* mince (Galetti et al., 2017). *C. maenas* mince is meat that has been mechanically extracted from the shell after the crabs are boiled or steamed. In a study conducted at the University of Maine, researchers evaluated consumer opinions on the empanada, and discovered most participants (n = 87) had a favorable opinion on them. In general, 49% of meat was mechanically extracted from the shell, which is impressive considering the extraction rate is 42% for Dungeness and blue crabs. Companies could look to incorporate the *C. maenas* mince extraction in croquettes, cakes, dips, quiches and sausages in the future (Galetti et al., 2017).

2.7.7 Bait for recreational anglers (North America)

Another current market that could be expanded upon is the use of *C. maenas* as bait for recreational anglers. In Cape Cod, Massachusetts, hard-shell *C. maenas* is sold as bait for Tautog for $1-$1.25 USD per pound (Personal Communication, 2021). The crabs are sold for upwards of $40 per bushel (1 bushel equates to 2 five-gallon buckets, or about 9.5 gallons). This represents the highest price per pound for hard-shell *C. maenas* in North America.

Like all *C. maenas* markets, there are considerable barriers to the expansion of the bait industry; it is both a specialized and seasonal market. The economic value of crabs harvested for this market is high, but consumer demand is low because it is limited to recreational tautog anglers during late spring to early fall. For fishermen looking to supplement their incomes on a seasonal basis, the bait market represents a valuable opportunity. However, fishermen interested in harvesting large volumes of crab year-round should pair this market with others.

2.7.8 Forage fish replacement in Agrifeeds

Researchers from the University of New Hampshire investigated the potential of utilizing ground-up, minced whole *C. maenas* (referred to as Green Crab Mince, or GCM) as a protein replacement in aquaculture and livestock feeds (Fulton and Fairchild, 2013). When compared to menhaden (a species commonly used in fish feeds), the substitute exhibited promising results in terms of fatty acid profile, amino acid profile, mineral composition and mercury content. Due to a high ash content (presumably from the minced shell), GCM is not suitable for some species of fish, such as salmonids, but has great potential as a meal substitute for ash-resistant species including cobia and flatfish. The GCM market would probably be unsustainable from a business model as a complete fishmeal substitute for larger farms because it would require massive quantities of feed. However, a smaller-scale market, such as a finisher feed in recirculating aquaculture systems could be attainable.

The three species of fish commonly harvested for the reduction industry (the boiling down of fish to oil for use in vitamins and fish feeds), which makes up 25% of the world's wild-capture fisheries, are menhaden, herring and Peruvian anchoveta. Coincidentally, these species also happen to be preyed upon by top predators like striped bass, cod, and blue-fin tuna. The overfishing of the predators and their food sources has caused massive declines in their populations. A market in which *C. maenas* is utilized as a substitute in agrifeeds would take pressure off the traditional reduction industry and could potentially have ecosystem-wide benefits.

2.8 Research Questions

Following an extensive investigation relating to *C. maenas* population dynamics in New England and the upwards trajectory of populations, this study was conducted to better understand the feasibility of a *C. maenas* fishery designed to supplement lost incomes of fishers due to the effects of climate change. While there are several reasons it makes sense for fishermen to target *C. maenas*, in reality there are few individuals harvesting and selling them. There are several reasons for this, including a lack of markets and a gap in fishermen and consumer education. The aim of this research was to better comprehend current *C. maenas* markets, factors encouraging or preventing the fishing of *C. maenas*, and the steps needed to develop a successful industry in New England. Interviews were conducted with fishers to better understand opportunities and challenges in the supply chain that could be addressed to develop reliable markets and consequently, a fishery that is more desirable to enter and sustain.

For this research, I asked this question: **"What would create an economically viable *C. maenas* fishery?**

This will be examined from several angles:

- Who, if anyone, is fishing for *C. maenas*?
- Do any current fishing incentives exist for *C. maenas*?
- What are the barriers preventing fishing and industry development?
- Is it currently economically viable, or could it be viable in the near future, to target *C. maenas?*

3. Research Methods

This project relied on a cross-sectional, qualitative design. Interviews were conducted to capture the primary sector of the *C. maenas* supply chain: commercial fishermen. Fishers are essential to the development of commercial *C. maenas* markets because they are the base of the supply chain. This research investigated price points, or price per pound received dockside by fishers, for both soft-shell and hard-shell *C. maenas* to better understand the dynamics and motivations behind targeting *C. maenas* as part of a fishery. Specifically, at what price points does fishing for *C. maenas* become an attractive option as supplemental income or potentially a primary target species. The research also investigated barriers preventing the targeting of *C. maenas* by fishermen and obstacles inhibiting further development and scalability of a New England *C. maenas* industry. In addition, the research also explored what the framework of a *C. maenas* fishery might resemble in the future and how fishery regulations, or a lack thereof, could affect that. Once the interviews were completed, responses were transcribed and analyzed.

3.1 Fishermen Interviews

From March to April 2021, 13 interviews were conducted with Maine-based fishermen concerning the development and expansion of commercial *C. maenas* markets. These interviews consisted of subjects who had previously, were currently, or had never fished for or sold *C. maenas*. The population was divided by fishermen's primary targets: Lobsters, soft shell clams, *C. maenas* and oyster aquaculture. Interviews ranged from 8 minutes to 45 minutes in duration. Interview questions focused on the barriers to fishing and scalability of a *C. maenas* fishery, benefits, and minimum prices per pound required for both hard-shell and soft-shell crabs. Baseline questions were also inquired about (general fishing locations, types of dealers sold to, boat size etc.) (appendix 1). The interviews themselves were semi-structured and conducted via phone. A semi-structured interview is a conversation between a researcher and a participant where the researcher comes prepared with questions. Through a conversational manner, the researcher can examine themes that may not be established (Clifford et al., 2016).

3.1.1 Interview Recruitment

Since the sample size (n = 13) was relatively small, a weighted recruitment technique was implemented. Public fisheries data was obtained from the Maine DMR in the form of excel spreadsheets. The spreadsheets contained contact information for all Maine *C. maenas* license holders from 2016 to 2020, and all Maine commercial fisheries license holders from 2016 to 2020. In order to make it more relevant, data was limited to license holders from 2019 and 2020. *C. maenas* license holder data was then cross analyzed with the commercial fisheries license holder data to reveal any additional licenses held by *C. maenas* license holders. A modified spreadsheet was created which contained additional licenses with the highest abundance among those with a *C. maenas* license. These percentages were used to guide interview participant recruitment. Participants were recruited via emails using contact information from DMR license holder data and a combination of convenience sampling and snowballing from relevant contacts.

3.1.2 Interview Analysis

After permission was obtained from the subject, interviews were recorded using the TapeACall app on an iPhone. Responses were later transcribed by hand. An inductive coding approach was taken in order to find any common themes and statements throughout (Fereday and Muir-Cochrane, 2006). These searches started very broad and eventually narrowed down to about five major themes in both sets of interviews. Pie charts as well as a SWOT analysis were also developed.

3.2 SWOT Analysis

In order to better understand barriers to the industry and the potential future path for success for a New England *C. maenas* fishery, a data supported Strengths, Weaknesses, Opportunities, Threats (SWOT) Analysis was performed. It is updated to include the most recent information regarding the *C. maenas* markets. A SWOT Analysis is viewed as a key strategy to organize the framework required to move an industry forward. The top row consists of internal factors that can have positive or negative impacts on the industry. These include factors like people, knowledge (or lack thereof) and marketing. The bottom row lists external factors that can influence the future path of the industry, such as environment, society and climate (Gurel and Tat, 2017). This specific SWOT analysis was created using information from literature, conversations with experts in the field, market analysis and data from the results of the interviews conducted in this study.

4. Results

4.1 *C. maenas* Licenses

The total number of individuals in possession of a commercial *C. maenas* license in Maine for years 2019 and 2020 is 167. For this study it was important to determine what additional commercial fishing licenses individuals with a *C. maenas* license possessed because most fishermen do not primarily target *C. maenas*. For industry development, it is necessary to figure out what types of fishers are likely to target *C. maenas* as a form of income supplementation. The following is a summary of the most common commercial fishing licenses held by those in addition to a *C. maenas* license (figure 3). The data is derived from spreadsheets provided by Maine DMR and focuses on the years 2019 and

2020. Commercial Shellfish licenses were the most common among fishermen, with a 40% abundance among those with a *C. maenas* license. Other additional licenses of note were Commercial Fishing Single (21.5%), Commercial Fishing Crew (21%), Marine Worm Digging (19%) and Lobster Class 2 and Class 3 (12% & 13%). 21% of fishermen only possessed a *C. maenas* license.

For recruiting purposes for the study, licenses that permit the capture of several species were disregarded. This included Commercial Fishing Crew (CFC), Commercial Fishing Single (CFS), Commercial Fishing Pelagic and Anadromous Crew (CPC) and Commercial Fishing Pelagic and Anadromous Single (CPS).

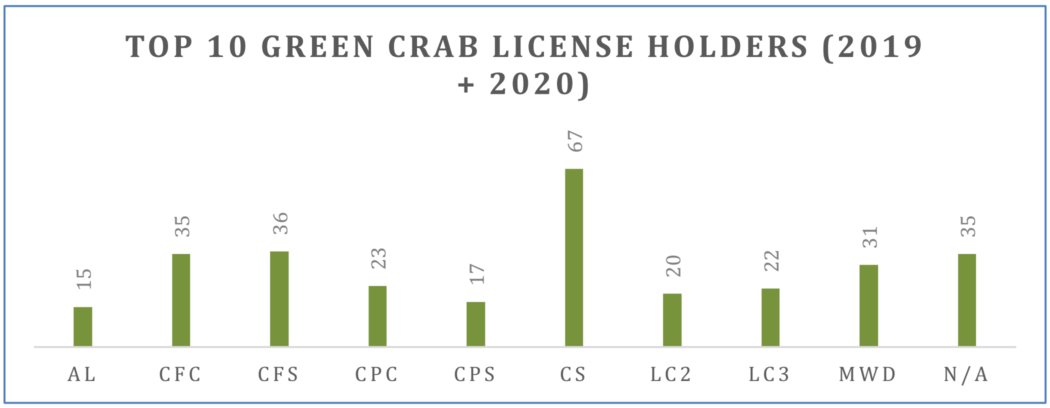

Figure 3. Additional commercial licenses held by individuals in possession of a Maine green crab license. AL = Aquaculture, CFC = Commercial Fishing Crew, CFS = Commercial Fishing Single, CPC = Commercial Fishing Pelagic and Anadromous Crew, CPS = Commercial Fishing Pelagic and Anadromous Single, CS = Commercial Shellfish, LC2 = Lobster/Crab Class 2, LC3 = Lobster/Crab Class 3, MWD = Marine Worm Digging, N/A = Not Applicable (only hold green crab license).

