National Management and Control Plan for the European Green Crab (*Carcinus maenas*)

Prepared for the Aquatic Nuisance Species Task Force by the European Green Crab Working Group

June 2024

European Green Crab Working Group Members

Ted Grosholz, University of California, Davis – Plan Manager
Theresa Thom, U.S. Fish and Wildlife Service – Plan Liaison

Adrianne Akmajian, Makah Tribe
April Blakeslee, East Carolina University
Tim Counihan, U.S. Geological Survey
John Darling, U.S. Environmental Protection Agency
Tammy Davis, Alaska Department of Fish and Game
Catherine de Rivera, Portland State University
Shawn Evenson, Lummi Nation
Linda Fernandez, Virginia Commonwealth University
Jason Goldstein, Wells National Estuarine Research Reserve
Emily Grason, Washington Sea Grant
Christy Juhasz, California Department of Fish and Wildlife
Joseph Krieger, NOAA Research
Mark Lewandowski, Maryland Dept. of Natural Resources
Sean McDonald, University of Washington
Karen McDowell, San Francisco Estuary Partnership
Marissa McMahan, Manomet, Inc.
Stephens Phillips, Pacific States Marine Fisheries Commission
Allen Pleus, Washington Department of Fish and Wildlife
Greg Ruiz, Smithsonian Environmental Research Center
Steve Rumrill, Oregon Dept. of Fish and Wildlife
Robert Russell, Maine Dept. of Marine Resources
Linda Shaw, NOAA Fisheries
Kate Sherman, Pacific States Marine Fisheries Commission
Carolyn Tepolt, Woods Hole Oceanographic Institution
Tom Therriault, Canada Department of Fisheries and Oceans
Brian Turner, Washington Department of Fish and Wildlife
Danielle Verna, Prince William Sound Regional Citizens' Advisory Council
Alison Watts, University of New Hampshire
Genelle Winters, Metlakatla Indian Community

TABLE OF CONTENTS

ACKNOWLEDGMENTS

We thank Don MacLean, Dr. Susan Pasko, and the leadership of the Aquatic Nuisance Species Task Force for the opportunity to update the European Green Crab Management Plan. We thank the many federal, state and local agency members as well as several tribal and First Nation groups for their time, effort and irreplaceable help, particularly during regional listening sessions, which has been invaluable for developing this updated national management plan.

Suggested citation: ANSTF European Green Crab Working Group. 2024. National Management and Control Plan for the European Green Crab (*Carcinus maenas*). Submitted to the Aquatic Nuisance Species Task Force (ANSTF). June 2024. 63 pages + appendices.

EXECUTIVE SUMMARY

The National Management and Control Plan for European Green Crab (EGC) was developed by a multi-agency European Green Crab Working Group for implementation by the Aquatic Nuisance Species Task Force following final approval. The purpose of this plan is to guide local, state, and federal agencies, Tribal communities, and other stakeholders in detecting EGC in the earliest stages of invasion, responding rapidly to new detections to determine extent of invasion, and to implement immediate containment or eradication actions. The overall objective is to minimize the likelihood of further spread and establishment in other locations and reduce the impacts in areas where EGC are already established. This plan aims to serve as the baseline for the development and implementation of, as well as the integration with, regional plans such as the Salish Sea Transboundary Action Plan for Invasive European Green Crab and the Early Detection and Rapid Response Plan for Invasive European Green Crab (*Carcinus maenas*) in Alaska 2023–2028 (previously known as the Alaska Action Plan for Invasive European Green Crab).

EGC (*Carcinus maenas*) is one of the most successful invasive predators in coastal marine systems, having established populations on five continents. The ecological and economic damage caused by EGC is well documented on both coasts of North America. On the Atlantic coast, EGC has been an established invader for at least 200 years, although its geographic range continues to expand into Atlantic Canada. On the Pacific coast, EGC arrived in the late 1980s and, consequently, is now at an earlier stage of range expansion and population growth. EGC is a notorious invader that can tolerate broad temperature and salinity ranges. Individual EGC females can produce hundreds of thousands of larval offspring that can disperse over hundreds of kilometers along coastal regions. EGC have a broad diet that includes eelgrass, bivalve molluscs, crustaceans, polychaetes and other prey. EGC has been implicated in historic declines and current losses of commercial bivalves in the eastern U.S. and maritime Canada, as well as impacts to native species including eelgrass habitats along both coasts of North America.

Recognizing the potential for ecological and economic impacts of EGC caused by their expanding geographic range, *Carcinus maenas* was the first marine taxon recognized as an aquatic nuisance species by the Aquatic Nuisance Species Task Force (ANSTF) in November 1998. Following designation, the ANSTF approved the original European Green Crab Management Plan in 2002. This European Green Crab Management Plan updates the previous plan and provides a more focused approach for future management. The new approaches are based on significant changes in the distribution of EGC, the many new technologies available for identifying sources and mechanisms of spread, better information regarding the tradeoffs among local suppression vs. eradication, and new approaches for managing and distributing data to managers and decision makers. We describe current plans for coordinating the activities of scientists, resource agencies, Tribal and First Nation organizations, and other entities.

In this plan, we describe the following eleven priority goals:

1) Prevention to minimize the likelihood of future introductions
2) Monitoring to support early detection and inform management strategies
3) Rapid response to coordinate management strategies and actions for new invasions

4) Emergency management to coordinate management strategies and actions for rapidly expanding populations
5) Containment and control of established populations to minimize impacts
6) Eradication of populations to eliminate impacts
7) Research to understand invasion risks and to improve or develop new management strategies
8) Economic analysis to quantify tradeoffs among management strategies
9) Outreach education to explain management strategies
10) Data management for effective coordination and distribution
11) Adaptive management to evaluate and modify plan implementation

To accomplish the goals of this plan, we recommend that the ANSTF establish an EGC Implementation Team consisting of members of local, state and federal agencies, Tribal communities, universities, NGOs, shellfish growers, and other relevant stakeholders. The EGC Implementation Team would meet to evaluate progress towards achieving the goals of the National Management and Control Plan for EGC using the best available science and the best use of resources. The purpose of this plan is to provide guidance for efforts to prevent future introductions, to rapidly detect and respond to new invasions of EGC before they become established and create ecological and economic damage, and to manage current populations that pose an undue threat to resources of importance for ecosystems and local cultures.

INTRODUCTION AND BACKGROUND

Purpose and Justification

Recognizing the potential for ecological and economic impacts of EGC caused by their expanding geographic range, *Carcinus maenas*, the European green crab (EGC), was the first marine taxon recognized as an aquatic nuisance species by the Aquatic Nuisance Species Task Force (ANSTF) in November 1998. Following that designation, the ANSTF called for development of a Management Plan. In 2000, a Green Crab Committee was appointed by the ANSTF and developed the first European Green Crab Management Plan, which the ANSTF finalized and approved in 2002. The initial management plan was the result of several years of planning and research that culminated in two meetings of the Control Committee, in December 2000 in Gladstone, Oregon and in February 2001 in Davis, California. For 20 years, the plan guided natural resource managers on EGC management and served as a reference for regional plans. In June 2021, the ANSTF Control Subcommittee recommended that the 2002 EGC plan be updated to reflect the current knowledge, range, and control options of the species.

In 2022, a multi-agency working group was established to revise and update the 2002 EGC plan. Input on development of the updated plan was sought through multiple forums and venues including email requests for submissions, in-person meetings (local, regional, and national), regional listening sessions, and informal public comment periods. Comments received were addressed and, where appropriate, incorporated into the new draft that was reviewed and approved on July 19, 2023 by the ANSTF to be posted in the Federal Register for formal public comment. The Federal register notice was sent out Dec. 26, 2023. The public comment period was open through February 9, 2024. Following revisions by the European Green Crab working group based on public comments received, the final plan was submitted to the ANSTF at the May 2024 meeting (May 9, 2024). The final plan was approved on May 9, 2024.

This revised plan updates the 2002 management plan and provides a focused and updated management approach for European green crab. The new approaches outlined in this plan represent significant changes based on the expanded distribution of EGC, many new technologies available for identifying sources and mechanisms of spread, better information regarding the tradeoffs among local suppression vs. eradication, and new approaches for managing and sharing data with managers and decision makers. We describe current plans for coordinating the activities of scientists, resource agencies, Tribal and First Nation organizations, and other entities. This revised EGC plan adds new distribution information and summarizes recent research on population genetics, physiology, and range limits. It also provides detailed trapping protocols, recommendations for coordinating ongoing management efforts, and a summary of the legal framework and relevant statutes for EGC across the United States. This plan includes 11 goals, 23 objectives, and 12 specific strategies with prioritized actions and evaluation criteria. The purpose of this updated national European Green Crab (EGC) Management and Control Plan is to guide local, state, and federal agencies, tribal communities, and other stakeholders in detecting EGC in the earliest stages of invasion, responding rapidly to new detections to determine extent of invasion, and implementing immediate containment or eradication actions. The overall objective is to minimize the likelihood of further spread and establishment in other locations and reduce the impacts in areas where EGC are already established.

Biology and Ecology

North American Introduction and Spread

The European green crab (EGC) *Carcinus maenas* is now one of the most ecologically and economically damaging predators in nearshore coastal communities of both eastern and western North America. Beyond North America, EGC is a notorious and successful aquatic invader worldwide with established populations in South Africa, Japan, Argentina, and Australia (Gardner et al. 1994, Thresher 1997, Geller et al. 1997, Hidalgo et al. 2005). Native to Atlantic Europe and northwest Africa, EGC colonized eastern North America in the early 19th century and now occurs from Newfoundland to Maryland (Fofonoff et al. 2023). In contrast, EGC is a recent arrival to western North America, where it successfully colonized San Francisco Bay, California, in 1989-90 (Cohen et al. 1995). Its impacts on both natural ecosystems and commercial fisheries are well-established (Ruiz et al. 1997, Grosholz 2002, Grosholz et al. 2002) as is its ability to expand its range rapidly (Grosholz 1996).

The western North America invasion has undergone a rapid range expansion with EGC spreading over 2,150 km in less than 35 years since their initial introduction into San Francisco Bay, which most likely occurred via shipments of bait worms from east coast sources. By 2000, EGC had been detected in every significant bay and estuary from Elkhorn Slough to Barkely Sound, B.C., almost certainly due to larval dispersal (Grosholz et al. 2000, Yamada 2001, Duncombe and Therriault 2017, Behrens Yamada et al. 2021). Establishment was not continuous or linear along this range expansion, however. Though green crab quickly established self-recruiting populations in California, as evidenced by high numbers of multiple age classes, they apparently failed to establish in coastal embayments of Washington and Oregon for several decades after their first detections. During this period, in Washington EGC were only periodically detectable following years of strong El Nino/ENSO events, indicating the importance of northward larval advection from established populations further to the south, in California. By the mid-2000s EGC, were established along much of the west coast of Vancouver Island (Gillespie et al. 2007). This pattern is consistent with population genetic data that suggest spread from the initial California introduction to the rest of the west coast, with no evidence for multiple introductions to the west coast (Tepolt et al. 2009, Tepolt et al. 2022). By the mid-2010s, EGC had spread northward into the Central Coast of British Columbia, Canada (BC). In 2012, a well-established EGC population was reported from Sooke Basin on the Canadian side of the Strait of Juan de Fuca (Behrens Yamada et al. 2017). Starting in 2016, EGC were detected elsewhere in the central portion of the Salish Sea (Grason et al. 2018), and are currently well established in the Lummi Nation sea pond in Washington waters of Puget Sound and in smaller persistent populations at several other locations, including Drayton Harbor/Boundary Bay (WA), Ladysmith Harbor (BC), and the northern Olympic Peninsula (WA) including Makah Bay (WA). Concurrently, dramatic increases were seen in Washington’s coastal estuaries starting in around 2019, and have continued through the present exceeding any previous detections. The continued trend of increase, along with the decoupling of "outbreaks" with oceanographic predictors such as ENSO indices, indicates a recent state shift of Washington coastal estuaries to established populations. More recently, EGC have been found on the northeastern side of Vancouver Island including Port Hardy and have been detected in Haida Gwaii (BC) in 2020 and near Metlakatla on Annette Island in Southeast AK in 2022.

The eastern North America invasion has had a much longer and more complicated history. EGC have had two major introduction events to eastern North America, the first in the early 19th century to the Mid-Atlantic United States, and the second in the late 20th century to Nova Scotia (Roman 2006). The first introduction extends back to the early 1800s when they were likely introduced from the holds of wooden ships. During the early 20th century, EGC spread along the northeastern coast eventually reaching Nova Scotia and New Brunswick. The distribution of EGC then expanded considerably when the second colonization event to the Gulf of St. Lawrence and Prince Edward Island occurred in the 1990s, likely through ballast water (Audet et al. 2003, Cameron and Metaxas 2005, Roman 2006). The crab has most recently spread to Newfoundland, and genetic evidence suggests that larval movement via ship traffic from Nova Scotia is the most likely vector for the initial introduction to Placentia Bay, NL (Blakeslee et al. 2010, Darling 2011).

Population Genetics and Gene Flow

Population genetics work using microsatellites and the mitochondrial COI gene identified south-central Atlantic Europe as the source region for the initial EGC introduction to the East Coast of North America by 1817 (Bagley and Geller 2001, Carlton and Cohen 2003, Roman 2006, Darling et al. 2008). An expansion of EGC into the Canadian Maritime provinces in the 1980s was facilitated by a second introduction from a genetically distinct northern European source population (Roman 2006, Darling et al. 2008). All EGC on the West Coast of North America appear to be descended from the initial introduction into San Francisco Bay from a source in the original East Coast introduced range. We are not aware of any contribution from the second, more northern East Coast introduction (Bagley and Geller 2001, Darling et al. 2008, Tepolt et al. 2009, Tepolt and Palumbi 2015, CK Tepolt, pers. comm.). While *C. maenas* has invaded in hybrid populations with its Mediterranean congener *C. aestuarii* in some parts of the world, extensive population genetics work with multiple markers has exclusively found *C. maenas* genetic signatures in North America (Geller et al. 1997, Darling et al. 2008).

On the East Coast, crabs from the two introductions have mixed to form an extensive introgression zone (Darling et al. 2014, Jeffery et al. 2017, 2018). Specific directions and rates of admixture vary with marker type, with non-neutral mtDNA spreading faster than neutral microsatellites and single-nucleotide polymorphisms or SNPs, and appear to be responding to a complex set of oceanographic, selective, and demographic processes (Pringle et al. 2011, Darling et al. 2014, Lehnert et al. 2018). Further complicating these patterns, the recent expansion to eastern Newfoundland was derived from an admixed population, likely from Nova Scotia (Blakeslee et al. 2010). As of 2015, the most recent study to track admixture over time, East Coast EGC represented a complex mosaic of genetic backgrounds ranging from fully first introduction to fully second introduction and spanning a wide range of introgressed backgrounds (Lehnert et al. 2018).

On the West Coast, EGC have expanded their range rapidly from a single source in San Francisco Bay, despite significantly reduced genetic diversity (Darling et al. 2008, Tepolt et al. 2009, Tepolt and Palumbi 2015, Tepolt et al. 2022). In this region, high-throughput population genomics has been particularly helpful in elucidating fine-scale structure where more traditional genetic markers provide no or limited resolution (Bagley and Geller 2001, Darling et al. 2008, Tepolt et al. 2009, Tepolt et al. 2022). Overall, gene flow and dispersal are high among sites, with a few notable exceptions: embayments, where input of outside larvae is restricted, rapidly develop distinctive population genomic signatures due to isolation and loss of allelic diversity (Grosholz et al. 2021b, Tepolt et al. 2022, CK Tepolt, in prep.). One such site is Seadrift Lagoon in central California, which has a distinct genetic signature and significant loss of diversity relative to surrounding sites (Grosholz et al. 2021b, Tepolt et al. 2022). Interestingly, this site also shows an unusual thermal physiology and population dynamics uncoupled from those of neighboring embayments, demonstrating the importance of dispersal on the West Coast (Tepolt and Somero 2014, Grosholz et al. 2021b). Another site with a distinctive EGC population signature is Sooke Basin on the southern end of Vancouver Island, and the location of the first EGC population within the Salish Sea (CK Tepolt, in prep.). This population is believed to have resulted from an accidental introduction from well-established populations on the west coast of Vancouver Island (Curtis et al. 2015). This site opens to the Strait of Juan de Fuca, within the Salish Sea, but remains oceanographically disjunct with tidal exchange restricted by a very narrow opening, resulting in little to no recruitment of outside larvae.

Aside from hydrographically isolated embayments including Seadrift and Sooke, gene flow is sufficiently high and frequent to homogenize the neutral population genetic signature from central California through northern Vancouver Island along the species' coastal Pacific range (Grosholz et al. 2021b, Tepolt et al. 2022, CK Tepolt, in prep.). This agrees with observations that year-to-year recruitment variability is largely consistent along the coast, and suggests that most embayments are not self-recruiting (Behrens Yamada et al. 2021, Grosholz et al. 2021b). This is reinforced by the spread of larvae from Sooke Basin, a site in southeastern Vancouver Island with a highly individual genetic signature: larvae with Sooke signatures have been found as much as 400 km away in embayments opening to the Pacific coast, demonstrating the large dispersal potential of EGC larvae (CK Tepolt, in prep.). Population genomic dynamics are more complex and still in flux within the Salish Sea, where the species has been expanding its range since 2017. Extensive genomic tracking of this expanding range edge, as well as the northern edges in Haida Gwaii (British Columbia) and Alaska is ongoing (CK Tepolt, pers. comm.).

Selection and Thermal Tolerance

The first suggestion of a molecular basis for thermal tolerance in EGC came from the discovery that the expansion of the species on the East Coast occurred in concert with a second introduction of EGC bearing a genetically distinct mix of mitochondrial COI haplotypes indicating a northern European source (Roman 2006). It was proposed that an infusion of new, cold-adapted genotypes might have permitted the species' spread north into Maritime Canada from its previous apparent range limit in southern Nova Scotia (Roman 2006). Later physiological work linked two mtDNA lineages from this second introduction to increased fitness of male EGC at cold temperatures; interestingly, this effect was not observed for female crabs (Coyle et al. 2019). There is also a suggestion that new recruits bearing mtDNA from the second (northern) introduction may be at a selective disadvantage in more southern sites, though this has not been rigorously tested (Williams et al. 2015). Given that very different mtDNA lineages now exist in a wide range of nuclear genetic backgrounds in the East Coast introgression zone, it is possible that mito-nuclear interactions also influence fitness in the species – something that has been demonstrated in other species but has not yet been studied in EGC (Sunnucks et al. 2017, McKenzie et al. 2019). Mitochondrial selection likely plays no or little role in West Coast adaptation, as only a single COI haplotype has been recorded in this population to date (Darling et al. 2008). However, this may change in the future if a second introduction of EGC brings new genetic diversity, either from the East Coast, or from another global population.

There is also robust evidence for nuclear genomic variation in influencing thermal tolerance and adaptation in EGC on both coasts of North America. Variation at a region of the nuclear genome, containing at least 28 different genes, was strongly correlated with thermal physiology – especially cold tolerance – in a global study including Europe and both coasts of North America (Tepolt and Palumbi 2020). This region likely represents a supergene, probably an inversion polymorphism, which is a block of genes inherited together due to reduced recombination (Tepolt and Palumbi 2020). Supergenes have been proposed as a mechanism for effective selection in high gene flow environments, and have increasingly been found to permit adaptation along environmental gradients when dispersal is high (Tigano and Friesen, 2016, Barth et al. 2017, Hollenbeck et al. 2022). In EGC, this temperature-sensitive supergene was strongly correlated with latitude and winter temperature on the West Coast, across populations derived from a common source in under 30 years (Tepolt et al. 2022). Standing genetic variation at this supergene evolved in the species' native range and was carried through to the East and then West Coasts through two serial introductions (Tepolt and Palumbi 2020, Tepolt et al. 2022). It was proposed that this variation provides an adaptive substrate for the species' North American expansion despite a substantial loss of genetic diversity, and may play an important role in allowing the species to adapt rapidly as it spreads across environmental gradients (Tepolt et al. 2022).

Physiology and Environmental Tolerance

Physiological limits contribute substantially to determining the distribution of EGC, in terms of both the extent of their geographic range and their abundance patterns within bays and estuaries. Adult EGC are eurythermic: they are capable of surviving winter freezes, especially if they move to sublittoral habitats in cold areas such as Newfoundland, Norway, and Iceland (Blakeslee et al. 2010). Depending on their source population and acclimation temperature, they also can survive temperatures above 35°C for short periods of time (Kelly et al. 2011, Tepolt and Somero 2014). Most EGC can right themselves as low as 4.5°C, and all males with mitochondrial haplotypes originating from northern Europe could (Coyle et al. 2019). Similarly, they remain active and feeding in aquaria for days when kept as low as 9°C to as high as 27°C, but not 30°C, and juveniles and smaller adults were mobile after a week in the freezer (de Rivera, unpublished data and observations). However, temperatures below 10°C decreased molting, and below 7°C decrease feeding and molting, and colder temperatures increase mortality, though genetics and acclimation history likely create variation among populations in the exact temperature thresholds that lead to such impacts (Kelley et al. 2013, Tepolt and Somero 2014). Such decreases in activity at cold temperatures can drive relatively lower per-capita capture rates of EGC that are often observed during winter months.

As with most marine species, EGC larvae (zoeae) are less thermotolerant than eurythermic adults. Zoeae kept in a lab require temperatures above 10°C and below 25°C to molt successfully, and their survivorship peaks around 17.5°C (de Rivera et al. 2007). Larval survival also decreases when warm temperatures (21, 24°C) are combined with food limitation (Torres and Giménez 2020, Giménez et al. 2021). However, the relationship between larval survival and temperature varies greatly among populations (Šargač et al. 2022). This variation may be due in part to genetic differences among populations; other work has linked thermal tolerance in adults to variability at specific genetic regions (Coyle et al. 2019, Tepolt and Palumbi 2020). Warmer water temperature also decreased EGC larval size in some studies, which could affect their survival (Mohamedeen and Hartnoll 1989), though this was not observed in other studies (Torres and Giménez 2020). Increasing temperature shortens larval development duration of EGC, following a negative decelerating function (de Rivera et al. 2007). Zoeal development of EGC takes almost twice as long at 12.5° C (59 days on average) as it does at 20°C (approximately 30 days); however, this rate varies across populations (de Rivera et al. 2007, Dawirs and Dietrich 1986, Mohamedeen and Hartnoll 1989, Nagaraj 1993).

Adult EGC are euryhaline: they have high osmoregulatory capacity, surviving salinities ranging from 4 to 52 ppt (Broekhuysen 1936, Ameyaw-Akumfi and Naylor 1987, McGaw and Naylor 1992, Klassen and Locke 2007). However, most EGC live from mid estuary to fully marine coastal areas. Their low salinity tolerance typically stops at 10 ppt (Broekhuysen 1936), perhaps because extended exposure to low salinities increases energy and oxygen demand (Legeay and Massabuau 2000). The low end of this range is consistent with findings that they increase their locomotor activity around 10 ppt (McGaw et al. 1999). On the west coast, EGC are found in higher abundances in lower salinity waters where native cancrid crabs are less able to compete, providing EGC with refugia and facilitating their spread (Hunt and Behrens Yamada 2003).

Like thermal tolerance, larval EGC especially zoeal stages 2-4 are more susceptible than adult stages to salinity extremes (Cieluch et al. 2004). Larval salinity tolerances are likely especially important for limiting the distribution of EGC especially within estuaries with variable salinity regimes. Postlarval (megalopal) EGC are able to weakly osmoregulate (Nagaraj 1993, Cieluch et al. 2004). Zoeal larvae, however, had impaired development below 25 ppt and did not survive short-term exposure to estuarine salinity (1 day at 14 ppt or 3 days at 20 ppt) (Anger et al. 1998, Bravo et al. 2007, Klassen and Locke 2007). As with temperature, the extent and peaks of salinity-induced mortality differ among maternal lines (Bravo et al. 2007). Exposure to lower salinity lengthens larval development time and competency thresholds, which may have implications for dispersal (Spitzner et al. 2019). However, dispersal distances are not simply a function of larval development time and can be strongly influenced by ocean currents, larval behavior, and other factors (See and Feist 2010, Gharouni et al. 2015, 2017).

Although osmotic and thermal stress each increase metabolic demand, warmer water may help ameliorate some of the negative effects of low salinity because it increases the osmoregulatory capacity of larval EGC and speeds development, reducing the amount of time they are in this vulnerable stage (Torres et al. 2021). Indeed, the combination of decreased salinity and warming yielded much higher larval survival than expected given results for decreases in each factor individually (Spitzner et al. 2019). Again, the effect of these variables on development rate and survivorship varies within and between populations (Spitzner et al. 2019, Šargač et al. 2022). This variation may reflect the fact that larval tolerance is shaped by a range of factors, including the environment experienced as embryos, heritable genetic variation, and prior maternal conditions (Torres et al. 2021).

Range Limits and Habitat

Temperature is thought to be the main constraint to establishment and main environmental driver of northern range limits (Welch 1968, Beukema 1991, Audet et al. 2003, Carlton and Cohen 2003, Compton et al. 2010). Larval recruitment strength varies with temperature, with EGC recruiting both earlier and over a broader timespan in warmer years (Strasser and Günther 2001). EGC recruitment strength was linked to winter temperatures over a 40-year period in New England (Welch 1968). Years with warmer water temperature, stronger northward flow in winter, and a late biological spring transition have been associated with spread and enhanced recruitment of EGC on the Pacific coast of North America (Behrens Yamada and Kosro 2010, Behrens Yamada et al. 2015, 2021). Similarly, atypical oceanographic conditions including warm water anomalies were associated with episodic, enhanced spread of EGC populations in Australia (Thresher et al. 2003). Based on variable oceanographic conditions, larvae theoretically could disperse over large distances over the maximum 83-day development time in cold waters (Dawirs 1985, de Rivera et al. 2007, Brasseale et al. 2019, Behrens Yamada et al. 2021), while reduced recruitment as well as range contraction were documented after cold years (Berrill 1982, Audet et al. 2003). More recent studies using acoustic telemetry have explored the seasonal movements of adult EGC and their habitat use in estuaries, including the movements and position of of ovigerous crabs over the course of their egg development cycle (Zarrella-Smith et al. 2022, Burke et al. *in prep*).

The potential range of EGC extends beyond the present distribution and is predicted to extend even further poleward given warming and sufficient propagule pressure (de Rivera et al. 2007, 2011, Compton et al. 2010, Kelley et al. 2013, Lyons et al. 2020). Moreover, as temperatures increase with climate change, the frequency of colder winters with conditions below the thermal threshold for EGC is decreasing (Easterling et al. 2000, Meehl et al. 2000). The shorter larval duration that accompanies warmer waters should decrease mortality from predation, UV exposure and the many other high risks for planktotrophic decapod larvae (McConaugha 1992). In theory, the more equatorial range limits may contract poleward due to thermal constraints of heat tolerance (Kelley et al. 2011). However, in North America it appears that southern range limits are constrained by factors other than temperature, notably oceanographic barriers to spread on the west coast and interactions with blue crabs on the east coast (Grosholz and Ruiz 1995, de Rivera et al. 2005).

Within their physiological envelope, EGC are reported to utilize a broad range of habitat types in Europe and eastern North America. Postlarval crabs are abundant in the intertidal and shallow subtidal zone, occurring as deep as 55 m. They occur in unstructured sandy and muddy bottoms, are commonly found in saltmarshes and seagrass beds, but are often found to be most densely concentrated around protective three-dimensional structure such as pilings, shell piles/reefs, or aquaculture structures. They also use woody debris and cobble and rocky substrates. EGC often utilize protected habitats within estuarine systems, ranging from ocean inlets up into intertidal marshes, though their population density can very locally between systems (Raposa et al. 2020). In eastern North America, ECG have shown seasonal movements within estuaries, with a migration to deeper waters tied to temperature decreases in autumn (Zarrella-Smith et al. 2022). Female ECG tend to be found in deeper water than males (Rewitz et al. 2004, Fulton et al. 2013), and ovigerous crabs tend to be found in downstream locations when compared with non-ovigerous females (Burke et al. in prep.) which may be tied to migrations towards the open ocean associated with the release of larvae (Baeta et al. 2005). While EGC can cover great distances throughout these estuarine habitats, determined by tracking individuals with acoustic telemetry tags, their mean core use area (50% UD) home range size is only a small (<1%) percentage of available subtidal habitat, which suggests EGC impacts are localized and acute (Burke et al. *in prep*.). Earlier telemetry studies estimated that EGC may range only 50-100 meters along shoreline over a single tide cycle (P.S. McDonald. unpubl. data). Several ongoing efforts to describe the meter-scale movement ecology of EGC links individual movements with population-level estimates of distribution and abundance and may help inform management at a local level.

Although EGC are common and ecologically important in the rocky intertidal communities of eastern North America (Menge 1983, 1995), their utilization of similar rocky habitats appears to be relatively limited in western North America (Grosholz and Ruiz 1996, unpubl. data), similar to habitat use in southern Africa where the coast can also be quite exposed (Hampton and Griffiths 2007). Recent observations have shown that EGC will occupy exposed rocky shores in some locations in western North America, possibly as less desirable habitat as densities in more favorable habitats increase, which is often the case as the invasion progresses. Other environmental factors may also influence the range limits of EGC, although data are lacking for many of these. One such factor is ocean acidification, the increasing levels of seawater $p\mathrm{CO}_2$, which has been shown to affect other crustaceans by decreasing egg production and hatching success and survival of adults and larvae, and reducing growth rates (Whiteley 2011), but which has not been studied in EGC.

Ecological Interactions

Biotic factors can also influence or modify range limits. For instance, predators and parasites have the potential to influence the range of EGC through impacts on abundance and dispersal. There is strong evidence that the southern limit of the EGC in eastern North America is limited by predation by blue crabs (*Callinectes sapidus*) (de Rivera et al. 2005). Although it is evident postlarval and adult EGC have a variety of potential predators, from fish and birds to mammals and invertebrates, their effect on EGC distribution and abundance appears limited in most areas. Within its present ranges, EGC is often the most abundant crab species in lower intertidal zones in soft-sediment bay and estuaries of Europe, Australia (Tasmania), and both coasts of North America (Tettlebach 1986, Grosholz et al. 1996, Ruiz et al. 1998). However, in the northeastern United States, EGC has been increasingly displaced in the intertidal zones by a newer invasive crab, *Hemigrapsus sanguineus* (Lohrer and Whitlatch 2002, O'Connor 2014, Bloch et al. 2015), a shore crab native to East Asia.

In terms of parasites, EGC have demonstrated clear signatures of parasite escape (i.e., a significant loss of parasite diversity in non-native ranges) of metazoan parasites on both North American coasts compared to native European populations (Torchin et al. 2001, Blakeslee et al. 2009, 2016, 2020). This loss of parasites (particularly parasitic castrators) has been suggested as a potential mechanism for enhanced demographic success in non-native populations of EGC (Torchin et al. 2001). However, host specificity needs to be examined before biocontrol efforts are used; research on the parasitic barnacle *Sacculina carcini* showed that its use could infect and potentially impact native crabs on the west coast (Goddard et al. 2005). Microparasite diversity is less understood in introduced EGC populations, but a study by Bojko et al. (2018) suggests that microparasite diversity between native and non-native populations does not significantly differ. Thus, EGC may be more likely to acquire novel microparasites versus macroparasites in non-native regions, but further investigations are needed to assess this.

Ecological Consequences

The impacts of EGC on a broad range of native species and habitats have been firmly demonstrated. Their broad diet includes bivalve molluscs, crustaceans, polychaetes and other benthic species. Several studies in central California have documented reductions in native clams and shore crabs by 90% due to predation by EGC (Grosholz and Ruiz 1996, Grosholz et al. 2000, Yamada 2001, Grosholz 2005). Further studies have also shown the potential for EGC to impact young of the year Dungeness crabs through competition for food and shelter as well as predation (McDonald et al. 2001). Studies from Atlantic Canada have shown that EGC have also reduced abundances of native mud crabs there (Gehrels et al. 2016). EGC have also been shown to have deleterious effects on lobsters (*Homarus americanus*) through competition for space and resources that, in turn, leads to reduced recruitment and lower catch rates (Rossong et al. 2006, Goldstein et al. 2017, Rayner and McGaw 2019). Studies from other regions such as Australia have documented substantial impacts of EGC on native bivalves and other benthic fauna (Proctor 1997, Walton et al. 2002). These impacts on native fauna have also been well documented in their native European range (Ebling et al. 1964, Dare and Edwards 1976, Reise 1978, Davies et al. 1980, Dare et al. 1983, Reise 1985, Jensen and Jensen 1985). Of substantial concern for benthic ecosystems is the widely-documented impact of EGC on eelgrass beds in many locations including the Canadian Maritimes (Malyshev and Quijon 2011, Garbary et al. 2014), New England (Davis et al. 1998, Neckels 2015), and Newfoundland (Matheson et al. 2016) as well as potential impacts in the Pacific Northwest (Howard et al. 2019). The impacts of EGC are necessarily dependent on the native resources present in a given location and region.

Determining which ecosystem elements are at risk and quantifying changes in those elements in response to EGC invasion is a key part of prioritizing management strategies (see Goal 5 below).

In addition to their direct and indirect impacts on other benthic fauna, EGC can also act as a vector for pathogens and diseases of other organisms that can have negative impacts on other crustaceans, shellfish and other marine organisms. For example, previous studies have shown that EGC is host to 72 pathogens and parasites (Boiko et al. 2021) including Pink Crab Disease (*Hematodinium* sp.) (Davies et al. 2019) and the very serious oyster disease ostreid herpes virus OsHV-1 (Brookelaar et al. 2018). There is very real worry that EGC has the potential to introduce and transmit internal parasites to novel hosts in the new range with potentially serious outcomes (Bojko et al. 2018, Boiko et al. 2020).