Throughout New England, *C. maenas* licenses are either extremely affordable or not required at all. In Maine, a *C. maenas* license costs just $10 USD annually, and can be renewed from the Maine DMR website (Maine.gov, 2021). In Massachusetts, individuals can legally fish for and sell *C. maenas* after receiving a free Authorization from the State DMR (Mass.gov, 2021). In New Hampshire and Rhode Island, it is legal to fish for *C. maenas* without any paperwork. These relaxed regulations, likely because of the invasive nature of *C. maenas* (and environmental and socioeconomic benefits of population reduction), make it enticing for fishermen to at least purchase a license. For most, the potential benefits of getting involved in the fishery outweigh any risk involved. An oyster farmer interview participant described the reasoning for his purchase of a *C. maenas* license:

> "I think it's definitely a low barrier of entry. It makes it much more enticing the fact that it's cheap and that you can't throw a stick without hitting a green crab. All those things made me more interested, that's why I bought the license, like I'll be out ten bucks if I don't even participate, like whatever."

It is not uncommon for fishermen to possess several commercial fishing licenses, even if they may never utilize some of them. This should be accounted for when examining *C, maenas* license holder data. Data suggests from 2019 and 2020, 167 Maine residents held a *C. maenas* license. This does not mean, however, that they have ever actually utilized the license. From 2016 to 2020, there was an increase in commercial *C. maenas* licenses (Figure 4). This trend is not unexpected for a fledgling fishery, but it can be deceiving not knowing how many licenses have actually been utilized.

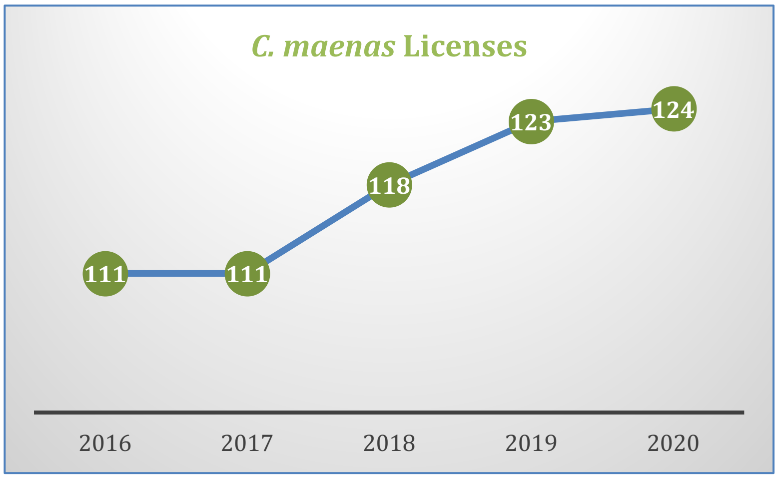

Figure 4. Annual commercial *C. maenas* licenses in the State of Maine from 2016 to 2020. Data derived from the Maine DMR.

4.2 Demographics of *C. maenas* Fishers

Of the 13 fishermen interviewed, 4 (31%) were primarily clam diggers, 4 (31%) were lobster fishers, 3 (23%) possessed just a *C. maenas* license and the remaining 2 (15%) were oyster farmers (figure 5). Each of these groups brought valuable perspectives about the barriers to the development of a *C. maenas* fishery, although there was also considerable overlap between them. These perspectives are explained below.

4.2.1 Clam Diggers

Of the 167 Maine fishermen with a *C. maenas* license, 67 (40%) also possessed a Commercial Shellfish license. This license permits the holder to "fish for, take, possess or transport shellfish within state limits or sell shellstock… to a wholesale seafood license holder" (Maine Legislature, 2020). For the purpose of a Commercial Shellfish license, the Maine DMR defines shellfish as "shellstock clams, quahogs other than mahogany quahogs, and oyster shellstock". This means fishermen can harvest wild clams, including razor clams, soft shell clams, surf clams and littlenecks, as well as wild oysters. Commercial Shellfish licenses were the most abundant among those with a *C. maenas* license.

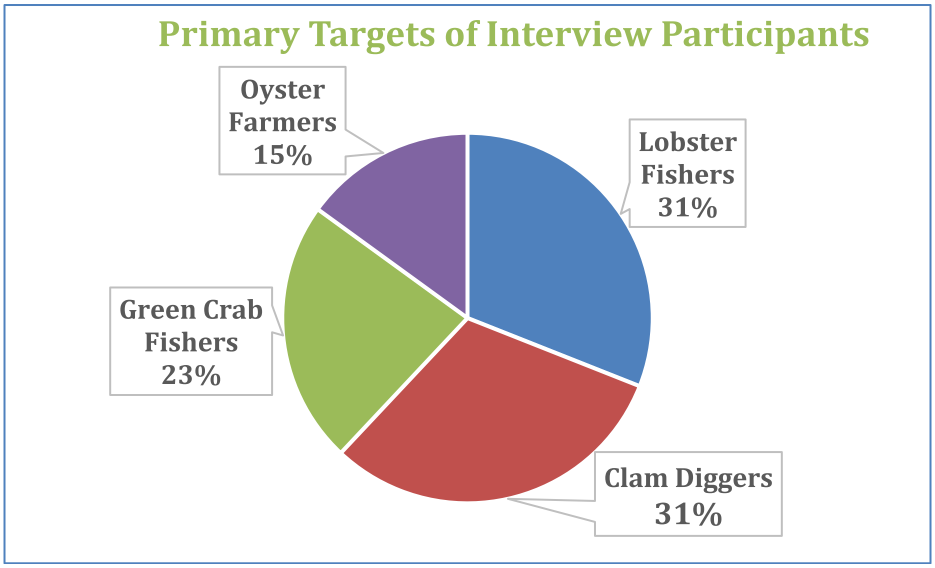

Figure 5. Primary commercial fishing targets of interview participants, N = 13. Of the participants, 4 (31%) targeted lobsters as their primary source of income, 4 (31%) targeted soft shell clams, 3 (23%) possessed just a C. *maenas* license, and 2 (15%) were oyster farmers.

4.2.2 Lobster Fishers

Of the individuals with a *C. maenas* license, 45 (27%) also possessed some variety of a lobster license. It is possible for one fisherman to have multiple types of lobster licenses, so for the purpose of the research, any fishers with multiple lobster licenses were marked as having one license. The possible licenses include Class I, Class II, Class III, Apprentice, and a Student License. All license holders are permitted to "fish for, take, possess, ship or transport within the state lobsters or crabs and sell lobsters or crabs the license holder has taken" (Maine Legislature, 2020). The main difference is Class II license holders may engage one unlicensed crew member to assist with fishing, while Class III license holders can engage up to four unlicensed crew members. Student and Apprentice lobster fishers must fish under the supervision of a class I, II, or III lobstermen (Maine Legislature, 2020). According to DMR, Class II and Class III licenses were the most popular among *C. maenas* license holders.

A distinction needs to be made between inshore and offshore lobstermen. "Inshore" is defined as 0-3 miles from the coast and is regulated at the state level. The "offshore" fishery is located 3-20 miles off the coast and is regulated at the federal level. All lobster fishers interviewed in the study operated in the inshore fishery. In general, inshore areas are fished during the summer months and lobstermen travel offshore during the winter and early spring. Of the two, inshore lobstermen are the most likely to be successful fishing for *C. maenas* for multiple reasons. Since *C. maenas* are a coastal species, populations will only be found near estuaries.

4.2.3 Oyster Farmers

Among the individuals who possessed a commercial *C. maenas* license, 15 (9%) fishermen also possessed an aquaculture license. In the State of Maine, an aquaculture license authorizes the holder to “remove, possess, transport within the state limits or sell cultured organism” (Maine.gov, n.d.). The most economically valuable farmed species in Maine are Atlantic salmon, blue mussels, oysters and seaweed (Seagrant, n.d.). Oyster farmers were the only demographic targeted as potential *C. maenas* fishers because they encounter *C. maenas* daily and have the potential to shoulder seasons with the *C. maenas* fishery.

4.3 Incentives to Fish for *C. maenas*

The New England *C. maenas* fishery is not only underdeveloped, it is almost nonexistent. Unlike most commercial fisheries, there are no available public landings data from the Maine DMR. A major advantage the potential *C. maenas* fishery holds over more established fisheries, however, is limited barriers to entry. There are several factors that contribute to making this fishery appealing to fishermen in search of income supplementation, including limited fishing expenses and an abundant resource with no catch limits.

4.3.1 Fishing Expenses

When targeting *C. maenas*, overall fishing expenses are relatively cheap. The general necessities required include traps of some sort, a commercial license, legal bait, a small boat (not required) and gas. Eel or fukui traps are commonly used, but makeshift traps can be constructed for cheap by using inexpensive and easily accessible materials. To increase efficiency, fishermen can alter the traps with zip ties or lead fishing weights (Bergshoeff et al., 2019). In Maine, legal bait requirements are the same as for lobster bait. Several interview participants possessed a pogie license and expressed their bait expenses are next to nothing anyway. In addition to the above equipment, a storage tray is needed to store peeler crabs while they molt to soft-shells. The trays can be manufactured for a relatively inexpensive price by combining high density polyethylene (4 mm mesh oyster bags) and lobster crates.