Some recent studies have found beneficial aspects of the green crab invasion in specific habitats, for example New England salt marshes that have experienced substantial degradation show salt marsh cordgrass recovery from green crab reducing the functional density and herbivory of a native intertidal herbivorous crab *Sesarma reticulatum* (Bertness and Coverdale 2013, Coverdale et al. 2013, Bertness et al. 2014). However, recent work suggests that these effects of EGC on marsh vegetation are not ubiquitous even within New England salt marshes and may be relatively site specific and context dependent (Moore and Schmitz 2021).

Economic Consequences

Current estimates of the economic impacts of EGC are largely focused on shellfisheries. Following the introduction and expansion of EGC through the northeastern U.S., they had substantial impacts on the soft-shell clam industry in the earlier part of the 20th century (Glude 1955, Ropes 1969). Recent estimates of losses of shellfish to ECG include losses in years of high recruitment on the west coast as well as chronic losses annually for east coast fisheries (Grosholz et al. 2011). These include expenses such as fences, cages, and trapping to mitigate EGC impacts in commercial beds (Walton 2000, Grosholz et al. 2011). In eastern Maine, climate-driven increases in sea surface temperatures (see Pershing et al. 2021) are believed to be responsible for recent population surges of EGC and a major contributor to the 75% decline in commercial landings of soft-shell clams (Tan and Beal 2015, Beal et al. 2016, Beal et al. 2020). Economic costs have also been estimated for future potential losses to Canadian fisheries (Klassen and Locke 2007).

It should be noted that there have been several alternative uses for EGC that might potentially generate revenue to offset the costs of EGC harvest for mitigating impacts on commercial targets and provide 'incentive programs' that could reduce their abundance in priority areas. These include the use of EGC as compost for agriculture, which is currently the endpoint for EGC harvested in some control programs (Grosholz et al. 2021a). Potential or actual uses of EGC also include food products (https://www.greencrab.org/) (Kang et al. 2019, Greiner et al. 2021, Bradt and McMahan 2022), pet food, bait, fishmeal (Fulton and Fairchild 2013), and even a EGC whiskey called "Crab Trapper" (www.tamworthdistilling.com). Creating new markets for EGC (e.g., soft-shelled product) also provides the potential to offset some of the fisheries losses to EGC by creating new economic opportunities for local residents, though different fishing methods yield varying break-even points for harvesters with the small commercial market for ECG (St-Hilaire et al. 2016).

It is important to separate the potential economic benefits from the likelihood that commercial harvest will contribute significantly to the reduction of green crab populations. In general, commercial harvest programs have the potential to play a supplementary role in managing small, isolated populations. However, it is important to recognize the different goals of trapping for population reduction vs. commercial harvest. Population reduction often involves intensive and longer term trapping at specific sites in order to produce a significant reduction in the impacts of EGC. This often means trapping populations down to a level where the catch-per-unit-effort (CPUE) would likely be lower than would be commercially viable. In contrast, commercial trapping would typically involve adjusting fishing efforts spatially to focus on populations that were the most abundant (and most cost effective) with the highest CPUE. The difficulty of maintaining a commercial fishery for invasive species, while simultaneously reducing their ecosystem and economic impacts, have been demonstrated in other regions where fisheries for invasive species have been considered (Azzurro et al. *in prep.*).

It should also be cautioned that development of an EGC fishery has other downsides. Particularly for regions where EGC is still expanding, creating a market for EGC provides incentives that may encourage individuals to move EGC beyond their current range into previously non-invaded habitats. Also issues regarding interstate transport of EGC from locations of high abundance may create conflicts with differences between statewide regulations. In short, developing a green crab fishery for commercial benefits requires careful review and planning to ensure that these programs do not result in further spread of EGC or any additional harm to native species (Pasko and Goldberg 2014).

Jurisdictional and Cultural Considerations

Efforts to address invasive species fall along a continuum, varying among state, Tribal, federal, and other jurisdictions. For example, each state has its own legal principles found in its constitution, statutes, administrative rules, and case laws, and therefore there will inevitably be policy differences among the states. In addition, there are geographical differences that may require variability in each state's respective laws. Penalty provisions are a complex mix of civil and criminal penalties for violations of invasive species laws and regulations. To the extent that the states can develop a coordinated, mutually acceptable system of monitoring, response, communication and management actions, there will be regional and larger scale benefits. Currently, laws and regulations addressing invasive species are inconsistent, potentially hampering prevention and enforcement efforts on both state and federal levels. Invasive species like EGC are an international and global problem that do not respect borders and cannot be handled by any single jurisdiction alone.

Although every state has some statutory and regulatory provisions addressing invasive species, the below summary includes legal authorities and regulations specifically enacted to address EGC. A general summary of management actions and ongoing activities related to EGC is included in Appendix B.

Federal Authorities, Roles, and Responsibilities

Federal authorities, roles, and responsibilities for branches and departments of the federal government, as they pertain to invasive species, are summarized and outlined in Appendix I (page 9) and Appendix III (page 30) of the 2015 Federal Policy Options paper by the Interagency Committee on the Movement of AIS onto and off of Federal Lands and Waters for the National Invasive Species Council (NISC) and the Aquatic Nuisance Species Task Force (ANSTF). This paper is available online through the NISC website in their publications section: https://www.doi.gov/invasivespecies/other-publications.

Additional information about the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990, and the National Invasive Species Act of 1996 can be found through the Aquatic Nuisance Species Task Force website: https://www.fws.gov/program/aquatic-nuisance-species-task-force/about-us.

Laws and policies guiding invasive species management at the Department of the Interior are summarized within Appendix E (starting on page 39) within the Department of the Interior Invasive Species Strategic Plan 2021-2025. This summary includes federal laws and administrative policies such as Executive Orders and Departmental Manuals. The DOI Invasive Species Strategic Plan is available online: https://www.doi.gov/sites/doi.gov/files/doi-invasive-species-strategic-plan-2021-2025-508.pdf

Bureau and Office missions and roles in invasive species management within the Department of the Interior are summarized in Appendix A (starting on page 26) within the Department of the Interior Invasive Species Strategic Plan 2021-2025 available online: https://www.doi.gov/sites/doi.gov/files/doi-invasive-species-strategic-plan-2021-2025-508.pdf

Alaska

EGC are classified as banned invasive species in Alaska regulations. Possession and transport of banned invasive species is prohibited which means it is against the law to collect or transport them without a valid permit. See Alaska regulation Section 5 AAC 41.075 - “Classification of banned invasive species” for additional detailed information and a complete list of banned invasive species (https://www.adfg.alaska.gov/index.cfm?adfg=invasive.FAQ). Alaska statute (AS 16.35.210) prohibits knowingly releasing, or transporting, possessing, importing, or exporting non-indigenous fish (which includes invertebrates) for the purpose of release into state waters.

Washington (State)

EGC is a Prohibited Level 1 species and may not be possessed, introduced on or into a water body or property, or trafficked, without department authorization, a permit, or as otherwise provided by rule. (RCW 77.135.040)
https://wdfw.wa.gov/species-habitats/invasive/carcinus-maenas#regs-seasons

Washington (Tribes)

Shellfish have always been a part of the diet and culture of Western Washington Tribes and remain an important commercial, ceremonial, and subsistence harvest resource today. Many

Tribes in Washington State were party to the 1974 *U.S. v. Washington* ("Boldt Decision"). The Boldt Decision (and subsequent decisions) reaffirmed and interpreted treaties signed in the 1850s by Tribes and the U.S. federal government to support Tribes' right to harvest up to 50% of all fisheries resources that reside in and pass through their Usual and Accustomed Areas. In 1994, Judge Rafeedie extended this interpretation to shellfish resources. These decisions also establish Tribes as *co-managers* of fisheries with Washington State. In addition to being legal co-managers, Tribal governments in Washington State have been leaders in EGC research, monitoring, and removal efforts. Individual tribal governments retain inherent sovereign rights to manage finfish and shellfish resources, including decision-making about setting fishing seasons, licensing, gear types, etc. Tribal fisheries and fisheries management decisions are distinct from and not subject to the regulations of Washington State. Individual tribal governments should be engaged directly in order to identify EGC regulations and to develop meaningful coordinated action on EGC management. Additionally, any plans or recommendations should recognize Tribal Treaty Rights and federal treaty trust responsibilities.

Oregon
Recreational harvest of EGC is allowed, with a daily bag limit of 35 individual crab of any size or sex, and is separate from other crab species. Commercially harvesting EGC is prohibited. An Oregon Department of Fish and Wildlife (ODFW) Shellfish License is required.
https://myodfw.com/articles/oregon-shellfish-regulations

California
There are no regulations that prohibit the take of EGC. Green crabs fall under California Code of Regulations Title 14, section 29.05, which covers general invertebrates, and gear restrictions for crustaceans, section 29.80. The daily limit for general invertebrates is 35 individuals. Some locations have restrictions on time of day of harvest, for example in San Francisco Bay, invertebrates may not be taken at night, except from the shore.
https://wildlife.ca.gov/Fishing/Ocean/Regulations/Sport-Fishing

Maine
Both recreational and commercial harvest of EGC is allowed with a state issued license. Individuals may hold a lobster or crab fishing license, or a commercial green crab only license. Commercial EGC only licenses may be issued only to an individual. A license is not required to fish for, take, possess, or transport EGC for personal use if crabs are taken by hand or by a method exempted from licensing requirements. (Title 12, Section 6808)
https://www.mainelegislature.org/legis/statutes/12/title12sec6808.html

New Hampshire
EGC can be taken in any quantity by any legal method. A license is required to take more than 12 individual crabs or by trap. Persons licensed to take lobster and/or crab by trap are required to purchase trap tags up to the maximum allowed by their license
https://www.eregulations.com/newhampshire/fishing/saltwater/lobster-crab

Massachusetts

Invasive crabs can be harvested with a Letter of Authorization (LOA) from the Massachusetts Division of Marine Fisheries. Closed season on harvest is January 01–April 30, inclusive. Closed season on trap gear is November 1–May 15, inclusive. (Section 37A: Green crabs) https://malegislature.gov/Laws/GeneralLaws/PartI/TitleXIX/Chapter130/Section37A

Rhode Island – EGC not mentioned in crab harvest regulations.

Connecticut
EGC is considered under regulation as a bait species and can be taken using limited types of nets and traps (used to catch bait species only). A recreational license is required in the marine district, and taking of bait species is for personal use only and not for sale. https://www.eregulations.com/connecticut/fishing/recreational-fishing-bait-species-lobster-crabs

New York – EGC not mentioned in crab harvest regulations.

New Jersey – EGC not mentioned in crab harvest regulations (only as bait species).

Delaware – EGC not mentioned in crab harvest regulations.

Maryland
EGC are prohibited from being removed from the waters of one watershed and introduced into the waters of another watershed. Prohibited from import, transport, sale, purchase, and possession in Maryland. The Maryland Department of Natural Resources may adopt regulations to limit or prohibit the importation, use, catching, or possessing of the following nonnative crab species, which are determined to be harmful to the ecology and natural resources of the State. (Section 4-816. Nonnative crab species) https://govt.westlaw.com/mdc/Document/N66EC56109CE511DB9BCF9DAC28345A2A?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

Management actions may have different and/or additional permitting, regulatory procedures, and restrictions given the various jurisdictional authorities for the associated lands and waters. Sensitive areas, critical habitat for listed species, sensitive cultural sites, religious sites of significance, and other locations will have additional mitigation requirements and restrictions, including limitations on data availability and reporting. Traditional knowledge is an important component of natural resource management, including tribal perspectives on invasive species, the importance of traditional ecological knowledge, and the unique cultural dimensions of invasive species for individual tribes. Tribes are important partners and leaders in invasive species management and understanding these human dimensions of management is vital for building political and community support to implement policies, laws, and regulations (McNeely 2001).

GOALS OF THE PLAN

Implementation of EGC management plan goals does not require sequential application. Selection of which goal or goals to apply is based on where management entities are on the invasion curve and multiple other factors such as authorities, funding, and management priorities. In this plan, we describe the following eleven priority goals:

1) Prevention to minimize the likelihood of future introductions
2) Monitoring to support early detection and inform management strategies
3) Rapid response to coordinate management strategies and actions for new invasions
4) Emergency management to coordinate management strategies and actions for rapidly expanding populations
5) Containment and control of established populations to minimize impacts
6) Eradication of populations to eliminate impacts
7) Research to understand invasion risks and to improve or develop new management strategies
8) Economic analysis to quantify tradeoffs among management strategies
9) Outreach education tools to explain management strategies
10) Data management for effective coordination and distribution
11) Adaptive management to evaluate and modify plan implementation

Goal 1. Prevention to Minimize the Likelihood of Future Introductions

Prevention, for the purposes of this plan, means management strategies that aim to stop or reduce the arrival of EGC, either larvae or adults, resulting from the human-mediated transport/transfer of EGC from one location to another. Natural larval transport by marine currents is not a human-mediated action and is not covered under this goal, as it is impossible to manage.

The initial invasions of EGC, like most aquatic invaders, are the result of human-mediated vectors and multiple pathways of introduction and spread (Carlton 1989, Carlton and Geller 1993, Ruiz et al. 1997). These include ship-based vectors including ballast water and ship hulls (although the latter is unlikely for EGC), but also a number of other non-ship based pathways including: 1) shellfish shipments including oysters, clams, and mussels, 2) containers with live bait and live seafood with live algal packaging materials, 3) inter-harbor transport of nets and traps, 4) escape or release from research and education facilities, and 5) movement of marine construction equipment or associated sediments and sands. Vectors that were important means of introduction historically like aquaculture are now carefully regulated and pose little threat currently (Williams et al. 2013).

The most likely means by which EGC was introduced to east coast was initially to the Long Island Sound area via solid ballast in the early 1800s (Carlton and Cohen 2003), with a second introduction ~150 years later to Nova Scotia via ballast water (Roman 2006). On the west coast, the initial introduction into San Francisco Bay was most likely via seaweed packing in lobster or bait shipments from the eastern United States (Carlton and Cohen 2003). However, the subsequent spread of EGC along on the east and west coasts following the initial introduction has largely been through natural dispersal of larvae in coastal waters.

Importantly, even in areas where EGC are already present, there are real concerns for the introduction of new genotypes via ongoing or repeated transport of EGC propagules from established populations in other regions. In addition to increasing propagule pressure, generally, multiple introductions can facilitate rapid adaptation and spread, by allowing selection to act on genetic variants that evolved in a wide range of environments (Suarez and Tsutsui 2008, Rius and Darling 2014, Qiao et al. 2019). There is compelling evidence that the introduction of new genetic variation via a second introduction from northern Europe may have jump-started the northern spread of EGC in eastern North America (Roman 2006). Therefore, identifying the most likely pathways for introduction of new genotypes and individuals, including ballast water and transport in bait boxes, is an important component of future prevention.

Objective 1.1. Assess and mitigate living industry pathways

Living industry pathways involving the unintentional movement of propagules include the live bait and seafood industry, as well as the aquarium and pet trades (Williams et al. 2013). Considerable data support the idea that both live bait and seafood continue to be a source of new EGC propagules through the movement of live packing material such as macroalgae that generally accompanies shipments of bait and seafood (Cohen 2012, Blakeslee et al. 2016). Also, the movement and transfers of shell stock and aquaculture gear among sites with/without EGC also represent a significant risk of introducing EGC to currently uninfested areas.

Studies have also shown that there are effective management options available to mitigate the potential for transfer or movement of EGC via the movement of live bait and seafood as well as shell stocks and aquaculture gear. These include inexpensive osmotic shock treatment (e.g., fresh water) of packing materials and the use of substitute materials that can reduce the risk of introduction of invasive propagules (Blakeslee et al. 2016). The likelihood of intentional movement of EGC for live bait and seafood varies considerably among states and could increase if a fishery for EGC was established. Recent studies have shown that movement of shellfish products and equipment can result in unintentional introductions such as the transport of mussels used for biotoxin monitoring transported into the Sooke Basin on Vancouver Island (Curtis et al. 2015).

In Washington, EGC is listed as a level 1 prohibited species and cannot legally be “possessed, purchased, sold, propagated, transported, or released into state waters” (Drinkwin et al. 2019). Similarly, EGC are designated in Oregon as a level 3 Controlled Species that “may be harvested recreationally pursuant to OAR 635-039. Once harvested, it is unlawful to return green crab to state waters.” Oregon has established a recreational daily catch limit of 35 EGC, and it is unlawful to take EGC in Oregon for commercial purposes. California does not have special restrictions regarding harvest of EGC other than the fishing restrictions that apply to all crabs.

Recently, live EGC were sold in seafood markets in California (B. Pernet, Cal. State Univ. Long Beach, pers. comm.), and live EGC were found at a seafood market in Seattle, apparently imported from the East Coast without the seller's knowledge of being prohibited. Thus, the threat of an emerging capture fishery and the attendant concerns are increasing.

Because of restrictions that vary considerably among states, EGC can be sold live in seafood markets in California, while it is a prohibited species in Washington. Discrepancies among state laws not only can create confusion, but may also provide incentive to harvest and or/transport EGC illegally to sell in a less restrictive state. Consequently, there is a clear need to standardize the status of EGC or at least limit incentives to move EGC across state borders. In the future, further legal or regulatory analysis is needed to determine the best way to standardize the legal status of EGC in the United States.