C. maenas are commonly found in high densities in estuary habitat and along sheltered rocky intertidal habitat. This proximity to shore makes it feasible that fishermen could set successful traps utilizing a small boat or even no boat at all (at low tide). When a boat is in use, fuel costs are less because a fisherman does not have to travel as far as they would for lobsters. A lobster fisher explains this comparison in more detail:

> “The gas, I certainly think you could catch a lot of green crabs in shallower water, for lobsters you have to travel to get to deeper water, that’s not a concern when it comes to green crabs… So if I had to make a comparison, I think it would be cheaper to capture green crabs than when it comes to lobsters.”

4.3.2 Limited Management

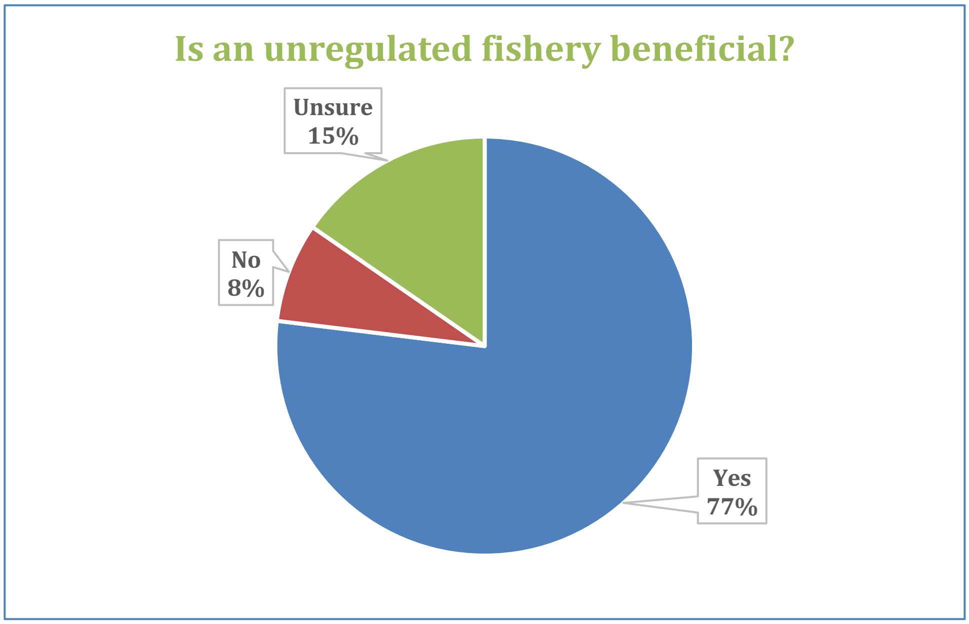

Figure 6. Perspectives of interview participants on how beneficial limited regulations are in the *C. maenas* fishery. 10 participants believed an unregulated fishery to be beneficial, 2 were unsure, and 1 thought it was detrimental.

According to interview data, an unregulated fishery is considered highly advantageous to the growth and development of a fledgling fishery, such as the *C. maenas* industry (Figure 6). Of the 13 participants, 10 expressed the lack of regulations as being beneficial to the fishery, while 2 participants were unsure and 1 thought it could be detrimental.

An important facet of the Maine *C. maenas* fishery to consider is the limited management by regulatory authorities. Throughout New England, and especially in Maine, *C. maenas* are viewed first and foremost as an invasive species. As far as NOAA and DMR are concerned, the primary priority is to decrease the population and mitigate its socioeconomic and environmental effects (Kanwit et al., 2014). For this reason, there are minimal *C. maenas* fishing regulations in Maine. For example, the Maine Department of Marine Resources states that an approved *C. maenas* trap must either be a "top-entry trap with an opening on top of the trap that has a minimum diameter of 3.66 inches", or "a trap constructed with any opening less than 1.5 inches wide". All traps must also have an escape panel with a minimum size of 3.75 inches x 3.5 inches. These regulations are in effect to limit by-catch in the fishery. Other measures enacted to limit by-catch include trawl-trap limits, designated fishing areas (limited to state of Maine territorial waters) and prohibited lobster by-catch (Maine Legislature, 2020). Though this may seem like a lot of rules, it pales in comparison to regulations in established fisheries, such as the Maine lobster fishery. It is also important to note that none of the regulations in the *C. maenas* fishery are in place to protect the population (there are no size, age, sex or volume limits), rather they are in place to protect populations of other fisheries.

The combination of low fishing expenses and limited regulations make the *C. maenas* fishery an easier endeavor for inexperienced fishermen trying to break into commercial fisheries. *C. maenas* can be described as an abundant resource with no catch limits. A major problem, however, is finding markets to sell crabs to.

4.4 Establishing a *C. maenas* Fishery: Challenges to Overcome

The following is a summarization of the biggest factors preventing fishers from targeting *C. maenas* and obstacles prohibiting the further development of the industry. They are defined as Barriers to Fishing and Barriers to Scalability.

4.4.1 Barriers to Fishing

Barriers to fishing is a major part of the data collected for this research and could help to inform stakeholders and fishers about the future of the *C. maenas* industry. 'Barriers to fishing' details what is preventing fishermen from specifically targeting *C. maenas* as a source of income. According to interview participants, there are three major barriers to fishing, which include the price per pound of hard-shell crabs, limited fishing experience, and challenges with product distribution (Figure 7).

4.4.2 Barriers to Scalability

Barriers to Scalability describes factors which prohibit the expansion of the *C. maenas* industry. While intrinsically tied to the fishery, many of these obstacles are related to issues in other aspects of the supply chain. The five barriers outlined by interview participants include: Market price, consumer education, reliable supplies of soft-shell crabs, marketing (advertising), and product distribution (Figure 8).

4.4.3 Market for Hard Shell Crabs

According to fishermen, the biggest barrier to both fishing and scalability is the market price of *C. maenas*, especially for hard-shell crabs (Figures 7 and 8). This trend was true for all interview participants, regardless of what their primary targeted fishery was.

A distinction was made between the price of soft-shell crabs and the price of hard-shell crabs. Price per pound of soft-shell crabs was not considered a barrier because the price has been set at $2-$3 USD per crab, an acceptable market price for fishermen. The price for hard-shell crabs, however, has yet to be set and fluctuates depending on the market.

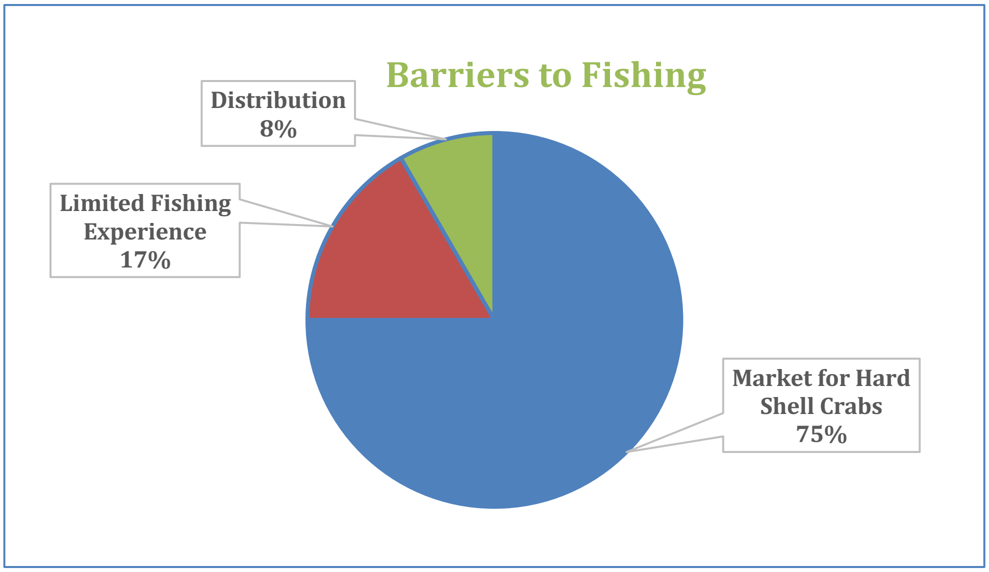

Figure 7. Participants perspectives on the largest barriers to targeting *C. maenas*. 12 of 13 participants responded to the question, 9 of whom believed the biggest barrier was limited markets for hard-shell crabs. 2 fishers believed limited fishing experience was a barrier, and 1 fisher thought product distribution was the biggest obstacle.

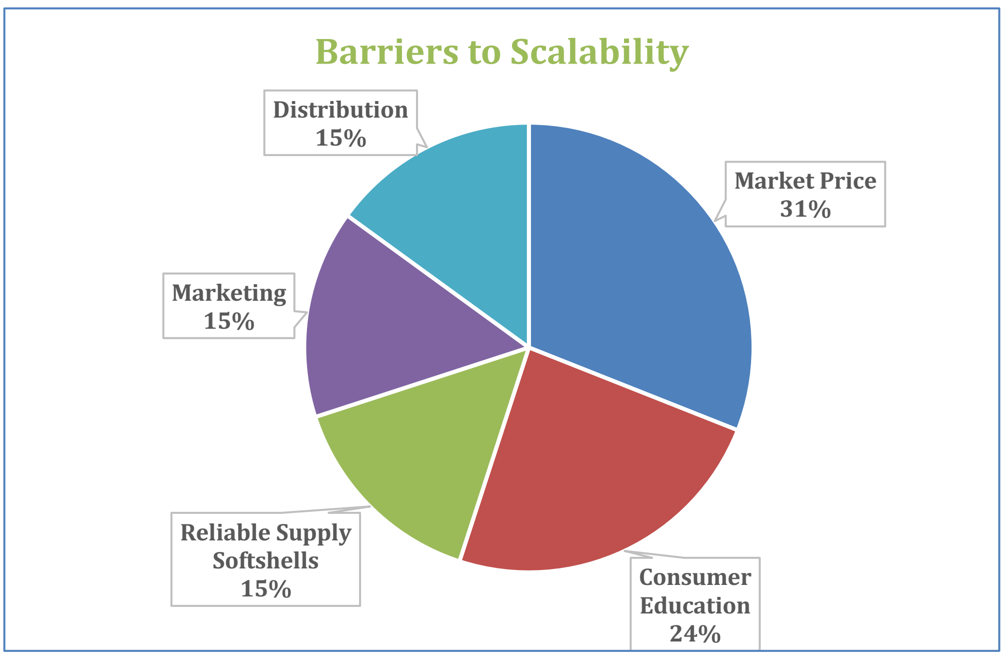

Figure 8. Participants perspectives on the largest barriers to industry expansion. All 13 participants responded to the question, 4 of whom believed the biggest barrier was market price for hard-shell crabs. 3 fishers believed limited consumer education was a barrier. 2 fishers each believed reliable supplies of soft-shell crabs, product marketing and product distribution were all significant obstacles.

4.4.4 Limited Fishing Experience

Another key barrier to fishing is an overall lack of experience in the fishery (according to 17% of participants). This problem stems from a lack of established *C. maenas* fishing practices and a lack of an established market. Therefore, fishers are unaware of where they can sell crabs to. A lot of fishermen "don't have a sense in the market, they don't have a sense in where they would take them, they don't have a sense of what price they would get". In order to convince more fishermen to target *C. maenas*, a fishery framework needs to be further developed and advertised. Fishermen also need to be informed where they can sell their catch to.

4.4.5 Consumer Education & Marketing

Consumer education and marketing of product represent other major barriers to scalability. Of the 13 interview participants, 3 (24%) individuals mentioned minimal consumer education and demand as the single largest obstacle, while 2 (15%) individuals stated the biggest barrier was marketing of product.

4.4.6 Distribution

Distribution of product was a barrier to both fishing and the expansion of the industry. Of the 13 interview participants, 1 (8%) individual stated it was the most important factor preventing the targeting of *C. maenas* by fishers, while 2 (15%) participants mentioned it as a challenge to industry scalability.

4.4.7 Reliable Supply of Soft-Shell Crabs

2 (15%) participants stated a major barrier to expansion is the reliable supply of soft-shell crabs. According to interview participants, it is difficult for fishermen to identify and harvest enough peeler crabs to fulfill regular orders to restaurants, especially after a long day out on the water. The soft-shell crab market coincides with the busy seasons for most fishermen (May-August), and as a result, soft-shell harvesting is generally a form of income supplementation.

4.5 Minimum Price Per Pound

A major barrier for both fishing and the expansion of the New England *C. maenas* industry was the price per pound of hard-shell crabs. The majority of fishermen stressed they would target hard-shell *C. maenas* if they were offered an acceptable price, which in most cases, was believed to be at $1 USD per pound (Figure 9).

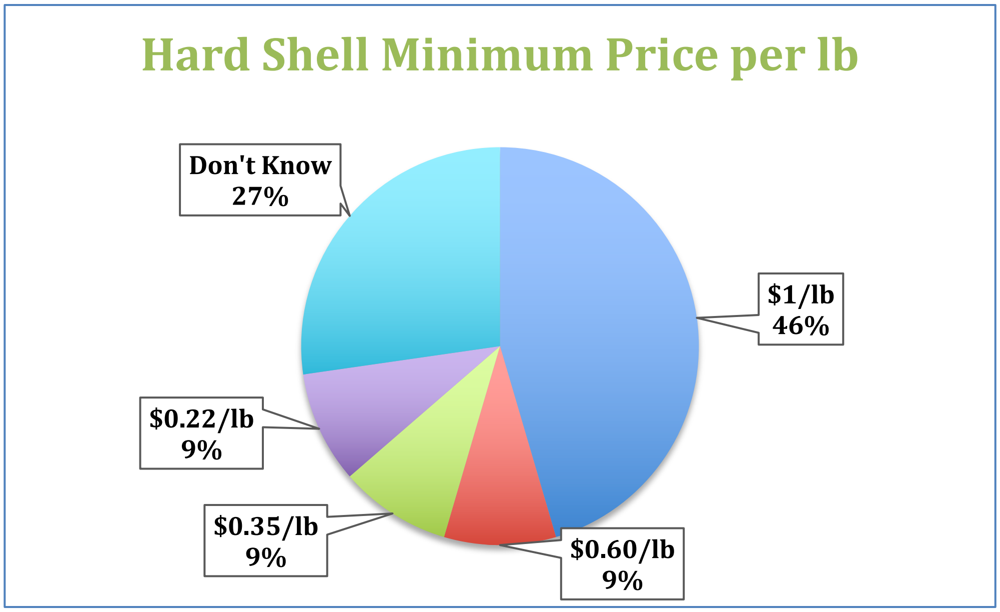

Figure 9. Fishers' perspectives on the minimum price per pound required to target *C. maenas* while fishing. 6 of the 13 participants placed their minimum price per pound at $1.00 USD. $0.60/lb, $0.35/lb, and $0.22/lb were all selected as minimum price points by single participants. The remaining 3 participants were unsure.

Eleven of the thirteen participants elected to respond to this question. Five said they likely would not target hard-shell crabs for less than $1 USD per pound, while one participant each would target *C. maenas* at $0.60 USD, $0.35 USD and $0.22 USD. The final three fishermen were unsure of a minimum price. It is important to note none of the participants who set their minimum price at $1 USD/lb had sold hard-shell crabs. However, both participants who selected $0.35 USD and $0.22 USD had previously harvested and sold hard-shells. It is possible this previous experience played into their thinking.

4.6 SWOT Analysis

A SWOT analysis was developed from data collected during interviews, personal conversations with industry experts and stakeholders, and a thorough literature review. The purpose of the SWOT analysis was to give insight into what the current *C. maenas* fishery landscape looks like and the current strengths and weaknesses of the industry. It is also a useful tool for determining recommendations and next steps the *C. maenas* fishery should take (Figure 10).

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>• Invasive species – easy to market
• Commercial fishery could positively impact environment and other fisheries (soft shell clams, mussels, etc)
• Limited barriers to entry – low bait and gas costs, licenses and traps are inexpensive
• Access for small-scale fishermen
• Lack of fishery regulations seen as beneficial
• Successful shedding and marketing of soft shells in small sample size
• Soft-shells sold at ludicrous prices - $2-$3 per crab
• Tautog bait represents economically viable seasonal market for hard shells
• Large volume of hard-shell crabs makes fishery practical if price per pound is high enough
• Ideal way to supplement incomes</td><td>• Overall lack of knowledge about shedding of soft-shell crabs and relevant markets
• Identification of peeler crabs is tough
• Soft-shell fishery lacks reliable supply to provide restaurants
• Soft-shell fishery has trouble scaling out of pilot stage
• At best, only 25% of harvest are viable peeler crabs – need to pair with hard shell markets
• Limited economically viable hard-shell markets
• Price per pound is biggest obstacle
• Education of all sectors of supply chain necessary – start with consumers
• Consumers associate green crabs as “dirty”
• Difficult to get information to move in wholesale industry/get wholesalers on board with green crabs
• Fishermen do not know where markets are and have difficulty finding buyers</td></tr>
<tr><th>Opportunities</th><th>Threats</th></tr>
<tr><td>• Partner with pet food companies – RootLab (Purina)
• Moeche modeled market promising if reliable supply issue is solved
• Soft-shell Co-op to “pool” crabs together
• Target farmers markets to educate consumers
• Utilize specialty food stores, such as Italian chains
• Connect with chefs to sell Moeche and green crab-based stocks
• Target young people who are having trouble getting lobster license/want to get involved in commercial fisheries or help the environment
• Mild winters could equate to larger harvests and earlier molts</td><td>• Climate variability – harsh winters could negatively impact population sizes
• If fishery becomes profitable, possible implementation of regulations could be seen as disruptive to fishermen
• Similar more established marketable crustaceans – ie Jonah crabs, blue crabs</td></tr>
</table>

Figure 10. A SWOT analysis that was created using data collected during this study. The two top sections depict strengths and weaknesses found within the fishery. The bottom sections detail opportunities and threats the industry could face as it expands.

5. <u>Discussion</u>

The research questions posed in this study were designed to determine the framework for an economically viable *C. maenas* fishery in New England. The following further elaborates on the results and returns to the research questions posed at the beginning of the study.

5.1 Demographics of *C. maenas* Fishers

5.1.1 Clam Diggers

Clam diggers were discovered to be an excellent candidate to target *C. maenas* as a form of income supplementation. There are several reasons why clam diggers could be interested in fishing for *C. maenas*. First off, the *C. maenas* population explosion has directly caused decreases to the Maine *M. arenaria* population. Clam diggers hate *C. maenas* and see them as threatening their livelihood. When asked what their first impressions of *C. maenas* are, three out of the four clam diggers interviewed described *C. maenas* as a "clam predator". The participants went on to describe how *C. maenas* "has done a number to the clam beds". Several of the fishermen believe that they can potentially assist the health of soft-shell clam populations by harvesting *C. maenas*, however it is only worth it if they can make a profit doing it.

In general, clam digging is a solo profession, and the lack of a crew could make it easier for them to make money while crabbing. The shouldering of seasons may not be possible for clam diggers because peak soft-shell clam season in Maine (May-September) also coincides with months where *C. maenas* are in high abundance. However, the possibility of income supplementation, especially during shellfish closures due to rainfall or days with weaker tides, was mentioned by participants: "Say if I only had a partial tide in the morning and I didn't feel like digging the other partial tide at the other end of the day… I'd consider splashing a few traps and seeing if I could make a couple hundred bucks."

5.1.2 Lobster Fishers

Lobster fishers were determined to be another strong candidate to double as *C. maenas* fishers. An obvious reason for this is the similarity between lobstering and crabbing. Both lobstering and crabbing are considered "fed wild capture fisheries", in which traps are baited and set. Lobster fishers use lobster pots, while *C. maenas* are caught in eel traps and fukui traps. In Maine, bait requirements for *C. maenas* are the same as those for lobsters. According to interview participants, overall expenses are less for lobstermen when targeting *C. maenas*. This is because less fuel is used, and crab traps are cheaper and easier to make than lobster pots.