Objective 1.2. Assess and mitigate shipping pathways

Shipping pathways include commercial and military shipping, mobile marine infrastructure (e.g., drilling platforms, construction barges, floating docks), and recreational boating. The evidence for long-distance transport via ships' ballast water is modest, although long-distance transport between continents suggests this may be an important, if infrequent, pathway. The risk of long-distance transport by ships is further reduced by evolving ballast water management through open sea exchange and ballast water treatment. However, local coastal transport by ships, especially within a single U.S. Coast Guard Captain of the Port Zone, continues to be a risk as ballast water management is generally not required. Historically, solid ballast (rocks and stones) was known to have transported a diverse array of maritime and terrestrial plants and animals and is suspected of being the pathway for initial EGC introduction into the eastern U.S. in the 19th century (Carlton and Cohen 2003). Solid ballast has largely been phased out in favor of ballast water, and is unlikely to pose much contemporary risk.

Transport of EGC via marine growth on modern ship hulls (biofouling) is not considered a high risk except in cases of extensive biofouling on the hull or in niche areas such as sea chests. More work needs to be done to assess the risks of EGC transport on mobile marine infrastructure, which often accumulates significant densities of marine growth before being moved to a new location. To date, however, we are not aware of any reports of EGC associated with these pathways.

Objective 1.3. Investigate and mitigate miscellaneous pathways

Additional pathways include shellfish and other marine aquaculture industries through infrastructure transfers between marine areas, and inter-harbor transport of nets and traps, escape or release from research and education facilities, and the movement of marine construction devices and marine sediments and debris. To date there are no verified reports of EGC introduction or spread via these pathways, although they still represent a potential risk.

Goal 2. Monitoring to Support Early Detection and Inform Management Strategies

Monitoring, for the purposes of this plan, means a systematic and designed sampling effort for EGC information-gathering purposes that is implemented consistently and on a routine schedule. Monitoring protocols are well defined and are relatively stable to evaluate changes over space and time. The specific purpose and geographic scope of any individual monitoring effort might vary to suit the project but should remain internally consistent.

This section underlines the critical importance of monitoring to enable a robust understanding of the presence, abundance, and demographic structure of new EGC populations, and to form the foundation of informed management action(s). In locations where EGC is still expanding its distribution, regular monitoring serves the critical role of early detection in which the aim is to find the first generation(s) of EGC settling within a water body. In this case, early detection would involve a response chain that would assess the status of the new invasion, determine the resources at risk, engage groups that have authority for the location/region, and develop the necessary management response. In locations where EGC populations are established and management and related activities are either ongoing or under consideration, monitoring data are critical for tracking trends such as rapid population growth, evaluating management thresholds and the potential impact of management interventions, and forecasting future shifts in densities, seasonality, habitat use, and impacts. Where control and removal are the focus, monitoring the effectiveness of the measures is crucial to understand when control objectives have been achieved. Coordination of early detection and ongoing monitoring efforts and networks across jurisdictions helps create an institutional framework for sustainable management capacity, and accelerates information sharing across jurisdictions.

Objective 2.1. Coordinate and expand monitoring networks

Because EGC populations are often highly connected by oceanography, monitoring plays an important role at both the local and the regional scale. Therefore, efficient management warrants regionally coordinated and integrated monitoring networks, conducted with knowledge of the capture probabilities and effectiveness of the gear used both for early detection and for tracking population status and trends. Coordinated monitoring is built on a shared understanding of what information is necessary for management decision-making. For example, understanding the level of effort needed to provide early detection capabilities is crucial to effective monitoring programs. Regional monitoring efforts should draw together local managers and scientists to agree on minimum data requirements and standardized monitoring approaches that will enable comparability across groups participating in monitoring. Relevant considerations include:

- Focused geographies and habitat types
- Targeted life stages
- Monitoring techniques and protocols
- Monitoring frequency and seasonality
- Minimum data standards

Identifying sites for early detection monitoring can involve considerable effort and require input from species distribution/habitat suitability modeling. We recommend using emerging methods that develop a robust ensemble model using several independent model estimates to determine the likelihood of invasion for a given site or set of sites (Howard et al. 2022). Given the selection of a particular site with this approach, the use of traps that can capture juvenile EGC, or young of the year (YOY), can often be instrumental in detecting the first generations of green crabs in a new habitat, and use of traps that are most sensitive for green crab will help detect populations at relatively low abundances. Using traps in habitats where young juvenile EGC have the greatest survivorship, typically in flow-restricted, structured, soft sediment, estuarine habitats at higher tidal elevations, will be most successful. A monitoring program should be effective for capturing juvenile EGC while also collecting information on all life stages. This will support both early detection and also characterize the demographic structure of the full local population. Targeting juveniles in monitoring efforts, regardless of the invasion status of a water body, has the added benefit of supporting local and regional population forecasting. Early detection trapping typically focuses on habitat types where the early settling recruits experience the greatest survivorship, and these habitats might ultimately contribute disproportionately to regional population growth. Thus, these habitats have additional value because they enable forecasting year-to-year population changes as the invasion progresses.

Conversely, managers should use site-specific knowledge to exclude potential sites or use independent datasets (e.g., presence of eelgrass beds, Tribal harvest sites) to further prioritize sites based on potential impacts to valued ecosystem components. Coordination of monitoring networks should involve the full range of individuals and groups affected by EGC invasions including management agencies, tribal entities, stakeholders, recreationists, and others. To date, many groups on both coasts have developed local monitoring efforts, and some have expanded to integrate across jurisdictions. Efforts to coalesce and coordinate these programs should draw on the expertise, experience, and goals of these local and regional programs, and ensure transferability and interoperability of data (see Goal 10).

The development of a coordinated regional monitoring and data-sharing network at the scale of the entire eastern or western U.S. is an important goal. Regional networks integrate subregions with very different levels of monitoring activity and will need to be responsive to the needs of all within the larger region. An example of regional or local coordination would be the need to integrate well-organized and highly active networks in Washington and the Salish Sea regions. Where possible, coordination with Canada’s Department of Fisheries and Oceans (DFO) will be necessary on both east and west coasts as EGC range extends beyond U.S. waters.

In the future, monitoring networks will increasingly need to leverage the efforts of community/citizen scientists and volunteers as the need for increased effort and longer-term management grows. This is both an opportunity for public education (see Objective 9.2 below), but also an important means to multiply the effort and to provide critical capacity for populating and managing spatially distributed networks. This will also require the capacity to both train and coordinate local community members, partners, and volunteers both in monitoring methods and in the collection and transfer of monitoring data.

Objective 2.2. Expand the development and use of new tools for early detection and population monitoring

Because trapping gathers the most directly observable information on the life stages of crabs that will affect resources locally, this technique remains the backbone of EGC population monitoring efforts. Nevertheless, development of other detection techniques could support and complement trapping for both early detection and ongoing population monitoring. These include genetic detection techniques like environmental DNA, as well as targeting early life stages of EGC through larval plankton tows or postlarval collectors.

2.2.1. Methods targeting early life stages. As a detection technique, baited trapping only captures EGC after they have been present at a site for several months. In theory, searching for earlier life stages could provide even more advance warning of a new or pending invasion. Both techniques could also support forecasting by observing spatial and temporal patterns of recruitment, and offer lead time for managers in planning control and removal efforts. Sampling for larvae via plankton tows, or early benthic phase juveniles using postlarval collectors have hitherto not been widely used as monitoring techniques, though early detections of larvae have occasionally been made prior to observation of adults in a water body. For example, in Prince Rupert, BC, EGC larvae were detected in plankton tows in the harbor, but no evidence of juveniles or adults has turned up in trapping efforts to date (T. Therriault, pers. comm.). In California, EGC were collected in plankton tows in Morro Bay in 1996, the same year a single individual adult found trapped there. This site is nearly 250 km south of the current range limit (Elkhorn Slough), and EGC ultimately failed to become established at the site (E. Grosholz, pers. comm.). Several challenges likely make it difficult to scale such efforts, including the substantial technical expertise and equipment required to capture and identify EGC at these stages, and the lack of consensus on the optimal protocols for targeting them. In addition, because these life stages experience the highest mortality rates, the relationship between cohort strength at very early life phases and subsequent recruitment to the adult stage or sites of concern remains poorly characterized and possibly difficult to predict. Nevertheless, the development of new detection techniques that target early life stages would be very useful where early detection is a goal (see Goal 6). Managers could increase the scope of local trapping efforts at a site following new detections of larvae or postlarvae.

2.2.2. eDNA detection and qPCR. Among other very promising methods to detect new populations or populations at low abundance include environmental DNA (eDNA), which is rapidly becoming one of the most valuable new additions to the biodiversity monitoring toolkit (Deiner et al. 2020). Given the potential sensitivity and cost effectiveness of the method, it has been explored as a means of detecting invasive species, particularly when they are newly introduced or at the edges of an expanding invasion front. However, approaches are also being developed that would aim to use eDNA methods to estimate population densities, therefore offering the potential to support ongoing monitoring and management of existing invasions.

There is now new work aimed at reconciling observations from eDNA sampling and trapping efforts in terms of both early detection capabilities and population assessment (Crane et al. 2021, Keller et al. 2022). By conducting eDNA sampling (utilizing the previously published primers from Roux et al. 2020, Westfall et al. 2022) alongside existing trapping efforts, Keller et al. (2022) developed a model to compare detection probabilities across sampling regimes and calculate the sensitivity and specificity of the assay. This eDNA assay showed comparable sensitivity to traps in detecting populations of EGC at a moderate density. The model results also suggested that adding eDNA data to trapping observations generally increased the certainty around estimates of EGC presence and population density, but this gain was most valuable at sites with low population densities or where trapping observations were sparse. Together these findings offer a few guidelines for potential utility of this eDNA assay in the EGC surveillance toolkit. In particular, eDNA could be used somewhat interchangeably with trapping to support early detection efforts, and thus managers might choose the tool or sampling regime that is most practical and resource efficient for their context and management goals. Indeed, the Keller study also offered a cautionary case study in which EGC was detected at a site beyond the invasion front, at which no adults apparently subsequently successfully recruited into the site and the eDNA signal did not persist. Thus, the detection was interpreted as likely having come from larvae that did not ultimately establish a local population. Furthermore, low eDNA concentrations can make detection of EGCs difficult even when sampled in positive control traps containing EGC, likely because ECG shed low levels of DNA during much of their life cycle and, like many benthic crustaceans, may be difficult to detect using eDNA methods alone (Crane et al. 2021)

Objective 2.3. Understand scales of dispersal and predict sources of new invasions

2.3.1. Develop models to predict sources of future invasions. In recent years, oceanographic modeling approaches have shed light on geographic patterns and mechanisms for spread of European green crab in range expansions. In some regions, oceanographic predictors of EGC recruitment success have been identified through long-term correlative datasets (Behrens Yamada et al. 2010, 2015, 2021). Additional recent studies draw on increasingly powerful and highly resolved ocean models incorporating larval behavior into simulations that can provide probabilistic estimates for EGC larval dispersal patterns (e.g. Banas and Hickey 2005, Brasseale et al. 2019).

Although some of these tools are already separately in use, collectively integrating the information and models currently available could both validate and seed increasingly accurate predictive simulations for green crab larval dispersal patterns, both spatially and temporally. This has value not only in forecasting future range expansions and identifying high-risk sites, but also in resolving recurrent source-sink and metapopulation dynamics that could identify high-value target sites for control efforts. For instance, modeling by Banas and Hickey (2005) revealed that circulation patterns within Willapa Bay, WA could lead to longer retention times, and greater local recruitment rates, for larvae released within the southern portion of that estuary. Thus, removal of crabs in that area may have a disproportionate impact on overall population growth rates within the estuary as a whole. When and where EGCs release their larvae may also influence subsequent larval dispersal and could inform predictive models for future management efforts; top-ranked models for estimating ovigerous crab positions within an estuary retained several covariates including days to estimated hatch, water temperature, month, lunar illumination, and carapace width (Burke et al. *in prep*.).

By quantifying the influence of underlying oceanographic mechanisms, these can potentially also identify periods, seasons, or years associated with high spread or survival of larvae, supporting both local and regional management efforts. As an example, simulations by Brasseale et al. (2019) demonstrated the time sensitive influence of storm-driven current reversals in the Strait of Juan de Fuca in advecting larvae from dense coastal populations to hitherto uninvaded shorelines of the Salish Sea. Population genomics confirmed these modeled predictions that coastal sites (and not Sooke Basin) were the source of the initial EGC colonization of the Salish Sea in Washington (C. Tepolt *in prep*.).

Both observations and preliminary modeling have shown that temperature plays a key role in dispersal as well; simulated +0.5°C and +1°C increases in temperature substantially increase the window of potential dispersal into the Salish Sea from outside (J. Du and W. Zhang *in prep*.). Such projections can help better predict and plan for changing EGC spread and distribution in a warming ocean. Finally, modeling efforts have focused largely on the species' expansion into the Salish Sea and population increase in the outer coast of Washington, where the species' presence and abundance has been highly dynamic since 2016. However, the recent expansion of EGC into northern British Columbia and southeast Alaska suggests an important role for modeling in assisting with management plans in this region. The coastline and islands of this northern region are extensive, hydrodynamically complex, and frequently very difficult to access, complicating early detection. Careful modeling in this area could greatly enhance management by suggesting sites that are most likely to receive larvae and thus should be targeted for monitoring efforts.

2.3.2. Use population genomic tools to determine sources and dispersal. Population genomics, using recently developed high-throughput sequencing technologies, can shed light on sources of new introductions, and provide insights into the extent to which animals are traveling between regions. In EGC, traditional population genetic approaches have identified the sources of initial introductions to the east and west coasts, and identified the role of secondary introductions in the expansion of the species in the northwest Atlantic (Roman 2006, Darling et al. 2008).

On the west coast, the increased resolution of population genomics has demonstrated that dispersal is high across much of the coast, with larvae regularly traveling both north and south and suggesting that individual estuaries have substantial larval input from outside areas (Tepolt et al. 2022). However, when oceanographic transport into an embayment is limited, it can become bottlenecked and rapidly develop a distinctive genetic signature (Grosholz et al. 2021b, Tepolt et al. 2022). Such embayments include the artificial Seadrift Lagoon in central California, Sooke Basin in southeastern Vancouver Island, and others under active study (Tepolt et al. 2022, C. Tepolt *in prep*.). These isolated areas may need to be managed differently from more open populations (e.g. Grosholz et al. 2021b), and, if larvae are dispersing out (but not in) can act as "tracers" to empirically trace individual larvae back to a specific source. For example, larvae bearing Sooke Basin DNA are regularly found outside the Salish Sea in Washington and Oregon, confirming extensive southern dispersal (C. Tepolt *in prep*.).

Given the dynamic nature of recent EGC spread on the west coast, continued genomic monitoring in key areas can inform management in multiple ways. First, it can identify regions of restricted dispersal, for which more local management plans may be most appropriate. Second, it will help rapidly detect any new introductions of EGC from outside of the west coast, such as ongoing bait box traffic. Finally, understanding where larvae are actually going provides an empirical test of modeled predictions, allowing ground-truthing of models and improving the accuracy of future predictions.

Goal 3. Rapid Response to Coordinate Management Strategies and Actions for New Invasions

Rapid response, for the purposes of this plan, means expedited and coordinated management strategies and actions based on new EGC detections for the time-sensitive purpose of determining scope of EGC invasion and containing or eradicating EGC before it spreads or becomes further established. Based on the outcome of rapid response actions, subsequent management strategies and actions may be implemented. Rapid response strategies are often dependent on the type of invasion scenario.

Objective 3.1. Develop an effective Rapid Response strategy

Although rapid response is a reactive strategy, successful rapid responses are dependent on pre-planning and training. Pre-planning includes development of frameworks for local or regional rapid response strategy implementation, establishing agreements between jurisdictions for implementation, identifying funding sources and processes for accessing emergency funding sources, inventorying and stockpiling response equipment and supplies, and development of operational protocols. A rapid response action may include coordination with one or more jurisdictional or affected entities including local, state, and federal resource agencies, tribal organizations, aquaculture operations, recreational organizations, private landowners, etc. to coordinate response actions and facilitate access in areas where new invasions or new outbreaks are occurring. Decisions about how and where to allocate rapid response resources are a critical part of managing invasions. It is important that decisions involving public (or private) funds include the full range of concerned participants. The determination of rapid response strategies should include policy considerations of social, economic, ecological, and cultural factors, which are often specific to a geographic area within larger operations.

A key to maintaining a rapid response strategy is to establish reliable funding before a declaring a rapid response action that can be quickly available to support an expedited rollout of rapid response management actions. In some states, an expedited response can be supported through their governor or legislature declaring an emergency to release funding and assign authorities. Discussions of new federal funding are forthcoming and these funds would ensure RR actions for high priority regions and locations. Supporting this critical function is among the very highest priorities for this management plan.

Once a new EGC detection triggers a RR, data management becomes a critical resource need so that authorities have the most current and up to date information about EGC distribution to support management actions across the geographic area of response. The data hub established below in Goal 9 would both organize and disseminate the information on changes in EGC distribution and population status. Among the products developed with the coordinated data hub would be alerts regarding sightings of EGC at previously uninvaded sites, and populations undergoing dramatic increases and impacts to surrounding resources.