Fishers with smaller crews (one to two people) are better candidates than ones with larger crews because they have fewer expenses. If a lobster fisher were to be offered a respectable price for hard-shell crabs ($0.80 - $1.00/lb, see Minimum Price per Pound), they could potentially make a profit with a larger crew based on sheer catch volume, however individual fishers or those with small crews are more likely to make a successful earning.

Income supplementation for lobster fishers may be increasingly important as waters warm. Increased SST along the North Atlantic coast have directly triggered declines in populations of the American lobster (*Homarus americanus*) in southern New England (Massachusetts, Connecticut, Rhode Island). In the last several decades, *H. americanus* abundance has declined by 70% due to a reduction in suitable nursery habitat from a combination of high summer SST and lower pH levels (Stancioff, 2016). In the GOM, recent *H. americanus* landings have been record-breaking. In 2016, fishers landed over 132 million pounds, 4 million pounds higher than any year previous. However, since the early 2000's, economic value (price per pound) for the industry has been on a steady decline (Figure 11). Developing economically viable markets for hard-shell *C. maenas* fisheries could be essential for lobster fishers in the future.

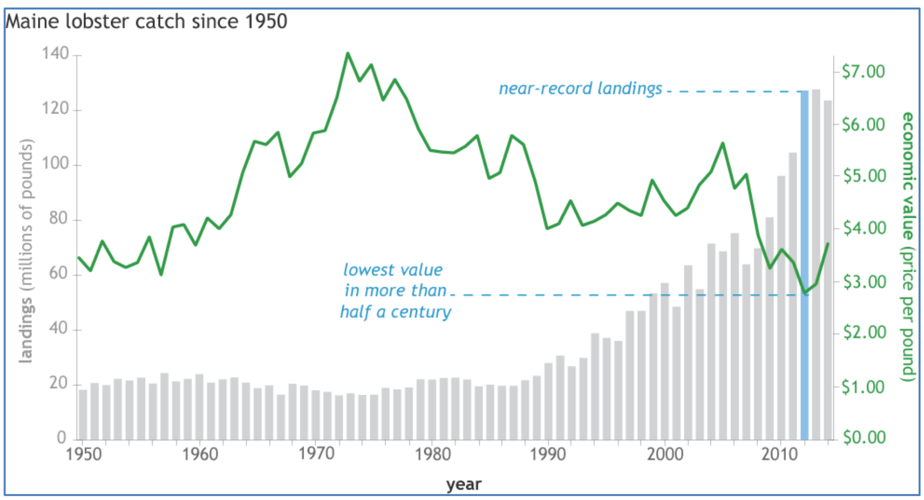

Figure 11. Maine lobster landings in millions of pounds and value since 1950. Chart adapted from Stancioff (2016).

5.1.3 Oyster Farmers

Oyster farmers occupational skills and seasonal framework give them an unique opportunity to diversify into both hard-shell and soft-shell *C. maenas* fishing. Similar to lobster fishers, oyster farmers constantly encounter *C. maenas* in their equipment, and consequently they view them as a nuisance. Most farmers also already own most of the equipment needed to fish for crabs and have a familiarity with estuary systems (prominent *C. maenas* habitat). A large part of a farmer's daily schedule constitutes "culling" (sorting) product by size for weekly harvests. The careful attention to detail necessary for a successful harvest can likely be adapted for the identification of "peeler" *C. maenas*, the phase directly before ecdysis.

Both soft and hard-shell *C. maenas* represent a way for oyster farmers to supplement their incomes during the off-season. In the northeast, farmers remove equipment from the water in early winter and do not replace it until early to mid-spring (water temperature dependent). This leaves a gap in their schedule where they can diversify, and potentially shoulder seasons by fishing for hard-shell *C. maenas* in the early spring. Shellfish closures due to excessive rainfall can also affect farmers operations on their leases. Fishing for, shedding and harvesting soft-shell *C. maenas* could potentially compensate for some loss of income.

The Maine fisheries and aquaculture framework is mostly small-scale, and most oyster farms are individually owned and employ small crews. Numerous small-scale farms sell to medium-scale distributors or directly to restaurants. If farmers expand to harvesting and selling *C. maenas*, they may be able to sell through the supply chain they have set up for their oysters. A downside to smaller suppliers is their "artisan" product is sometimes more expensive than that from a larger company. However, one thing they can offer which larger, more homogenized companies cannot, is diversity of product. Take for example, an oyster farmer interview participant discussing selling soft-shell *C. maenas*:

> " I think it's really cool to bring another product to market and add value for as a small-scale aquaculturist, add value for our customers so they would say 'Hey, ok I could get Island Creek Oysters cheaper for what I could get from [*redacted*], but Island Creek doesn't bring me fresh scallops, Island Creek doesn't bring me soft-shell green crabs, Island Creek doesn't go halibut fishing in the spring and bring me back a couple halibut to sell in my restaurants too'".

This type of personal connection that oyster farmers can make with the local restaurants they supply could be utilized for soft-shell *C. maenas*.

5.2 Current *C. maenas* Fishing Incentives

5.2.1 An Unregulated Fishery: Beneficial or Detrimental?

Over 70% of interview participants believed an unregulated fishery, such as the current *C. maenas* fishery, to be beneficial (Figure 6). There are multiple reasons for this. First, fewer regulations directly impact how much money a fisher can make. The *C. maenas* fishery has no limits on harvest volume or crab size, so any crabs caught are considered harvestable. This is different than highly regulated fisheries, such as the mid-Atlantic blue crab industry, where fishermen are prohibited from harvesting crabs with a length smaller than 5 inches (Staff Report, 2020). In some hard-shell markets, such as protein for pet food, size limitations (silver dollar sized crabs) can come into play that dissuade fishermen from harvesting them.

Another factor to consider is the possibility of reduced fisheries management equating to more effective invasive species management. Several interview participants believed that if high enough fishing pressure were to be exerted on the *C. maenas* population, there could be positive environmental and socioeconomic impacts. It is feasible that fisheries that are preyed on by *C. maenas*, such as commercial shellfisheries, could benefit from a reduction in the population. A lobster fisher interview participant further explains:

> "If we can start ripping these things out of here and make a living doing it, it will help many fisheries, not just gain support for these things and building a sustainable market, but hopefully we'll see the mussel bars and the clam flats start to get healthier, more productive."

However, a recent study conducted at the Downeast Institute in Maine determined "it is not possible to reduce [green crab] populations through trapping to save the [soft shell] clam fishery" (Beal, 2014). A key component in this is the fact that equipment such as fukui and eel traps fail to account for crabs small enough to fit through the mesh. These crabs can conflict considerable damage to soft shell clams despite their size, and there are even less markets for smaller hard-shell crabs (B. Beal, personal communication, 2021). Nevertheless, it is currently unknown if high fishing pressure could indirectly benefit fisheries that target species that utilize eelgrass beds as nurseries, such as summer flounder, striped bass and tautog.

The fear emphasized by multiple fishermen was how new regulations, if implemented, could potentially impact *C. maenas* harvests. If the industry were to explode and *C. maenas* fishing becomes more mainstream, fishers who had learned to crab with limited regulations would have to adapt. This is not uncommon in other fisheries where new regulations are constantly put into place to protect fish stocks or other species, such as Northern Right Whale management in the Maine lobster fishery. In order to avoid this, one fisherman suggested DMR should enact regulations from the start, so fishers are not caught off guard.

> "It seems to me what's gonna happen is somebody's going to get a hold of green crab fishing and figure it out, and go after it and then other people are going to learn about it and do it, and then the states gonna come say 'Oh no we've got to change everything because in our experience you're doing it all wrong' well what experience, you know? I would rather see them [DMR] come in with some regulations right up front and say, 'If you want to be a green crab fishermen you can fish 100 traps, you got to have tags, you got to do this, this and this.'"

It is important to note the majority of fishermen who agreed an unregulated fishery is beneficial also believed if a *C. maenas* industry starts to take shape, the DMR will likely step in and manage it. There seemed to be a certain level of distrust with regulatory authorities among the interview participants. One fisherman stated the State of Maine "has a history of under-regulating and then over-regulating fisheries". Multiple other fishermen cited the *C. maenas* fishery as a potential short-term, large gain industry, where a few fishermen discover viable markets and make a respectable profit. Comparisons to the Maine sea urchin industry arose, a fishery which collapsed due to sudden overfishing in the late 1990's, when Asian "Uni" markets exploded (Laclaire, 2021). All these scenarios would likely result in increased management from DMR.

A recent example of regulatory authorities enacting new regulations in a fishery while it is experiencing exponential growth is the Jonah crab (*Cancer borealis*) fishery. *C. borealis* is a species of stone crab native to the North Atlantic. There is little known about the population dynamics of *C. borealis*, and in 2010, when the creation of a valuable market suddenly increased landings, concern was raised they were being overfished. Delhaize America, a large grocery retailer and an important stakeholder in the *C. borealis* fishery, threatened to discontinue carrying any *C. borealis* product unless the industry engaged in management discussions. In response, processors, fishermen, state and federal management representatives and scientists collaborated on a formal Fishery Improvement Project (FIP) to create more sustainable fishing guidelines (Jonah Crab Fishery, 2014).

It is difficult to determine regulations for a fishery while it is experiencing exponential growth. Before the FIP was developed, the *C. borealis* fishery lacked regulations like minimum size limits and protections for spawning biomass (such as restrictions on "ripe" females). The *C. maenas* fishery lacks these regulations as well, and this *C. borealis* case study is an example of the worst-case management scenario viewed by some *C. maenas* fishers. However, even if *C. maenas* economic value continues to rise, it is unlikely regulations will be enacted due to their status as an invasive species.