Objective 3.2. Coordinate with Existing Incident Command Systems (ICS)
Although not required in part or in whole, use of an Incident Command System (ICS) should be considered for effective coordination and communication in RR actions. ICS is a standardized but flexible approach to incident management that was developed by the U.S. Forest Service, and recommended by several federal agencies and the Aquatic Nuisance Species Task Force. ICS is a subcomponent of the National Incident Management System (NIMS) released by the U.S. Department of Homeland Security in 2004. We note that Washington has an emergency decree in place and chose an ICS structure to respond to emergencies outlined in their plan. All regional management efforts would need to actively coordinate with this ICS regarding any proposed management actions. Development of national and regional ICS Incident Management Teams that could jump-start or support an ICS process would be a valuable resource for successful RR implementation. Indeed, garnering understanding and support for ICS is critical to their effectiveness and maintaining public and partner trust if and when they need to be invoked.

Goal 4. Emergency Management to Coordinate Management Strategies and Actions for Rapidly Expanding Populations

Emergency management, for the purposes of this plan, means planned management strategies and actions including assessment, or control effort over a given geographic area that requires a significant increase of resources. It is similar to a rapid response trapping effort except not expedited as the result of a new detection. Similar to rapid response, implementation of an ICS can greatly enhance emergency management response.

It is critical to be able to undertake emergency management actions for EGC populations that suddenly increase in size or rapidly begin to spread beyond previously established boundaries. In these situations, emergency management actions should be considered extensions of rapid response for planning, resource allocation, and implementation actions. Examples of EGC population outbreaks include those in Washington and eastern Maine, where populations that have persisted for several years with modest sizes experienced high recruitment and a sudden increase in population density and associated impacts. In the case of Washington, the state government responded quickly with emergency funding to manage this established but now much more potentially damaging EGC population. Access to emergency funding is critical to successful management where EGC has recently invaded and where relatively high-density populations may become established.

Objective 4.1. Conduct emergency management strategies and actions for rapidly growing or spreading populations

For EGC populations that are undergoing a rapid increase in size and density, most likely from increased recruitment, there is an urgent need to be able to respond with timely actions. EGC populations that had previously been at low abundance with little impact on surrounding habitats can change quickly as the result of a larger recruitment pulse with much greater impacts on commercial fisheries or features of ecological or cultural importance.

In order to adequately assess the risk of EGC impacts at a given site and, hence, the priority of that location for management action, it is important to also survey assets that might be at risk from EGC. This would include eelgrass beds, sensitive native species, commercial shellfish, cultural elements, etc. It is important to develop a baseline of ecosystem or human assets to quantify changes in these in response to growing/spreading EGC populations (see Goal 5 below).

Rapid EGC population growth and attendant impacts can be potentially fueled by climate-driven increases in sea surface temperatures (SST) or other environmental drivers. Rapid population growth in response to increased SST has been documented in parts of the northeastern United States including eastern Maine with negative consequences for soft-shell clam fisheries (Welch 1968, Tan and Beal 2015, Bricknell et al. 2021). Historically, higher temperatures and other oceanographic predictors such as El Niño events have accompanied population increases in EGC along the coasts of Oregon and Washington (Behrens Yamada and Kosro 2010, Behrens Yamada et al. 2015, 2021). Similar processes may be drivers of recent rapid population growth along the west coast (Grosholz, unpubl. data, Yamada, unpubl. data, WA Sea Grant).

Goal 5. Containment and Control of Established Populations to Minimize Impacts

Decisions about what management actions to undertake for a given EGC population must be based on the data collected for early detection and monitoring outlined above. Just as EGC abundance differs by location, so too do the tools available for controlling the population. Also, the priorities of organizations and entities with jurisdiction over the area in question must necessarily be part of the consideration for which actions to undertake. Information on crab population status, the status of the resources at risk, EGC population thresholds and extent of the impacts are all necessary parts of determining the management actions needed.

Objective 5.1. Reduce populations to minimize impacts

The standard tool continues to be the use of extensive networks of baited traps to both characterize and reduce EGC populations (Duncombe and Therriault 2017, Ens et al. 2022). Results from recent studies from flow-restricted estuaries on the California coast suggest that even local eradication may be very difficult to achieve. Even if populations could be reduced to levels approaching local eradication, the risk of overcompensatory reproduction could undermine eradication efforts (Grosholz et al. 2021b). Overcompensatory reproduction in EGC can occur, especially in flow-restricted waterbodies, when the removal of adults via trapping results in reduced cannibalism of recruits. This reduced control of new recruits can result in a surge in recruitment and increased population size in the following year (Grosholz et al. 2021b).

Where eradication is infeasible, an alternative strategy to consider can be controlling or suppressing established populations below levels that result in environmental, economic, or cultural resource harm. To establish targets for suppression or 'functional eradication' at high priority sites where ecosystem resources are at risk, previously collected data can be used to establish the relationship between local EGC densities (based on CPUE) and the damage to habitat elements of concern such as shellfish, eelgrass, etc. (see Green and Grosholz 2021). Functional eradication may be equally effective as complete eradication at reducing ecological impacts of EGC. Where populations are regularly connected by oceanographic processes, maintaining population suppression over the long-term may be prohibitive (Ens et al. 2022). However, a high priority location, either because of considerable ecological, economic or cultural value, can encourage the involvement of local community and citizen scientists and volunteers to maintain the population suppression over time (Grosholz et al. 2021b). Because of the high cost to collect empirical data, the determination of control targets may ultimately be based on best professional judgment of scientists and policy considerations of social, economic, ecological, and cultural risk factors.

As noted above, catch-per-unit-effort (CPUE) is often one of the most used measures of EGC risk and management effort to estimate population sizes, as well as targets for suppression or functional eradication thresholds. However, CPUE is only a coarse proxy for relative abundance of EGC in a given location at a specific time, and is very sensitive to factors such as gear type, placement and arrangement, effort level (number of trap sets or check), season, depth, and soak characteristics such as duration, daylight and tide cycles, and trap checking routines. Therefore, where CPUE is used in management, it must be clearly qualified by these factors (see Appendix A for definitions). As a demonstration of the importance of this factor, CPUE might range from 2 to 6,000 CPUE depending on these variables for the same 300 EGC captured, and thus it would be difficult to compare EGC risk thresholds or evaluate success over time without CPUE being caveated accordingly. Currently, there is no standard for these metrics for consistency in risk or success communications and this should be explored.

Overcompensation is a risk for population management at high densities, particularly in flow-restricted waterbodies and where removal of adults is the only option and it is very hard to remove smaller size classes (Grosholz et al. 2021b). This is not likely a risk at sites with low to moderate densities. At these sites with low to moderate densities, continued trapping to maintain populations at low levels, as much as can be sustained, is a recommended approach. We also recommend developing a flexible management plan for high priority sites that includes identifying resources at risk, determining suppression targets (e.g., functional eradication, long-term control), assessing the capacity of local volunteers and community scientists, and considering the use of potential eradication for small, isolated populations.

Objective 5.2. Use of additional methods
Other methods continue to be considered for reducing population size of EGC. These have included the use of sex pheromones to attract and remove crabs (Hardege and Terschak 2011). Work to isolate selective and effective compounds is ongoing and has identified several chemicals that are related to changes in behavior of males (Fletcher et al. 2022). These researchers proposed that specific combination of nucleotides such as uridine diphosphate and uridine triphosphate has been proposed as a way to increase the species selectivity of chemical attractants and reduce bycatch. In order to be used as a management tool, identified chemicals would need to be supplemented with effective and scalable delivery systems such as stable time-release baits. Use of lethal chemical controls was considered in the past (Hanks 1961), but the absence of a candidate for targeted use with limited collateral damage means use of chemical pesticides would be unlikely to be permitted currently.

Biological control methods that have been used effectively in some terrestrial systems have not been used in a marine system to date (Lafferty and Kuris 1996). Parasites including rhizocephalan barnacles like *Sacculina carcini*, which infects and castrates EGC in their native range, have been considered as a possible control agent (Thresher et al. 2000, Kuris and Lafferty 1992). However, these have never been used outside of the laboratory, and could certainly pose a risk to native species, including commercially and culturally important species. Studies have shown that *S. carcini* can infect native west coast crabs including shore crabs and Dungeness crabs, and causes greater mortality rates in these species than in EGC, ruling it out as a feasible biological control agent in that region (Goddard et al. 2005). While a biological control agent is not immediately available, it is a potentially important tool and future research on this as an available option should be supported.

Goal 6. Eradication of New or Established Populations to Eliminate Impacts

Eradication, for the purposes of this plan, means the complete removal or destruction of all EGC at every life stage from a geographically defined area. The likelihood of eradication of new or established populations of EGC is extremely low, and not recommended as a goal unless the population is geographically isolated or can be physically isolated from adjacent water bodies to prevent repopulation by natural larval dispersal or human-mediated pathways. In these situations, eradication could be attempted, possibly in combination with other methods. It needs to emphasized that complete eradication of an invasive marine organisms has only been achieved under a handful of very specialized circumstances such as the black-striped mussel *Mytilus sallei* (Bax 1999), the abalone parasite *Terebrasabella heterouncinata* (Kuris and Culver 1999), and the green alga *Caulerpa taxifolia* (Williams and Grosholz 2008).

Goal 7. Research to Understand Invasion Risks and to Improve or Develop New Management Strategies

Research, for the purposes of this plan, means field, lab, or other scientific actions implemented to investigate an aspect of an EGC invasion and for activities that do not fall into standard protocols of any of the above management strategies. Types of research may include improving efficiency/efficacy of priority management actions, increasing biological knowledge, and predicting/assessing EGC or other impacts.

The goal of this section is to identify new areas for research that may improve various aspects of EGC management. These include methods of detecting populations earlier with greater accuracy, habitat models that will identify habitats at increased risk for EGC invasion and impacts, and genetic and oceanographic models to predict with greater certainty the sources and dispersal mechanisms responsible for new invasions as well as population responses to climate change.

Objective 7.1. Improve and expand detection methods

Among the most important areas for future research is the detection of EGC invasions at levels below that which currently exist with trapping. Being able to identify the very earliest life stages of EGC would be an important advance for determining the presence of newly invaded sites. While targeted eDNA detection of *C. maenas* by qPCR represents the current state of the science, it is important to note that eDNA methodology is a rapidly advancing field and future developments including eRNA methods may yield additional useful tools. Several possible applications may prove useful to end-users in the future and may even warrant present-day investment.

7.1.1. eDNA metabarcoding. Targeted DNA-based monitoring may enable sensitive detections of invasive species such as EGC, but broader assessments of biodiversity that also detect these target species may ultimately prove more cost effective. DNA metabarcoding enables characterization of entire biological communities, providing both general biodiversity assessments as well as identification of known and previously unrecognized introduced species. These approaches have recently been employed with some success in marine environments (Bowers et al. 2021), and several studies have shown that metabarcoding of eDNA is capable of detecting invasive species, potentially providing early warnings of new incursions (Borrell et al. 2017, Westfall et al. 2019, Pearman et al. 2020, Duarte et al. 2021). EGC detection could thus be one outcome of broader marine biodiversity monitoring efforts based on eDNA metabarcoding. Caution is required in interpreting data from such efforts, as limitations to reference databases and errors in bioinformatics workflows can result in false positive detections (Darling et al. 2020). However, given the wealth of genetic information available for EGC it represents a best-case scenario for possible detection *via* metabarcoding, assuming appropriate quality control measures. The availability of highly sensitive species-specific assays for EGC would also allow follow-up assessments, meaning that incidental detections of EGC in metabarcoding-based biodiversity surveys could serve as preliminary screenings and provide early warnings that could be confirmed with targeted methods.

7.1.2. Robotic and* in situ *detection. The rise of eDNA methods has generated much interest in the possibility of remote sampling and *in situ* molecular detection. Interestingly, one of the earliest applications of such methods for detection of a marine invasive species targeted EGC (Harvey et al. 2012). In the past several years, significant advances in robotic sampling technology have brought these tools much closer to end-users. For instance, the Environmental Sample Processor (ESP) is a complete DNA laboratory deployable in sub-surface waters and capable of conducting *in situ* sampling, filtration, extraction, and nucleic acids analysis including PCR. The device has been deployed as a stationary monitoring unit or coupled with autonomous underwater vehicles and has been used to conduct real-time detection of target taxa including fish, microbes, phytoplankton, and invertebrates (Yamahara et al. 2019, Hansen et al. 2020). Importantly, recent work shows that it is possible to develop devices with similar capabilities at costs (several hundred US dollars) that may make them attractive for many monitoring applications (Formel et al. 2021). These tools could provide significant cost savings, particularly when coupled with the capacity of eDNA to detect EGC at the very edges of expected invasion limits where trapping is inefficient.

7.1.3. Environmental RNA*.* The ability of eDNA to persist in the environment may enhance detection probability, but it also can complicate interpretation if positive eDNA detections become removed in space or time from the actual presence of the target organism. The relative lability of environmental RNA (eRNA), in contrast, suggests that it may be a promising tool for more accurately reflecting the living portion of biological communities (Giroux et al. 2022). In addition, the association of RNA with active transcription means that eRNA signals could reflect aspects of biological communities (e.g., life-history stage, sex, metabolic function) not accessible using eDNA (Yates et al. 2021). Although work with eRNA introduces additional technical challenges, research has already shown that eRNA-based methods can provide more accurate assessments of living biotic communities than eDNA alone (Miyata et al. 2021, Greco et al. 2022), and may provide increased resolution for targeted invasive species monitoring (von Ammon et al. 2019). Future exploration of eRNA approaches may enhance EGC detection, enabling more accurate assessments of abundance and distribution or providing valuable additional information regarding population structure.

7.1.4. Effective early life stage collectors. A critical part of developing effective tools for monitoring and ED includes better methods for collecting early life stages of EGC. Environmental DNA and future eRNA don't necessarily require capture of individual larvae, since DNA can be recovered from sediments, water samples, etc. However, additional verification of EGC presence is still required to avoid false positives, so the importance of being able to track early instar larvae remains. Work to date suggests that light traps, although effective for cancrid and porcellanid crabs, are not as effective for EGC. Fibrous collectors for megalopae and early instar juveniles that have been used for other crabs have also not been shown to be particularly effective for EGC. Thus, there is a real need to develop better ways to collect these early life stages more efficiently.

Objective 7.2. Improve models for predicting risk of future invasions

New research is needed to examine the match between the physical bounds of habitats currently beyond the EGC distribution and the physiological limits of sensitive developmental stages. The goal of this work would be to determine which locations or regions are currently most likely at risk of new invasions or may become so in the future under climate change predictions.

7.2.1. Predicting recruitment and spread. Establishment of EGC beyond its current range boundaries and habitats is restricted by a range of environmental drivers, which are expected to change with climate. For example, unfavorable current flows may create hydrogeographic barriers to dispersal (Burden et al. 2014, Behrens Yamada et al. 2021). On the west coast, strong recruitment and extensive larval dispersal have accompanied strong El Niño years with warm sea surface temperatures, strong northward flow of coastal waters, and coastal circulation that maintains dispersing larvae near shore (Behrens Yamada et al. 2021). Long-term recruitment data from California has shown years of higher EGC recruitment associated with warmer El Niño conditions in contrast with cooler La Niña conditions (Grosholz et al., unpublished data). In the northeastern U.S., similar results show that surges in EGC populations have been associated with warming trends in the Gulf of Maine (Tan and Beal 2015, Beal et al. 2016). Thus, there is a real need for models that can mechanistically predict years of high EGC populations based on oceanographic parameters.

Using interannual variability in the El Niño-Southern Oscillation (ENSO) cycle and related oceanographic and atmospheric processes could be used to potentially predict either 'boom' or 'bust' years for EGC populations. Future projections are divergent in that general circulation models (GCMs) include warming sea surface temperature (SST), while other models examining increasing temperature differences between land and ocean indicate a future of stronger upwelling winds along eastern boundary regions like the United States west coast (Bakun et al. 2015). Locally increased upwelling and lower water temperatures could negatively affect EGC recruitment and dispersal. Other studies have shown strong winds can have more local effects and reversal of currents which can transport EGC larvae to new places, potentially leading to establishment (Brasseale et al. 2019). In short, there is a critical need to be able to use variability in oceanographic and atmospheric processes to predict recruitment and spread of EGC.

7.2.2. Habitat suitability modeling. Given that we know a considerable amount about the physiological limitations of larval and juvenile EGC, which are likely the limiting stages of future spread, there is a real opportunity to use habitat suitability modeling to help identify bays/estuaries that are most likely to be new sites of invasion (e.g., elsewhere in southeast AK). This approach would allow more focused EDRR efforts on bay/estuaries that would be high priority locations for new invasions. The results would involve development of habitat suitability models (=species distribution models) that would predict the suitability (=susceptibility) of sites as likely locations of new invasions. These could also be linked to better oceanographic models (e.g. Regional Ocean Modeling System [ROMS]) that might identify conditions under which EGC larvae would be most likely to be transported to new locations at risk for invasion (see Oceanographic Modelling above). These models should also reconsider previous views that EGC is limited to soft sediment habitats, given that EGC have recently been found on rocky shores from Oregon, Washington and British Columbia.