5.2.2 Limited Barriers to Entry Incentivize Young People

The limited barriers to entry in the *C. maenas* fishery include low license costs, limited fuel and boat costs, and traps that can be constructed from cheap and easily accessible materials. These few barriers make it more appealing to new fishermen, and the industry should target young people struggling to make it in other commercial fisheries, such as the lobster fishery. Due to highly enforced regulations, the Maine lobster fishery is very strict on who is granted a commercial license. Participants from the ages of 18 to 23 have an easier path through an apprenticeship program than most, which requires 200 days and 1,000 hours of fishing experience. Candidates over the age of 23, however, must wait their turn on the state lobster waitlist before they become eligible for a license. There are currently 209 individuals from seven zones on the state of Maine waitlist, some of whom have been waiting for over 15 years (Maine Legislature, 2020). A commercial clam digger used an anecdote to stress how hard it is for young people to break into the lobster industry:

> "I have a 21-year-old son that lives out here in the summertime that wants to become a lobsterman, but that's almost impossible for him. And he's been lobstering for 5 years, they're not gonna give him a license. So, I'm looking for something for my son so he can stay on this island and make a living [on why he's interested in green crabs]. That's what I'm looking for."

Lobster fishing and crabbing utilize many of the same techniques, such as operating boats and hauling traps. Inexperienced fishers can acquire skills while targeting *C. maenas* that are applicable to other commercial fishing operations, as well.

5.3 Barriers to Fishing and Scalability

There are several reasons it makes sense for fishers to target *C. maenas*, but in reality, there are few individuals harvesting and selling them. The following is an in-depth analysis of the biggest barriers to the New England *C. maenas* fishery.

5.3.1 Market for Hard-Shell Crabs

According to interview participants the biggest barrier to the further development of a *C. maenas* fishery is the price per pound of hard-shell crabs. The price per pound argument is simple: If fishermen cannot make any money selling *C. maenas*, there is no reason for them to target them in the first place. *C. maenas* exist in great abundance in Maine and the fishery has limited barriers to entry; one of the only things missing is an established price per pound of hard-shell crabs. In the words of a commercial lobsterman, "If you ever did get a price per pound of hard-shell green crabs, you'd see a fishery very quickly."

The value of hard-shell *C. maenas* could also indirectly impact the success of the soft-shell *C. maenas* fishery. After the initial harvest, fishermen will sift through their catch and set aside any peeler crabs they identify. However, even during peak soft-shell season, harvesters can expect a maximum of 25% of their catch to be pre-molt crabs. The lack of an established price for hard-shell crabs leaves fishermen with no market for upwards 75% of their catch. For this reason, the New England *C. maenas* fishery can be labeled a "two-phase" fishery, that is deficient in the second phase.

Another issue is the reliability at which fishermen can get an acceptable price for *C. maenas*. The amount of markets and buyers for hard-shell crabs in New England is minimal, and if fishermen are not convinced they can make a profit selling them, they may target more established species.

5.3.2 Consumer Education & Marketing

In order to develop an industry framework, a thriving market for *C. maenas* needs to be jumpstarted. This starts on the consumer end. If there is no demand for the product, distributors will not buy it from fishermen, leaving them without an incentive to fish *C. maenas*. Markets that can target consumers mostly include ones designed around human consumption, such as the Moeche industry and hard-shell value add-on products. The problem is, bad connotations exist within the public about *C. maenas*, mostly stemming from their classification as an invasive species. Several interviewed fishermen described a nasty "stigma" surrounding *C. maenas*, and the terms "dirty" and "gross" were mentioned multiple times. For example, a commercial lobsterman describes the public's perception of *C. maenas* in Maine:

> "A green crab's something you went and found and played with as a kid. Without giving it a second thought on 'hey is it worth something or is it good for eating'… Everybody's like 'Oh it's gross it's just a green crab'. I'm sure that people thought that lobsters were gross to eat at some point in history. It can't just go away, you've got to stick with it, prove to everybody that the money's there it's just not a mainstream thing yet".

To work past these nasty connotations, consumers must understand *C. maenas* are edible. Many consumers are not aware of the negative affects *C. maenas* have on the environment and that by consuming them they can feel like they are helping rid the ecosystem of a harmful invasive species while supporting local fishermen. The *C. maenas* industry should start to incorporate the famous "If you can't beat em, eat em" catchphrase that helped to jumpstart markets around other invasive species such as lionfish and Asian carp. In order to successfully advertise the lionfish market in Florida, the fishery paired with Wholefoods (Conant, 2020). While pairing with a nationally recognized grocer may be difficult for *C. maenas*, fishermen should start to advertise *C. maenas* by targeting farmers markets to educate consumers.

5.3.3 Product Distribution

Distribution of an aquatic invasive species like *C. maenas* represents an unique challenge to the expansion of the industry. There are minimal buyers throughout New England and some fishermen must travel further distances than normal to deliver their catch. In addition, some states have varying guidelines on the legality of transporting live invasive species across state lines. For example, in the state of Maine it is illegal to transport any live invasive plant or fish species (other than approved baitfish) throughout the state (Maine.gov, 2021). It is unclear if the transportation of live *C. maenas* is also prohibited.

If the market starts to expand, transportation of live crabs across state lines could complicate the issue even more. After a thorough literature review, it is clear various state regulations throughout New England prohibit the transportation of live terrestrial invasive species into states, but minimal results were discovered regarding aquatic species. Examples of flourishing markets for other aquatic invasive species include that of the Asian carp and lionfish, but these species are generally killed before transport. It is vital to ensure *C. maenas* remain alive in route to their destination, especially for the bait and soft-shell markets.

5.3.4 Reliable Supply of Soft-Shell Crabs

The adapted Maine Moeche model represents the most valuable market for *C. maenas*. Unlike the lack of demand associated with hard-shell markets, this soft-shell market based on human consumption has proven successful, albeit on a small scale. The problem, according to fishermen, is they cannot harvest enough soft shells to reliably keep up with the demand from restaurants. "Supply is the issue; we don't have enough people doing it consistently to get the product out so we can build the sales channels. There's no doubt in my mind the sales channels are there, I'm super confident of that." In Venice, Italy, where the traditional Moeche industry has been thriving for decades, families dedicate entire farms to the shedding and harvesting of *C. maenas* (M. McMahan, Personal conversation, 2021). If fishermen can generate a large enough workforce to harvest a sizeable number of soft shells on a consistent basis, the industry might start to expand. This could happen through a collective "pooling" together of crabs from different fishermen, or even through the implementation of a co-op.

5.3.5 Identification of Peeler Crabs

A significant issue in the soft-shell crab market is the identification of peeler *C. maenas*. Peeler crabs are crabs in which molting is imminent, and they usually exhibit signs that ecdysis will occur shortly (Van Engel, 1984). Identifying these crabs is key because it is the only way to successfully harvest soft-shell crabs. Once a fisherman has identified a peeler crab, it is placed in makeshift lobster crates and checked on daily until they start to shed. When soft, they are taken out of the water, placed in a tubber ware container, and stored in a refrigerator until sold.

The peeler crab identification process is much more challenging for *C. maenas* than for other species of crabs. For example, the blue crab, a common swimming crab found from Florida to as far north as Cape Cod, Massachusetts. In the mid-Atlantic, there is a flourishing soft and hard-shell market based around human consumption. Peeler blue crabs can be identified by a red or white line along their flipper. This line is the new shell forming under their current shell, and the color determines the timeframe in which they will molt (white = about a week, red = a couple days) (Lively, 2019). *C. maenas* lack paddle fins because they are not "swimming" crabs, so alternate signs are used to identify the peeler crabs. These include: 1. The presence of a "halo" or "greying" circle on the episternites (where the leg segments meet the body), 2. A darkening of the apex line, and 3. Shell looseness (Poirier et al., 2016). These "clues" can be extremely confusing and difficult for fishermen to master, especially after a long day at work. As a lobster fisher explains:

> "I tried playing around with them, and tried to figure out, and that's the biggest obstacle I see to this soft-shell fishery, it's just trying to get the green crabs in the state of being soft because it's very difficult to identify the subtle signs of when they're going to molt."

The identification of these peeler crabs is an ongoing process that must be mastered for the industry to expand.

5.3.6 Communication with Distributors

Another barrier to expansion of the *C. maenas* industry is the inability to disseminate information between distributors. Wholesalers are viewed as the middlemen in the seafood supply chain because they buy product directly from fishermen and distribute it to restaurants and markets. Without wholesalers, fishermen's product would not reach nearly as many end-consumers as it does. For example, in the state of Maine, fishermen can legally sell any fish or crustaceans they catch directly to consumers within the state (if they have a proper commercial fishing license). When crossing state lines, interstate commerce comes into play, and additional Maine Department of Agriculture, Conservation and Forestry licenses are required (Maine.gov, 2021). Any additional licenses necessary increases the likelihood fisherman would utilize distributors because it equates to less work for them.

An issue arises when discussing distributors roles in the expansion of a non-established fishery, such as the *C. maenas* industry. Unlike chefs, who like to tell a story with their food, distributors generally care most about the amount of money they can make. Consequently, many distributors don't share information regarding product with each other because they believe the harvester they are buying from is "their own little secret". An oyster farmer and former seafood dealer further explains wholesaler's role in the *C. maenas* industry:

> "I think it would be, disseminating information would definitely be the way to do it, making sure everybody knows who to sell to or knowing what their options are in terms of who they're selling to and in terms of price. Finding a place where there's a gap between the supply and demand. Finding a place where people are eating more green crabs than they can buy… But I think getting distributors and wholesalers to share information about who's buying and who's selling and what the price is would be tough."

In order for the *C. maenas* industry to expand to larger markets, wholesalers are necessary to disperse the final product (whether it be Moeche or value-add products) to wider consumer bases. A lack of cooperation between wholesalers could significantly impede progress.

5.4 Minimum Price per Pound of Hard-Shell Crabs

Nearly 50% of interviewed fishermen stated the minimum price they would target hard-shell *C. maenas* for is $1.00 USD per pound (figure 9). Using recent research and current Massachusetts *C. maenas* landings data, it is feasible to determine if a $1.00 USD per pound price point is realistically attainable.