New methods for assessing habitat suitability have been examined in which multiple model approaches are used to develop an ensemble model that can better predict sites that are most likely for future invasion (Howard et al. 2022). This ensemble approach, which can combine approaches such as MaxEnt, Boosted Regression Trees, Logistic Regression and other tools together with multiple data sources, has been useful in areas beyond the AIS realm. Combining models provides more robust predictions than any single model, particularly in situations where habitat data are limited or where current EGC distributions are incomplete. Data derived from different aspects of a species' biology increases the probability that suitable conditions (either environmental or habitat) are considered when making predictions for newly invaded areas, such as Canadian waters of the Salish Sea for EGC.

Objective 7.3. Develop new genetic and genomic tools for management

***7.3.1. Gene drives and genetic controls*.** While research is currently underway on genetically engineering population controls for invasive species, these approaches are still highly experimental and very little of this work has advanced to even small field trials in any system (Wedell et al. 2019), and none for EGC. Gene drives make use of the CRISPR-Cas9 approach to selectively cut a specific region of the genome and insert additional genetic material (Bier 2022). These new inserted genetic regions are genetically engineered so that they are passed down to all offspring, rather than the approximately 50% seen in typical Mendelian inheritance, meaning that they spread throughout a population much more quickly than a natural mutation (Bier 2022). In theory, gene drives can be designed to interfere with many aspects of a species' biology. In practice, most research in invasion is focused on gene drives to manipulate sex ratios (e.g., to ensure that all offspring are male or that all females are sterile).

Beyond the considerable technical hurdles that remain, using gene drives and related approaches for invasion management raise a number of unresolved ethical concerns (Oye et al. 2014, Webber et al. 2015, Esvelt and Gemmell 2017). Perhaps the most pressing of these have to do with the possibility that the genetically engineered DNA will make its way into non-target species or populations through either hybridization (with other species) or introgression (with native-range populations) (Weddell et al. 2019). The consequences of "escaped" gene drives are poorly understood, but potentially catastrophic. In addition, to date research into gene drives is largely focused on terrestrial species, primarily mosquitoes and rodents. EGC and similar marine species with extensive larval dispersal likely pose additional complications for designing an appropriate gene drive and effectively limiting its spread. Genetically engineered biocontrol agents also face significant issues with public support in the United States and globally.

7.3.2. Develop a high-quality chromosome-scale reference genome. Genomic tools are revolutionizing both our understanding of invasions, and how to control them, but their application has often lagged in non-model invasive species (Matheson and McGaughran 2022). In EGC, this work is hampered by the lack of a high quality, chromosome-scale reference genome. While inroads have been made on understanding how EGC adapts to new environments using genome-free approaches, many emerging tools and approaches require a genome. This lack is particularly glaring for EGC because of the likelihood that an inversion polymorphism plays a key role in rapid thermal adaptation in the species (Tepolt and Palumbi 2020, Tepolt et al. 2022). While the presence of an inversion has been inferred through other data, it requires a high-quality genome assembly to confirm and to fully understand the genes involved in this important adaptive mechanism. In addition, gene drives and other genetically engineered population controls involving genomic editing require a detailed understanding of genomic structure and function (Moro et al. 2018). While these approaches are still highly experimental (see Gene Drives & Genetic Controls text), the field is advancing rapidly and a high-quality genome is a prerequisite for research into the feasibility of genetic controls in EGC.

7.3.3. Understand the functional importance of genetic variation. Another key prerequisite to exploiting gene drives and other genetically based control efforts is to understand which regions of the genome underlie functional variation in EGC. Many genetic interventions target reproduction, and currently the sex chromosomes of EGC (and, indeed, their sex determination system) remain unknown (Chandler et al. 2018). In addition to facilitating potential future genetic interventions, identifying functional variation can help to predict the species' spread and response to future conditions based on the genetic makeup of individual populations (Hendry et al. 2011). For example, a genetic region has been identified in EGC that correlates strongly with temperature and thermal tolerance at a population level (Tepolt et al. 2022). While the full extent of this region is unknown without a reference genome, it appears to include functional variation in a gene that acts as a "master regulator" for hypoxia tolerance (Tepolt and Palumbi 2020). This suggests a potential mechanism by which populations tolerate thermal extremes, which are strongly linked to hypoxia in crustaceans (Giomi and Pörtner 2013), and a potential predictor for tolerance in new regions. Identifying the genetic regions underlying response to a range of stressors or potential control agents, aided by a reference genome, could help suggest and inform targeted management interventions, including gene drives, in the future (Moro et al. 2018).

Objective 7.4. Develop a better understanding of ecological interactions

Understanding current and future impacts of EGC on native species and other aspects of marine and estuarine food webs is key to predicting future impacts particularly in a changing climate. Invasion into new regions with different sets of native species and ecosystem attributes may result in different types and degrees of impacts as the result of EGC predation and habitat disturbance. Studies from the northeastern U.S. have documented a broad range of impacts of EGC that go well beyond simple impacts for predation including behavioral and morphological changes in native species (Trussell et al. 2003, Whitlow et al. 2003). Diverse indirect effects of EGC predation including increased abundances of other invaders in the system have been shown for EGC on the west coast (Grosholz et al. 2005). Thus, the impacts of EGC on native ecosystems can be diverse and not always easily quantified with basic monitoring schemes. It will be important for managers and researchers to work collaboratively to determine the extent of EGC impacts in any given area.

Objective 7.5. Develop more efficient capture-based removal tools

Despite the fact that baited traps have been the primary capture and removal tool for EGC across the globe, relatively little research has been put into improving capture efficiency across the range of trap types utilized in research and management. Yet for large scale and long-term control efforts, small gains in trapping efficiency could translate to substantial increases in management efficacy. Thus, this remains a profitable, and accessible, avenue for research.

In the United States, the majority of research efforts use either or a combination of cylindrical galvanized steel minnow traps (e.g. Gee-40) and the folding square Fukui fish trap. However, very little effort has been directed toward rigorous comparison of different gear types and modifications that contextualize the documented capture efficiency of Fukui traps. In Washington, management groups conducting population suppression have adopted alternative traps, including several called “shrimp traps” (e.g. Pro-Mar Heavy Duty Box/Shrimp Pot) which early modeling studies suggest may be up to an order of magnitude greater in capture efficiency than either minnow or Fukui traps. Other trap types are used on the east coast, and may also warrant consideration for their capture efficiency as well as personnel efficiency across deployment contexts such as boat versus shore based trapping. The efficacy of different trapping gear will vary across ecological and institutional contexts, depending on logistics, costs, staff and financial resources, as well as potential bycatch. No single tool will work well in all situations. Therefore, understanding how different gear systems will accomplish specific management goals would provide an improved tool kit for managers.

Goal 8. Economic Analysis to Quantify Tradeoffs Among Management Strategies

Here the primary aim is to understand the costs and benefits of conducting different management activities in order to make more cost-effective management decisions. Funding will always be inadequate for most management situations, so it will be important to determine how and whether to invest resources in strategies such as prevention or intensive early detection of early life stages vs. longer term strategies like control and suppression. The goal here is to apply known economic tools at different scales relevant to the current and ongoing spread of EGC. Economics helps evaluate EGC management alternatives to achieve a goal set by stewards at any scale (tribal, state, national, etc.) cost effectively. The EGC management goal can be defined biologically or in other ways for a recognized threshold to achieve. Any management option to achieve that goal can be compared by costs in order to allocate resources effectively to address EGC. Economics helps with characterizing and quantifying different cost categories related to these management options.

The Introduction to this report briefly refers to well-documented economic and ecological damages from EGC. These studies are initial and partial with more valuation and quantification needed across various realms of impacts not included in the earlier efforts that also relate to management choices. For example, Lafferty and Kuris (1996) quantify the commercial value of mussels, oysters, Dungeness crab, and rock crab that are potentially at risk in the western U.S. Other studies have also quantified the actual losses due to green crabs on commercially valuable shellfisheries (Grosholz et al. 2011). However, there are many other values both commercial and nonmarket that are at risk from EGC impacts. For example, wider economic effects that depend on healthy ecosystems include health, aesthetics, cultural heritage resources, lost time and recreational activities are included in economic analysis. Both direct and indirect costs could be included in an economic analysis and impact assessment, including but not limited to management costs (mechanical, chemical, and biological), research and monitoring programs, reduced yield(s), job losses, damage to infrastructure, ecological damage, and impacts to international trade and tariffs. The economic and social impacts of invasive species include both direct effects of a species on a variety of factors including ecosystem services (i.e. reduced resiliency to climate change), reduced biodiversity, property values, resource productivity, public utility operations, native fisheries, tourism, and outdoor recreation, as well as costs associated with invasive species control efforts.

Objective 8.1. Conduct an economic analysis of management strategies

Models that can quantitatively examine the current and future costs and benefits of different management options, including their timing and extent, should be employed to assist management decisions. This work would involve investigating the specific costs and benefits for investing in containing or suppressing current invasions as well as investing in early detection, vector management and other preventative management actions including enlisting public vigilance. A prior example that involves quantifying public values for managing vectors of invasion including ballast water is by Nunes and van den Bergh (2004), using travel cost and contingent valuation methods in the Netherlands addressing reduction strategies in major Dutch ports. Potential economic analysis for EGC in North America should also consider investments in managing invasion pathways intended to prevent future introductions relative to the management of populations once established. This would necessarily include: 1) quantifying economic damage using economic methodologies, 2) examining efficient measures of international trade that would allow prevention or delay of further introductions, 3) up-to-date bio-economic modeling which integrates economic and biological factors to facilitate decision-makers' abilities to more cost-effectively reduce impacts, and 4) investment in information provision to the general public as well as private sectors to help invasive species management.

Assessing the present and future economic impacts of EGC will require considerably more input from resource economists than is currently focused on the topic at present. Among the challenges facing managers, is quantifying the economic damage from EGC using real economic methodologies with ample resources to carry them out. Some current estimates that rely on the limited InvaCost database (Diagne et al. 2020) do not use traditional economic methods and are dominated by engineering estimates of crayfish, zebra mussel and *Caulerpa taxifolia* with questionable transfer of values from one time period and location to others. These estimates are best undertaken with the more accurate methods to estimate these costs, as reviewed in Economics of Invasive Species by Eiswerth et al. (2018). Some studies have generally described economic impacts of aquatic invasive species (Lovell et al. 2006), and others have focused on the economic costs of invasive aquatic crustaceans in particular (Kouba et al. 2022). Other studies help to address the costs and risks of national and international trade that may need to be the focus of intervention (Epanchin-Neill et al. 2021).

Goal 9. Outreach Education to Explain Management Strategies

The aim of this goal is to ensure that information regarding the management of EGC will be made available to the many entities involved with, or affected by, EGC and associated management activities. In addition to the need for information about EGC spread and impacts, there is an emerging need to educate and train volunteers and community scientists who will provide much of the capacity for green crab management in most locations.

Objective 9.1. Develop audience-specific messages

These messages should broadly address the status of the problem and identify the high priority areas, the need for public participation in those high priority areas, and the importance of coordination among groups. To date, outreach and education efforts regarding EGC have been piecemeal across most regions. Exceptions include recent efforts by WA Sea Grant in their establishment of Crab Team, a program that provides training and education for volunteers and partners who join an early detection and monitoring network for EGC across all state shorelines. (https://wsg.washington.edu/crabteam/about/). Other examples include the work of New Hampshire Sea Grant, which has a similar EGC project (https://seagrant.unh.edu/our-work/invasive-species/nh-green-crab-project). Finally, the U.S. Fish and Wildlife Service has also been using community volunteers in its work (https://www.fws.gov/species/green-crab-carcinus-maenas).

There is a need for education and outreach to a broad range of stakeholders including fishers, shellfish growers, Tribal community members, and segments of the public involved with coastal recreation or related activities. Not only should these various interest groups be made increasingly aware of the progress of the green crab invasion, but information must be distributed to these groups to educate them about existing problems surrounding EGC and other ANS and provide information on what to look for in predicted high recruitment years. Solicitations to become involved with volunteer monitoring programs such as that in WA should also be made concurrently with education mailings to try to expand the successful results of existing volunteer programs.

There has been increasing awareness of the risk posed by invasive species, including EGC, on the part of many in the aquaculture industry, including shellfish growers, and now the risk of introducing unwanted invaders through aquaculture activities has decreased dramatically (William et al. 2013). Methods for shipping commercial oysters, which historically had been a significant vector of 'hitchhiking' invaders, have changed substantially and now involve shipping larval oysters with little risk of associated invasions.

There is still an outstanding need to communicate targeted messages to live seafood and bait retailers, who may either have green crabs for sale, and who may not provide information to their customers about the risks of moving EGC to other areas. There is also a need to communicate to live bait dealers (see Goal 1), particularly west coast dealers who sell bait worms packaged in the northeast (often Maine) and shipped overnight to the west coast with dozens of taxa (Blakeslee et al. 2016).

Objective 9.2. Engage and educate community scientists and volunteers

There will never be enough trained professionals to undertake the monitoring and management tasks outlined in this plan. The increased partnership with community/citizen scientists and volunteer groups will be essential for providing the needed capacity now and in the future, and among the most important education goals is the training of these legions of diverse volunteers. These partners can contribute not only time and significant expertise to green crab management efforts at all stages of the invasion, but also generate local political capital in their communities critical to sustainability of management programs. Through access to private property and personal connections with neighbors, individuals engaged in green crab management through early detection, monitoring, and control can dramatically expand the scope, efficacy, and long-term survival of effort at any geographic scale. It is important to caution, however, that including non-staff participants in management is not free. Substantial effort must be put into recruiting, training, and maintaining engagement with participants in order for community-based programs to be cost effective, scalable, and durable. Coordination of such distributed efforts is necessary to ensure that they continue to be effective and avoid confusion.

Several regions have engaged community/citizen scientists and local volunteers in their management efforts, typically through monitoring networks or control efforts. On the west coast, one example is the Washington Sea Grant Crab Team, which has made extensive use of community and citizen volunteers and scientists in their monitoring and removal network. This provides a superb opportunity to engage and educate members of the public concerned enough to volunteer their time and resources to assist with EGC management. The process of training community scientists and volunteers allows for conversations about the impacts of EGC, pathways of dispersal and ways to help avoid further spread, and broader conversations about other invasive species.

Community scientists and volunteers have been part of management efforts in other regions as well. EGC management programs in California have used community and citizen scientists and volunteers in efforts to remove EGC from local estuaries. In addition to educating and training volunteers and community scientists in the monitoring and data collection process, the capacity that these scientists and volunteers have brought to the program has also provided a basis for future long-term management (Grosholz et al. 2021a). Alaska also has a developing community/citizen science program as does U.S. Fish and Wildlife Service among other groups.

There are well-developed community-based programs monitoring EGC in the northeast U.S., some involving student groups. Maine has monitoring programs both statewide and locally that have made use of groups like this. However, among the greatest needs is the training of the networks of participants. New Hampshire Sea Grant's Great Green Crab Hunt is an example of a community science initiative that trains volunteers to identify and remove green crabs from the shoreline. The Gulf of Maine Research Institute leads the Ecosystem Investigation Network, which includes a module on invasive intertidal crabs and provides training to educators and students.

Careful consideration is needed to target the activities and goals of any particular program to the audiences engaged, and the management goals that are served. Transparent and honest communication with participants about realistic goals and outcomes of the program and of management efforts is also incumbent on programs that work with volunteers and needed to maintain trust that results in long-term participation. Nevertheless, the benefits of engaging community members in research and management extend far beyond the data collected and green crabs removed and are a valuable component of any plan.

Objective 9.3. Measure success of the targeted information

Although often expensive and effort intensive, it is important to evaluate, where possible, the success of public information campaigns. These can be conducted more easily via remote methods, which can significantly reduce the cost and personnel overhead. Survey tools such as Qualtrics, SurveyMonkey and others can be used to develop profiles for focused user groups before vs. after engagement with an information campaign. Identifying the particular user group to whom educational materials would be targeted is key to successful evaluation as is identifying similar control groups who would not be provided with the same information. Conducting a pre-survey of members of the target group is helpful to test the interpretability of the questions and to correct any misinterpretations or confusions. Collaboration with social scientists and others familiar with conducting surveys and the use of appropriate language, survey ethics, and metrics for evaluation is also recommended.

Goal 10. Data Management for Effective Coordination and Distribution

The overwhelming priority for green crab management at all levels is the development of a single data hub where data from all United States and Canadian locations can be organized and curated with the goal of providing data products to a range of managers and other end users. Considerable work will be required to develop data standards for all contributors, ensure appropriate quality control/assurance for submitted data, develop agreements regarding data storage formats, curating/archiving, etc. Input planning will also need to consider the data products to be distributed to a range of end user groups including managers, scientists, Tribal communities, shellfish growers, and others with varying data needs. Data management plans and data sharing agreements may be necessary.

Objective 10.1. Expand and integrate existing data networks

Currently there are several databases large and small that hold green crab data from monitoring programs at various scales. These include regional databases for the west coast and the Salish Sea region, statewide databases in Alaska and Washington and more local databases managed by single agencies or Tribal groups.