5.4.1 Minimum Price vs Break-Even Price

A study conducted in Prince Edward Island, Canada (just 375 miles north of Bar Harbor, ME) gave insight into profit margins required to at least break even when harvesting hard-shell *C. maenas* under three circumstances: Crabs for bait ($0.50/lb CAD - $0.40/lb USD), crab for concentrate in Asian markets ($1.00/lb CAD - $0.80/lb USD) and lobster dockside price ($3.50/lb CAD - $2.81/lb USD). (St-Hilaire et al, 2016) Based on provincial surveys, it was estimated fishermen could harvest at least 32 tons of crabs annually from estuaries in Prince Edward Island (PEI).

The three fishing techniques analyzed in the study included crabs caught as by-catch via fyke nets (while targeting other species), baited *C. maenas*-specific traps while targeting other species, and the utilization of baited traps for *C. maenas* as the primary target species. After considering variable costs (which included bait, labor and miscellaneous costs like gas and extra rope), researchers determined the cheapest harvesting technique was a fishery predicated on by-catch ($1,365CAD/21 days - $1,095 USD), while the most expensive fishery was one in which *C. maenas* was the primary target ($5,886CAD/21 days – $4,704 USD). In order to break even, fishermen would need to net at least $0.15CAD/lb ($0.12/lb USD) dockside in the by-catch fishery, $0.87CAD/lb ($0.70/lb USD) dockside using baited traps as a supplemental species, and $1.32CAD/lb

($1.06/lb USD) dockside using baited traps as a primary target. At $3.50CAD/lb ($2.81/lb USD) dockside, all fishing scenarios would be quite profitable.

Given the study based in PEI, the minimum prices per pound detailed by interview participants seem perfectly reasonable. Considering the majority of fishermen primarily target alternate species (such as lobsters or mollusks), the most likely scenario is one in which fishermen target *C. maenas* as a form of supplemental income. Researchers placed the breakeven price in PEI for a supplemental fishery at $0.70/lb USD, which is well within the minimum price range of $0.22 - $1.00/lb USD. It is important to note that not only is PEI located in close proximity to Maine, the coastal geography is very similar as well; it is likely Maine fishermen could harvest rates in excess of the 32 tons per year in PEI.

5.4.2 Current *C. maenas* Landings Data

It is difficult to determine if a $0.70 - $1.00/lb minimum price for hard-shell *C. maenas* is feasible based on current market prices because there is so little data on market price points. However, there is available *C. maenas* landings data for the state of Massachusetts (Figures 12 and 13). Figure 12 outlines landings in pounds and in value from the state of Massachusetts from 2005 through 2019 (data from 2009 and 2010 was listed as "confidential" and was omitted from the charts). Figure 13 demonstrates the annual landings in pounds compared to the average annual price per pound of *C. maenas*. There was no available data for price per pound, so it was calculated by taking the annual total value and dividing it by total landings weight. The price per pound values may be misleading because they were an average; price points will vary depending on the market.

Compared to the $0.70 USD break-even price and $1.00 USD minimum price per pound for hard-shell crabs, the average *C. maenas* price per pound is low. However, price points are trending in the right direction. In 2019, landings were valued at $0.48 USD per pound, which is $0.05 higher than the prior year (n = $0.43). Since 2012, the average price has increased by $0.18 USD per pound. It is possible this is due to the existence of more *C. maenas* markets, or more demand for *C. maenas* markets. Public outreach, such as that routinely performed by organizations like Greencrab.org (in the form of workshops) could have brought more notoriety to the industry, as well.

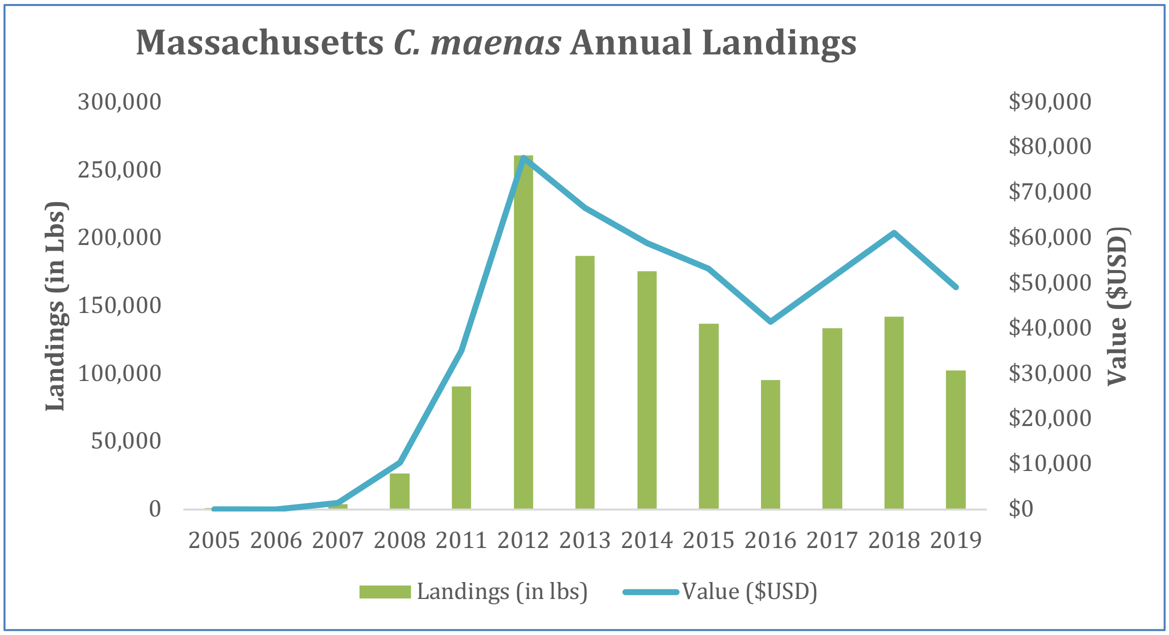

Figure 12. Annual Massachusetts *C. maenas* landings in pounds and value ($USD) since 2005. Data from the years 2009 and 2010 was omitted because it was confidential. Data courtesy of NOAA.

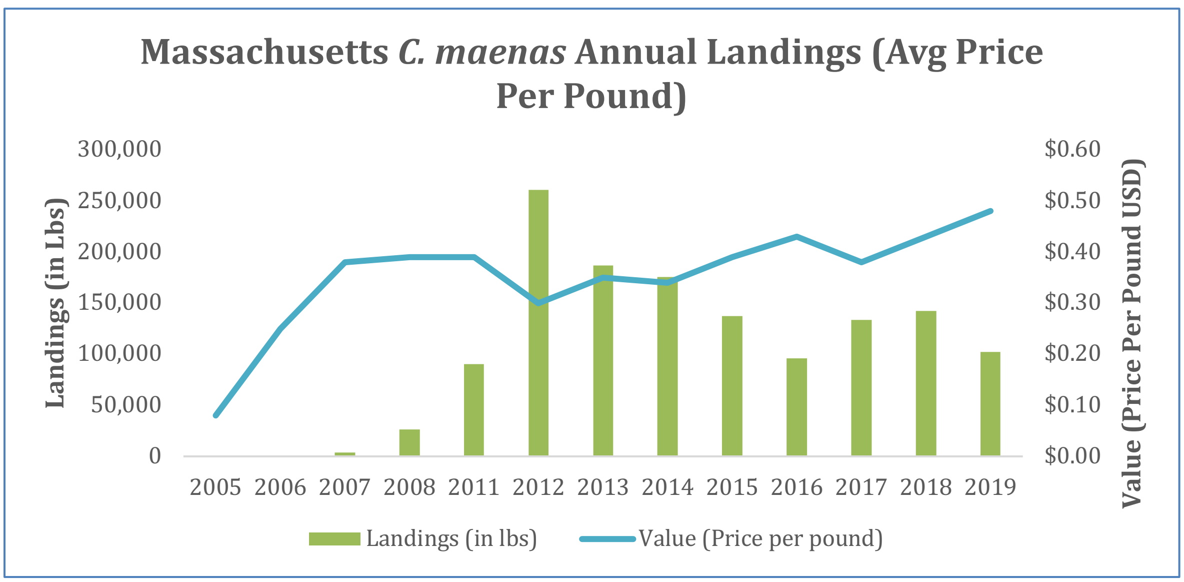

Figure 13. Annual Massachusetts *C. maenas* landings in pounds and value (price per pound, $USD) since 2005. Data from the years 2009 and 2010 was omitted because it was confidential. Data courtesy of NOAA

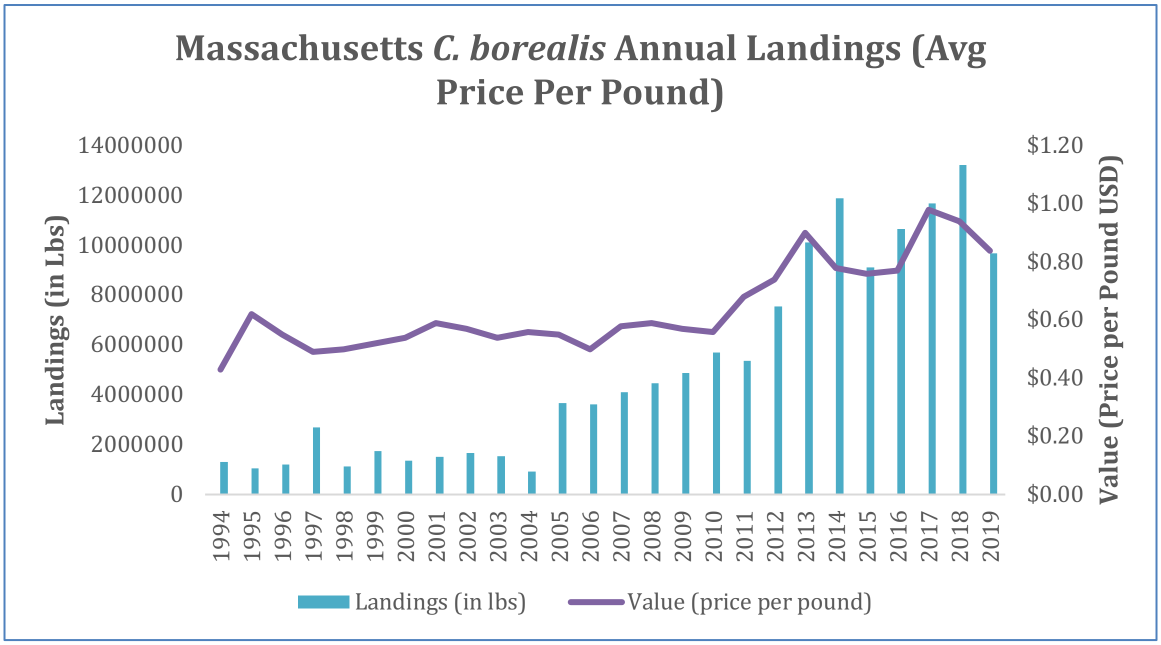

Figure 14. Annual Massachusetts *C. borealis* landings in pounds and value (price per pound, $USD) since 1994. Data courtesy of NOAA

5.4.3 Comparison to Jonah Crab Fishery

The increase in economic value overtime in the *C. maenas* industry can be compared to the rise in value of the Massachusetts *C. borealis* fishery (Figure 14). *C. borealis* is native to New England waters and was long viewed as a worthless by-catch in the lobster fishery. In the mid-2000's, there was minimal value for *C. borealis (*especially compared to lobsters), as price points maxed out around $0.50 USD per pound (Nosowitz, 2018). From 2010 to 2018, prices steadily increased, topping out at $0.98 USD per pound, a near doubling in value in just eight years. The causation for this absurd increase in economic value was the combination of decreased lobster landings in southern New England and the development of a market based on human consumption in the form of crab rolls.

In order for the *C. maenas* fishery to replicate the success of the *C. borealis* fishery, either one large market or multiple viable markets need to be developed. A market for human consumption such as crab rolls would be difficult considering the high shell-to-meat ratio in *C. maenas*. The soft-shell crab fishery has the most potential to become a monetarily ludicrous fishery because the profit margins are high ($2-$3 per crab). However, its success is reliant on creating reliable supply to provide to restaurants and finding successful markets for hard-shell crabs. One promising new market that could add considerable value to the *C. maenas* fishery is the use of crab meat as an alternate protein in dog food.

5.4.4 *C. maenas* as an Alternate Protein in Pet Food

The Purina-based pilot brand, RootLab, offers a dog food which utilizes *C. maenas* as a primary pet feed base. The brands mission is to create “the most nutritious and eco-conscious food for our dogs, ourselves and the planet” (RootLab, 2021). Their ‘Green Crab and Egg’ recipe is one of the choices in the Invasive Species line. RootLab does not source *C. maenas* directly from fishermen but buys from a third party (who buys from fishermen). The anonymous dealer processes *C. maenas*, freezes it, and sells RootLab mechanically extracted crabmeat (which comprises about 50% of the original crab weight). This product has the potential to take *C. maenas* mainstream because it is backed by a large stakeholder (Purina).

5.5 Study Limitations and Future Research

There are several limitations to this study that need to be addressed. Due to the amount of time allotted for the completion of this thesis (one year), the sample size of interview participants was smaller than preferred. Interview participants were comprised of just one sector of the seafood supply chain and residents of the State of Maine. Future studies should increase the number of participants and involve residents throughout New England. In order to get a more complete understanding of the *C. maenas* fishery, the perspectives of the entire seafood supply chain – fishers, distributors and chefs – should be analyzed. These studies could be conducted through a combination of interviews and surveys. Consumer opinions should also be dissected.

6. Conclusions & Recommendations

Since their introduction to the North Atlantic in the early 1800’s, *C. maenas* have gained a reputation as a destructive invasive species. They have decimated the Maine *M. arenaria* fishery and caused declines in eelgrass beds, which act as crucial nursery habitat for commercially important fish species. The increase in *C. maenas* populations have been spurred by increased SST in the North Atlantic (and especially the GOM), a result of high carbon emissions. This same rise in SST have caused 70% declines in the *H. americanus* landings in southern New England, while economic value has decreased in the GOM *H. americanus* fishery, which is responsible for 80% of Maine’s commercial value. SST are projected to increase steadily in the coming decades, resulting in a likely increase in *C. maenas* populations and decline in *H. americanus* landings. *H. americanus* fishers may be able to target *C. maenas* in order to supplement any lost income if they can overcome the challenges preventing the establishment of a successful fishery.

This research gives insight into the barriers prohibiting the development of a *C. maenas* fishery and establishes the framework for the industry moving forward. The biggest obstacle was determined to be the price per pound of hard-shell crabs. Minimum price points ranged from $0.22 USD to $1.00 USD per pound, and most participants agreed with the latter. Other barriers included few reliable markets, limited *C. maenas* fishing experience, and a disconnect between consumers and the rest of the seafood supply chain. Limited barriers to entry and a largely unregulated fishery are existing incentives that make the industry enticing for prospective fishers, especially young people or inexperienced fishermen.

For fishers to successfully supplement their income by targeting *C. maenas* they can either: 1. Pair soft-shell fisheries with a hard-shell fishery like the Tautog market, or 2. Exclusively harvest hard-shell crabs in large volumes to counteract lower price points. Both options are reliant on a viable price for hard-shell crabs. Current landings data places the price per pound of hard-shell *C. maenas* at $0.48 USD per pound. Though considerably lower than the minimum price point detailed by fishers, current trends show a promising increase in economic value. Only time will tell if the *C. maenas* fishery can develop into a significant industry.

6.1 Recommendations for the New England *C. maenas* fishery

- Target farmers markets to advertise local product. Inform consumers about the negative environmental and socioeconomic impacts associated with *C. maenas*. Bring value-add products or samples of Moeche – let consumers try *C. maenas* products
    - Convince fishermen to give out *C. maenas* to consumers
- Target local Italian grocer chains to sell Moeche (originally from Venice, Italy). Other invasive species, such as lionfish, have successfully partnered with large-scale grocery chains. In the future, it would be ideal if *C. maenas* markets follow in their footsteps, but the fishery should start small.
- Create co-ops to pool soft-shell *C. maenas*. The lack of reliable supply is one of the biggest issues in the soft-shell fishery. Restaurants can sell the crabs on a regular basis, but fishermen can't harvest enough to provide a reliable supply. A co-op created where fishermen combine harvests to fulfill orders to restaurants and split the profit could solve this issue.
- Research should be conducted on the viability of triggering molting in *C. maenas*. Successful artificial catalysts could quickly spur the development of a soft-shell fishery and increase economic value. Potential triggers could include water temperature, food, hormones, and light.
- Target young people. The limited barriers to entry to the *C. maenas* fishery can make it desirable for young people interested in getting involved in commercial fisheries. The younger generation also seems more environmentally conscious, and fishing for *C. maenas* can directly help the environment.
    - Webinars and in-person seminars should be utilized to attract the attention of the younger generation. Social media accounts designed around outreach can also be used. '
- Step up the marketing game. *C. maenas* should be easy to market to consumers; they are an invasive species, eating them is beneficial to environment. They are fresh, tasty, and a local substitute to the blue crab.
    - Partner with chefs in major New England cities to help tell the "story" of *C. maenas*.
- Follow up with RootLab and Purina about the possibility of alternate proteins in dog foods. If successful, could be the type of large-scale company the industry is looking to partner with.
- Further research should be conducted to better understand supply-chain perspectives in the industry.

    - Scientists and stakeholders should collaborate and scale up studies such as this one.
    - Future studies should also be aimed at assessing wholesale, chef and consumer perspectives on the *C. maenas* fishery.
- A stock assessment for the New England *C. maenas* population is necessary to better understand the potential of the fishery.

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8. Appendices

Appendix 1: Fishermen Interview Guide

- When I say green crabs what do you think of?

General Questions

- Where is your homeport, and how long have you been fishing for?
- What fishing permits and endorsements do you hold?
- What is the size of your boat?
- How would you describe the types of companies you sell to (ie are they distributors, restaurants…)?

Green Crabs

- Have you ever caught green crabs?
  - If so, was it as a by-catch or did you target them?
- Have you ever sold green crabs?
  - If so, did you find more success with soft shell or hard shell crabs?
    - Through what consumer base did you sell the crabs?
    - How much are you selling them for?
    - Have you experienced any increase (or decrease) in fishing expenses (gas for boat, crew, traps) while targeting green crabs?
    - What is the minimum price you would be willing to sell green crabs for?
    - Is there a price you would need to make to break-even?
  - If not, why not?
    - If you experienced a reduction of income from the harvest of your primary target species, would you consider selling green crabs?
- Green crabs are currently not being managed as a fishery; therefore there are no regulations on how many you can catch. Do you see that as being beneficial for fishermen?

The future of the fishery

- What do you see as the main obstacles preventing the prospective green crab fishery from scaling up?
- What do you see as the most important factors influencing whether or not people fish for green crabs?
- Do you consider this potential fishery as small-scale?
  - In your opinion, what is the potential of the scalability of this fishery?

Is there anything else you would like to add?

Appendix 2: Statements for Protection of Human Rights

"So before we start, I just want to make clear you understand you are not being pressured to participate in this study. At any time, if you feel uncomfortable or for any other reason, do not want to answer a question, you do not have to answer it. Your participation will be completely anonymous, and I will not use any personal identifiers in the study. "

"In order to completely understand this interview, I am going to be recording it, but this recording will not be shown to anyone else. It will help me to properly code the interview. Is that ok with you? Alright, I'm about to start recording."

Before I let you go, are there any fishermen you know of who might be interested in participating in this study?

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Appendix 3: *C. maenas* Fishery Systems Map