Our current recommendation is for an EGC data hub to be housed and curated by the Pacific States Marine Fisheries Commission (PSMFC). The PSMFC is currently managing EGC trapping data only from sources along the west coast region. Their data management has included distributing a data structure that participants have populated with their trapping data from multiple locations over multiple years. Presumably, the PSMFC data structure could be adapted to accommodate a range of regional data collection protocols, frequencies, etc. from a wide array of data sets from west coast partners. This database would ideally be structured to allow filtering and analysis of data on local, state, and regional scales, but also permit analysis at coast-wide scales. This proposed data hub would require new funding to allow PSFMC to develop the capacity to provide this function for all the participating entities on both East and West Coasts. We regard this as among the very highest priorities for funding.

For regions where EGC is expanding its range, among the highest priorities is a mechanism by which early detection of new invasions of EGC could be quickly integrated into the database and quickly communicated to the broader network via the USGS EDRR platform (see Objective 10.2 below). This will require a publicly accessible platform that would also permit rapid validation of any new records of EGC beyond the current range. The verification stage would be overseen by the Smithsonian Environmental Research Center (SERC) who have an extensive record of successfully documenting new AIS records for marine and estuarine species in North America. Their NEMESIS database is the most current and up to date database for new records and current distribution information and they have the expertise to document new EGC. Once the new EGC information regarding detection of a new EGC invasion has been verified, the data would be then included in the PSMFC database.

Regarding whom would be willing to participate, participation would be completely voluntary and that some entities may not be comfortable sharing data. Issues of data sovereignty are an important consideration particularly for Tribal institutions and would need to be agreed upon prior to any data sharing activities. Every effort would be made to ensure that the circumstances by which data are included are clearly acknowledged. Concerns about how the data could be shared and used by others, potential need to anonymize specific collection site information, and authority regarding the announcements of new invasion reports would be clearly addressed prior to data sharing.

Among the variables that continually plague efforts to standardize existing monitoring networks is the expanding use of different trap types in order to find the most effective model. Of course, this is a high priority particularly for trapping programs aimed at reducing EGC populations and their impacts as quickly as possible. However, there is now a long time series of EGC monitoring data extending back almost 30 years that has used a relatively standardized method and allowed comparison of catch per unit effort (CPUE) across many sites and many years. We encourage those aiming to develop a better trap type to continue periodic deployment of both old and new traps to allow calibration of any new trap types.

Objective 10.2. Develop tools for rapid data distribution

Among the most pressing needs is for real time or near real time data on EGC distributions, particularly in areas where they are expanding their range. Data on population status is also important in areas where EGC have long been established, but where changes in population status (e.g. rapid population growth) are necessary for management decisions including decisions that are based on population thresholds. Thus, the data hub (outlined in Objective

10.1) would need to provide this information in different forms depending on the needs of the managers and end users.

For regions where EGC is continuing to expand its distribution, amongst the highest priorities is the need for rapid communication of newly detected EGC populations in areas beyond their current distribution. The U.S. Geological Survey (USGS) is currently developing a centralized web-based network known as the National Early Detection Rapid Response (EDRR) Information System that would include providing 'alerts' to networks of end users for all AIS. This National EDRR Information System would not serve as the recipient of all the monitoring data, but would be able to serve as the conduit for communicating current EGC distribution as well as any updates or changes in the distribution. Among the important functions that would be available with the USGS National EDRR Information System is a timely alert function that would communicate verified information regarding any range expansion of EGC including any records and or newly established populations. This may also include mapping functions, information about the numbers and life stages detected, and other key information needed by managers to determine next steps. Although this emerging USGS EDRR platform will be one that is comprehensive for all AIS, USGS staff have committed to making EGC one of the target species for which data products specific to the needs of EGC management can be made available.

For all populations, we recommend that various data products be made available to end users including monthly updates of EGC populations beginning with high priority locations. These can be important at all locations including those where EGC has been established for considerable periods of time and where decisions regarding management options may be threshold dependent. This information could include observations such as a particular population that has dramatically increased in density or extent and where additional management intervention may be needed.

Objective 10.3. Develop a database listing groups participating in monitoring/management

In many regions, particularly those where EGC have been established for a long time such as the northeast U.S., there are a number of large and small groups undertaking EGC monitoring and management actions. Often these groups are unaware of other organizations in the region involved in similar activities. Therefore, in addition to developing a data hub for input of monitoring data of various kinds, we recommend developing a separate data directory that includes the names, principal actors, and management activities for these groups. This directory could also serve to orient national management entities without close ties to local or regional efforts that want to learn who is part of on-the-ground efforts, and who would be beneficial to include in consultations and decision making. This tool would aim to accelerate dissemination of information and communication across groups working in a shared geography, and reduce duplication of efforts.

Goal 11. Adaptive Management to Evaluate and Modify Plan Implementation

Objective 11.1. Institute an EGC Implementation Team to facilitate plan implementation

We strongly recommend that the ANSTF appoint an EGC Implementation Team to meet at least biannually to address coordination and implementation challenges presented by the plan activities, including prioritizing and filling data gaps as they emerge. The EGC Implementation Team membership would consist of scientists, state and federal resource managers, tribal governments, shellfish farmers and related commercial interests, education specialists, and others and would include an invitation to the Department of Fisheries and Oceans Canada and Canadian First Nations. Among the top priorities for the EGC Implementation Team would be working with database experts to address hurdles confronting managing the numerous different data sources and formats to coordinate and implement a data hub. We recommend ongoing discussions with many regional participants about the needs for data input and data products. The EGC Implementation Team would also provide strategic leadership for efforts to secure new funding for high priority activities ranging from direct management actions to new research directions. Finally, the EGC Implementation Team would also be responsible for evaluating and updating management plan implementation and would work towards future modification of the strategies and objectives of this Plan.

SELECTION OF APPROPRIATE GOALS FOR MANAGING EUROPEAN GREEN CRABS

Implementation of EGC management plan goals does not require sequential application. Selection of which goal or goals to apply is based on where you are on the invasion curve and multiple other factors such as authorities, funding, and management priorities.

1. Determine type of management goal(s) for proposed implementation.

Types of management goals include prevention, early detection, rapid response, emergency management, containment or control, eradication, and research. Table 1 provides the general purpose and time commitment for each management goal.

Table 1. Summary of management goals, goal purpose, and general time commitment.

Management Goal	General Purpose	General Time Commitment
Prevention	Stop the invasion or spread within a geographic area	Long-term
Early Detection	Identify early stages of invasion or spread within a geographic area	Long-term
Rapid Response	Reactive coordinated response to detection of a new population within a geographic area	Short-term

Emergency Management	Planned coordinated response to a rapidly growing or spreading population within a geographic area	Mid-term
Contain or Control	Limit range of or suppress established populations to mitigate impacts within a geographic area	Long-term
Eradication	Remove or eliminate a specific population within a geographic area	Mid- to Long-term
Research	Multiple purposes	Long-Term

2. Assess likely challenges for management goal implementation including jurisdiction, authority, priority, preparedness, resources, capacity, and complexity factors.

Jurisdiction

- Determine the jurisdictional scope of your governmental agency, service, or tribe to implement the management type action in the proposed geographic area.
- Determine the jurisdictional scope of other governmental agencies, services, or tribes if management type actions are to be implemented in a coordinated response.

Authority

- Determine if your governmental agency, service, or tribe has the authority to implement the management type action in the proposed geographic area.
- Determine what authorities are available if management type actions are to be implemented in a coordinated response.
- Determine timeline needed for receiving additional authorities before the management type action can be implemented

Priority

- Determine priority level to implement the management type action internally within your governmental agency, service, or tribe. This can include likelihood of success, managerial support, etc.
- Determine priority level externally, with partners if management type actions are to be implemented in a coordinated response.
- Determine timeline for receiving additional resources before the management type action can be implemented.

Preparedness

- Determine level of preparedness to implement the management type action internally within your governmental agency, service, or tribe.
- Determine level of preparedness externally, with partners if management type actions are to be implemented in a coordinated response.
- Determine timeline needed for preparations before the management type action can be implemented.

Resources

- Determine current internal resources (equipment and supplies) available to implement the management type action
- Determine current external resources available through partners and others if management type actions are to be implemented in a coordinated response.
- Determine timeline for receiving additional resources before the management type action can be implemented.

Capacity

- Determine current internal capacity (personnel and funding) available to implement the management type action.
- Determine current external capacity available from partners and others if management type actions are to be implemented in a coordinated response.
- Determine timeline for receiving additional capacity before the management type action can be implemented.

Complexity

- Scope of management type action to be implemented (simple to very ambitious).
- Size or number of geographic areas by management type response (small embayment to statewide).
- Number of management type actions to be implemented by geographic area.
- Lack in one or more factors above for determining management type.

3. Identify an existing or develop a new management strategy or action plan based on your selected goal(s).

4. Determine a management structure based on the selected goal(s) and assemble personnel and resources to implement.

SUMMARY AND CONCLUSIONS

We view the goals and recommended actions in this plan as a guide to address a wide range of management priorities that include prevention, monitoring and detection, rapid response, containment and control, future research, economic analysis, education and outreach and data management. Each state and region will likely prioritize these actions differently by identifying the locations and resources that are most at risk and connecting the partners, securing the funds, and engaging in the management strategies that best address those priorities.

The level of concern about EGC impacts varies considerably among states and regions. EGC has been in the northeastern U.S. for well over 200 years and its density and impacts are still expanding at the northeastern end of its range in the United States. However, EGC is viewed as more of a harvestable resource than as an ecological threat through much of the northeastern U.S. range. Levels of concern and associated management focus also varies considerably on the west coast. EGC is loosely regulated and is available for sale in live markets in southern CA, however it is viewed as highly threatening in WA and AK and is a prohibited species in WA.

To manage the continuing expansion and impacts of the EGC, we advocate a unified but adaptive approach that will take advantage of the lessons learned and progress made to reduce the impacts of EGC on ecosystem resources and human cultures. The recommendations we present in this management plan illustrate the need for informed decision making by integrating members of multiple jurisdictions into a cohesive regional information network. This network will help to mitigate the spread and impact of EGC in priority areas where particular management strategies are feasible and effective.

To accomplish the goals of this plan, we recommend that the ANSTF establishes an EGC Implementation Team consisting of members of local, state and federal agencies, Tribal communities, universities, NGOs, shellfish growers, and other relevant stakeholders. The EGC Implementation Team would meet to evaluate progress towards achieving the goals of the EGC Management Plan using the best available science and the best use of resources.

The purpose of this plan is to provide guidance for efforts to prevent future introductions, to rapidly detect and respond to new invasions of EGC before they become established and create ecological and economic damage, to manage current populations that pose an undue threat to resources of importance for ecosystems and local cultures, and reduce the impacts in areas where EGC are already established. This plan aims to serve as the baseline for the development and implementation of, as well as the integration with, regional plans such as the Salish Sea Transboundary Action Plan for Invasive European Green Crab and the Alaska Action Plan for Invasive European Green Crab.

REFERENCES

Ameyaw-Akumfi, C. and E. Naylor. 1987. Spontaneous and induced components of salinity preference behaviour in Carcinus maenas. Mar. Ecol. Progr. Ser. 37:153-158.

Anger, K., Spivak, E., Luppi, T. 1998. Effects of reduced salinities on development and bioenergetics of early larval shore crab, *Carcinus maenas*. Journal of Experimental Marine Biology and Ecology 220:287–304.

Audet, D., Davis, D.S., Miron, G., Moriyasu, M., Benhalima, K., Campbell, R. 2003. Geographical expansion of a nonindigenous crab, *Carcinus maenas* (L.), along the Nova Scotian shore into the southeastern Gulf of St. Lawrence, Canada. J Shellfish Res. 22:255–262.

Azzurro, E., T. Bahri, J. Valbo-Jørgensen, M. Xuechan, P. Strafella and M. Vasconcelos. 2023. Fisheries management responses to aquatic invasive species (AIS) in the context of climate change. Food and Agricultural Organization (FAO) Technical Paper (in prep.).

Baeta, A., H.N. Cabral, J.M. Neto, J.C. Marques, and M.A. Pardal. 2005. Biology, population dynamics and secondary production of the green crab *Carcinus maenas* (L.) in a temperate estuary. Est. Coast. Shlf. Sci. 65:43-52.

Bagley, M.J. and J.B. Geller. 2001. Microsatellite DNA analysis of native and invading populations of European green crabs. In: Marine Bioinvasions: Proceedings of the First National Conference (ed. by J. Pederson), pp. 241–243. Massachusetts Institute of Technology, MIT Sea Grant College Program, MITSG 00-2, Cambridge, MA.

Bakun, A., B.A. Black, S.J. Bograd, M. García-Reyes, A.J. Miller, R.R. Rykaczewski, and W.J. Sydeman. 2015. Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems Curr. Clim. Change Rep. 1:85–93.

Banas, N.S. and B.M. Hickey. 2005. Mapping exchange and residence time in a model of Willapa Bay, Washington, a branching, macrotidal estuary. J. Geophys. Res. 110: C11011 doi:10.1029/2005JC002950.

Barth, J.M. I., Berg, P. R., Jonsson, P. R., Bonanomi, S., Corell, H., Hemmer-Hansen, J., Jakobsen, K. S., Johannesson, K., Jorde, P. E., Knutsen, H., Moksnes, P. O., Star, B., Stenseth, N. C., Svedäng, H., Jentoft, S., & André, C. 2017. Genome architecture enables local adaptation of Atlantic cod despite high connectivity. Mol. Ecol. 26:4452–4466.

Bax, N. J. 1999. Eradicating a dreissenid from Australia. Dreissena 10:1-5.

Beal, B.F., D.-M. Nault, H. Annis, P. Thayer, H. Leighton, and B. Ellis 2016. Comparative, large-scale field trials along the Maine Coast to assess management options to enhance populations of the commercially important softshell clam, Mya arenaria L. J. Shell. Res. 35:711-727.

Beal, B.F., C.R. Coffin, S.F. Randall, C.A. Goodenow, K.E. Pepperman, and B.W. Ellis. 2020. Interactive effects of shell hash and predator exclusion on 0-year class recruits of two infaunal intertidal bivalve species in Maine, USA. J. Exp. Mar. Biol. Ecol. 530: DOI10.1016/j.jembe.2020.151441.

Behrens Yamada, S. and P.M. Kosro. 2010. Linking ocean conditions to year class strength of the invasive European green crab, *Carcinus maenas*. Biol. Invas. 12:1791–1804.

Behrens Yamada, S., W.T. Peterson, and P.M. Kosro. 2015. Biological and physical ocean indicators predict the success of an invasive crab, *Carcinus maenas*, in the northern California Current. Mar. Ecol. Prog. Ser. 537:175–189.

Behrens Yamada, S., J.L. Fisher, and P.M. Kosro. 2021. Relationship between ocean ecosystem indicators and year class strength of the invasive European green crab (*Carcinus maenas*). Progress in Oceanography 196: 102618.

Behrens Yamada, S., R.E. Thomson, G.E. Gillespie, and T.C. Norgard. 2017. Lifting barriers to range expansion: the European Green Crab *Carcinus maenas* (Linnaeus, 1758) enters the Salish Sea. J Shell. Res. 36:201–208.

Behrens Yamada, S., G.E. Gillespie, R.E. Thomson, and T.C. Norgard. 2021. Ocean indicators predict range expansion of an introduced species: Invasion history of the European Green Crab *Carcinus maenas* on the North American Pacific Coast. J. Shell. Res. 40:399–413.

Berrill, M. 1982. The life cycle of the green crab *Carcinus maenas* at the northern end of its range. J. Crust. Biol. 2:31-39.

Bertness, M.D. and T.C. Coverdale. 2013. An invasive species facilitates the recovery of salt marsh ecosystems on Cape Cod. Ecology 94:1937-1943.

Bertness, M.D., C.P. Brisson, T.C. Coverdale, M.C. Bevil, S.M. Crotty, and E.R. Suglia. 2014. Experimental predator removal causes rapid salt marsh die-off. Ecol. Lett. 17:830-835.

Beukema, J. J. 1991. The abundance of shore crabs *Carcinus maenas* (L.) on a tidalflat in the Wadden Sea after cold and mild winters. J. Exp. Mar. Biol. Ecol. 153:97-113.

Bier, E. 2022. Gene drives gaining speed. Nature Rev. Gen. 23:5–22.

Blakeslee, A.M.H., C.L. Keogh, J.E. Byers, A.M. Kuris, K.D. Lafferty, and M.E. Torchin. 2009. Differential escape from parasites by two competing introduced crabs. Mar. Ecol. Prog. Ser. 393:83-96.

Blakeslee, A.M.H., C.H. McKenzie, J.A. Darling, J.E. Byers, J.M. Pringle and J. Roman. 2010. A hitchhiker's guide to the Maritimes: anthropogenic transport facilitates long-distance dispersal of an invasive marine crab to Newfoundland. Divers. Distrib. 16: 879–891.

Blakeslee, A.M.H., A.E. Fowler, J L. Couture, E.D. Grosholz, G.M. Ruiz and A.W. Miller. 2016. Vector management reduces marine organisms transferred with live saltwater bait. Management of Biological Invasions 7: 389-398.

Blakeslee, A.M.H., R.B. Barnard, K. Matheson, K. and C.H. McKenzie. 2020. Host-switching among crabs: species introduction results in a new target host for native parasites. Mar. Ecol. Progr. Ser. 636:91-106.

Bloch, C.P., K.D. Curry and J.C. Jahoda. 2015. Long-term effects of an invasive shore crab on Cape Cod, Massachusetts. Northeast. Natur. 22:178-191.

Bojko, J. P.D. Stebbing, A.M. Dunn, K.S. Bateman, F. Clark, R. C. Kerr, S. Stewart-Clark, A. Johannesen, and G. D. Stentiford. 2018. Green crab *Carcinus maenas* symbiont profiles along a North Atlantic invasion route. Diseas. Aquat. Org. 128:147-168.

Bojko, J., A.L. Burgess, A.G. Baker and C.H. Orr. 2021. Invasive non-native crustacean symbionts: diversity and impact. J. Invert. Pathol. Doi:10.1016/j.jip.2020.107482.

Borrell, Y. J., L. Miralles, H. Do Huu, K. Mohammed-Geba and E. Garcia-Vazquez. 2017. DNA in a bottle-Rapid metabarcoding survey for early alerts of invasive species in ports. PLoS One 12: e0183347.

Bowers, H., X. Pochon, U. von Ammon, N. Gemmell, J.-A. Stanton, G.-J. Jeunen, C. Sherman and A. Zaiko 2021. Towards the Optimization of eDNA/eRNA Sampling Technologies for Marine Biosecurity Surveillance. Water 13(8):1113.

Bradt, G. and M. McMahan. 2022. The Green Crab Guide: In the Field and in the Kitchen. New Hampshire Sea Grant Publication.

Brasseale, E., Grason, E.W., McDonald, P.S., Adams, J., MacCready, P. 2019. Larval transport modeling support for identifying population sources of European green crab in the Salish Sea. Estuaries and Coasts 42:1586–1599.

Bravo, M.A., Cameron, B., Metaxas, A. 2007. Salinity Tolerance in the Early Larval Stages of *Carcinus maenas* (Decapoda, Brachyura), a Recent Invader of the Bras d'or Lakes, Nova Scotia, Canada. Crustaceana 80:475–490.

Bricknell, I.R., S.D. Birkel, S.H. Brawley, T. Van Kirk, H.J. Hamlin, K. Capistrant-Fossa, K. Huguenard, G.P. Van Walsum, Z.L. Liu, L.H. Zhu, G. Grebe, E. Taccardi, M. Miller, B.M. Preziosi, K. Duffy, C.J. Byron, C.T.C. Quigley, T.J. Bowden, D. Brady, B.F. Beal, P.K. Sappati, T.R. Johnson, and S. Moeykens. 2021. Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine. Rev. Aquacul. 13:460-503.

Broekhuysen, G.J. Jr. 1936. On development, growth, and distribution of *Carcinides maenas* (L.). Arch. Neerlandaises de Zoologie 2:257-399.

Burden, C.T., Stow, A.J., Hoggard, S.J., Coleman, M.A., Bishop, M.J. 2014. Genetic structure of *Carcinus maenas* in southeast Australia. Marine Ecology Progress Series 500, 139–147.

Burke, E.A., J.S. Goldstein, B.C. Gutzler, and N.B. Furey. Meter-scale movements of the invasive green crab *Carcinus maenas* measured with acoustic telemetry in a Gulf of Maine estuary (in preparation).

Cameron, B. and A. Metaxas. 2005. Invasive green crab, *Carcinus maenas*, on the Atlantic coast and in the Bras d'Or Lakes of Nova Scotia, Canada: larval supply and recruitment. J. Mar. Biol. Assoc. U. K. 85:847-85.

Carlton, J.T. 1989. Man's role in changing the face of the ocean: Biological invasionsand implications for conservation of near-shore environments. Conserv. Biol.3:265-273.

Carlton, J.T. and J.B. Geller. 1993. Ecological roulette: The global transport and invasion of nonindigenous marine organisms. Science 261:78-82.

Carlton, J.T. and A.N. Cohen. 2003. Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. J. Biogeog. 30:1809–1820.

Chandler, J.C., A. Elizur, and T. Ventura. 2018. The decapod researcher's guide to the galaxy of sex determination. Hydrobiol. 825:61–80.

Cieluch, U., Anger, K., Aujoulat, F., Buchholz, F., Charmantier-Daures, M., Charmantie, G., 2004. Ontogeny of osmoregulatory structures and functions in the green crab *Carcinus maenas* (Crustacea, Decapoda). Journal of Experimental Biology 207, 325–336.

Cohen, A.N., J.T. Carlton, and M.C. Fountain. 1995. Introduction, dispersal, andpotential impacts of the green crab *Carcinus maenas* in San Franscisco Bay, California. Mar. Biol. 122:225-237.

Cohen, A.N. 2012. Aquatic invasive species vector risk assessments: Live saltwater bait and the introduction of non-native species into California. Final report for California Ocean Science Trust.

Compton, T.J., Leathwick, J.R., Inglis, G.J. 2010. Thermogeography predicts the potential global range of the invasive European green crab (*Carcinus maenas*). Diversity and Distributions 16, 243–255.

Coverdale, T.C., E.E. Axelman, C.P. Brisson, E.W. Young, A.H. Altieri, and M.D. Bertness. 2013. New England salt march recovery: Opportunistic colonization of an invasive species and its non- consumptive effects. PLoS One 8:e73823.

Coyle, A. F., Voss, E. R., Tepolt, C. K., and Carlon, D. B. 2019. Mitochondrial genotype influences the response to cold stress in the European green crab, *Carcinus maenas*. J. Exp. Biol. *222*(17):jeb203521

Crane, L. C., J. S. Goldstein, D. W. Thomas, K. S. Rexroth and A. W. Watts. 2021. Effects of life stage on eDNA detection of the invasive European green crab (*Carcinus maenas*) in estuarine systems. Ecol. Indicat. 124.

Curtis, L.J.F., D.L. Curtis, H. Matkin, M. Thompson, F. Choi, P. Callow, G.E. Gillespie, T.W. Therriault, and C.M. Pearce. 2015. Evaluating transfers of harvested shellfish products, from the west to the east coast of Vancouver Island, as a potential vector for European Green Crab (*Carcinus maenas*) and other non-indigenous invertebrate species. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/014. vi + 74 p.

Dare, P.J. and D.B. Edwards. 1976. Experiments on the survival, growth, and yield of relaid seed mussels (*Mytilus edulis* L.) in the Menai Strait, North Wales. J. Cons. int. Explor. Mer. 37:16-28.

Dare, P.J., G. Davies, and D.B. Edwards. 1983. Predation on juvenile Pacific oysters (*Crassostrea gigas* Thunberg) and mussels (*Mytilus edulis* L.) by the shore crabs (*Carcinus maenas*). Fisheries Research Technical Report #73. Ministry of Agriculture, Fisheries, and Food, U.K. 15pp.

Darling, J.A. 2011. Interspecific hybridization and mitochondrial introgression in invasive *Carcinus* shore crabs. PLoS ONE 6(3): e17828.

Darling, J.A., M.J. Bagley, J. Roman, C.K. Tepolt CK and J.B. Geller. 2008 Genetic patterns across multiple introductions of the globally invasive crab genus *Carcinus*. Mol. Ecol. 17:4992–5007.

Darling, J. A., Tsai, Y. E., April, M. H., and Roman, J. 2014. Are genes faster than crabs ? Mitochondrial introgression exceeds larval dispersal during population expansion of the invasive crab *Carcinus maenas*. *Royal Society Open Science*, *1*, 140202.

Darling, J. A., X. Pochon, C. L. Abbott, G. J. Inglis, A. Zaiko and B. Leroy. 2020. The risks of using molecular biodiversity data for incidental detection of species of concern. Diver. Distrib. 26: 1116-1121.

Davidson, T.M., A. Larson and C.E. de Rivera. 2009. Early detection and rapid response plan for the European Green Crab, *Carcinus maenas*, in Alaska. Aquatic Bioinvasion Research & Policy Institute prepared for the Alaska Department of Fish and Game.

Davies, C.E, F.M. Batista, S. H. Malkin, J.E. Thomas, C.C. Bryan, P. Crocombe, C.J. Coates and A.F. Rowley. Spatial and temporal disease dynamics of the parasite Hematodinium sp. in shore crabs, *Carcinus maenas.* Paras. Vect. 12: 472.

Davis, R.C., F.T. Short and D.M. Burdick. 1998. Quantifying the effects of green crab damage to eelgrass transplants. Restor. Ecol. 6: 297-302.

Dawirs, R.R. 1985. Temperature and larval development of *Carcinus maenas* (Decapoda) in the laboratory; predictions of larval dynamics in the sea. Mar. Ecol. Prog. Ser. 24:297-302.

Dawirs, R.R., and A. Dietrich. 1986. Temperature and laboratory feeding rates in *Carcinus maenas* L. (Decapoda: Portunidae) larvae from hatching through metamorphosis. J. Exp. Mar. Biol. Ecol. 99: 133–147.

Deiner, K., H. Yamanaka and L. Bernatchez. 2020. The future of biodiversity monitoring and conservation utilizing environmental DNA. Environ. DNA 3: 3-7.

de Rivera, C.E., G.M. Ruiz, A.H. Hines, and P. Jivoff. 2005. Biotic resistance to invasion: Native predator limits abundance and distribution of an introduced crab. Ecology 86:3364-3376.

de Rivera, C.E., N.G. Hitchcock, S.J. Teck, B.P. Steves, A.H. Hines, and G.M. Ruiz. 2007. Larval development rate predicts range expansion of an introduced crab. Mar Biol 150, 1275–1288.

de Rivera, C.E., E.D. Grosholz, and G.M. Ruiz. 2011. Multiple and long-term effects of an introduced predatory crab. Marine Ecology Progress Series 429: 145–155.

Diagne, C., B. Leroy, R.E. Gozlan, A.C. Vaissiere, C. Assailly, L. Nuninger, D. Roiz, F. Jourdain, I. Jaric, and F. Courchamp. 2020. InvaCost, a public database of the economic costs of biological invasions worldwide. Sci. Data 277: DOI10.1038/s41597-020-00586-z

Drinkwin, J., A. Pleus, T. Therriault, R. Talbot, E.W. Grason, P.S. McDonald, J. Adams, T. Hass and K. Litle. 2019. Salish Sea Transboundary Action Plan for Invasive European Green Crab. Puget Sound Partnership.

Duarte, S., P. E. Vieira, A. S. Lavrador and F. O. Costa. 2021. Status and prospects of marine NIS detection and monitoring through (e)DNA metabarcoding. Sci. Total Environ. 751: 141729.

Duncombe, L. G. and T. W. Therriault. 2017. Evaluating trapping as a method to control the European green crab, *Carcinus maenas*, population at Pipestem Inlet, British Columbia. Manag. Biol. Invas. 8:235-246.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O. 2000. Climate extremes: Observations, modeling, and impacts. Science 289, 2068–2074.

Ebling, F.G., J.A. Kitching, L. Muntz, and C.M. Taylor. 1964. The ecology of Lough Ine: XIII. Experimental observations of the destruction of *Mytilus edulis* and *Nucella lapillus* by crabs. J. Anim. Ecol. 33:73-82.

Eiswerth, M., C. Lawley and M. Taylor. 2018. Economics of invasive species. Oxford Research 354 Encyclopedia of Environmental Science.

Ens, N.J., B. Harvey, M.M. Davies, H.M. Thomson, K.J. Meyers, J. Yakimishyn, L.C. Lee, M.E. McCord and T.G. Gerwing. 2022. The Green Wave: reviewing the environmental impacts of the invasive European green crab (Carcinus maenas) and potential management approaches. Env. Rev. 30:306-322.

Epanchin-Niell, R., A. Liebhold, C. McAusland, P. Muebaze, and M. Springborn, M. 2021. Trade and invasive species: tackling a moving target. Rev. Environ. Econ. Pol. 15:180-190.

Esvelt, K. M., & Gemmell, N. J. 2017. Conservation demands safe gene drive. PLoS Biology *15*:1–8.

Fletcher, N., J.A. Terschak, H.D. Bartels-Hardege, F. Bublitz, P. Schirrmacher and J.D. Hardege. 2022. A pheromone bouquet controls the reproductive behaviour of the male shore crab, *Carcinus maenas*. Aquat. Ecol. 56:419–427.

Fofonoff P.W., G.M. Ruiz, B. Steves, C. Simkanin, and J.T. Carlton. 2023. National Exotic Marine and Estuarine Species Information System (NEMESIS).

Formel, N., I. C. Enochs, C. Sinigalliano, S. R. Anderson and L. R. Thompson. 2021. Subsurface automated samplers for eDNA (SASe) for biological monitoring and research. HardwareX 10: e00239.

Fulton, B. A. and E. A. Fairchild. 2013. Nutritional analysis of whole green crab, *Carcinus maenas*, for application as a forage rish replacement in agrifeeds. Sustain. Agr. Res. 2:126-135.

Fulton, B.A., E.A. Fairchild and R. Warner. 2013. The green crab *Carcinus maenas* in two New Hampshire estuaries. Part 1: Spatial and temporal distribution, sex ratio, average size, and mass. J. Crust. Biol.33:25–35.

Garbary, D.J., A.G. Miller, J. Williams and N.R. Seymour. 2014. Drastic decline of an extensive eelgrass bed in Nova Scotia due to the activity of the invasive green crab (*Carcinus maenas*). Mar. Biol. 161:3-15.

Gardner, N.C., S. Kwa, and A. Paturusi. 1994. First recording of the European shore crab *Carcinus maenas* in Tasmania. Tas. Nat. 116:26-28.

Gehrels, H., K.M. Knysh, M. Boudreau, M.H. Thériault, S.C. Courtenay, R. Cox, and P.A. Quijón. 2016. Hide and seek: habitat-mediated interactions between European green crabs and native mud crabs in Atlantic Canada. Mar. Biol. 163: 152.

Geller, J.B., E.D. Walton, E.D. Grosholz, and G.M. Ruiz. 1997. Cryptic invasions of the crab *Carcinus* detected by molecular phylogeography. Molecular Ecology 6:901- 906.

Gharouni, A., M.A. Barbeau, A. Locke, L. Wang, and J. Watmough. 2015. Sensitivity of invasion speed to dispersal and demography: an application of spreading speed theory to the green crab invasion on the northwest Atlantic coast. Mar. Ecol. Progr. Ser. 541:135-150.

Gharouni, A., M.A. Barbeau, J. Chasse, L. Wang, and J. Watmough. 2017. Stochastic dispersal increases the rate of upstream spread: a case study with green crabs on the northwest Atlantic coast. PLoS ONE 12(9):e0185671.

Gillespie, G.E., A.C. Phillips, D.L. Paltzat, and T.W. Therriault. 2007. Status of the European green crab, *Carcinus maenas*, in British Columbia - 2006. Can. Tech. Rep. Fish. Aquat. Sci. 2700: vii + 39 p.

Giménez, L., Chatterjee, A., Torres, G., 2021. A state-space approach to understand responses of organisms, populations and communities to multiple environmental drivers. Commun. Biol 4:1–10.

Giomi, F., H.O. Pörtner. 2013. A role for haemolymph oxygen capacity in heat tolerance of eurythermal crabs. Front. Physiol. 4:110.

Giroux, M. S., J. R. Reichman, T. Langknecht, R. M. Burgess and K. T. Ho. 2022. Environmental RNA as a Tool for Marine Community Biodiversity Assessments. Sci Rep 12: 17782.

Glude, J.B. 1955. The effects of temperature and predators on the abundance of the soft-shell clam, *Mya arenaria*, in New England. Trans. Am. Fish. Soc. 84:13-26.

Goddard, J.H.R., M.E. Torchin, A.M. Kuris, and K.D. Lafferty. 2005. Host specificity of *Sacculina carcini*, a potential biological control agent of introduced European green crab *Carcinus maenas* in California. Biol. Invas. 7:895-912.

Goldstein, J.S., E.M. Morrissey, E.D. Moretti, E.D., and W.H Watson III. 2017. A comparison of the distribution and abundance of European green crabs and American lobsters in Great Bay Estuary, New Hampshire, USA. Fish. Res. 189: 10-17.

Grason, E.G. , P.S. McDonald, J. Adams, K. Litle, J.K. Apple, A. Pleus. 2018. Citizen science program detects range expansion of the globally invasive European green crab in Washington State (USA). Manag. Biol. Invas. 9:39-47. DOI: https://doi.org/10.3391/mbi.2018.9.1.04

Greco, M., F. Lejzerowicz, E. Reo, A. Caruso, A. Maccotta, R. Coccioni, J. Pawlowski and F. Frontalini. 2022. Environmental RNA outperforms eDNA metabarcoding in assessing impact of marine pollution: A chromium-spiked mesocosm test. Chemosphere 298:134239.

Green, S. J. and E. D. Grosholz. 2021. Functional eradication as a framework for invasive species control. Frontiers in Ecology and the Environment 19: 98-107.

Greiner, D.M., D.I. Skonberg, L.B. Perkins, and J.J. Perry. 2021. Use of invasive green crab *Carcinus maenas* for production of a fermented condiment. Foods 10:659.

Grosholz, E.D. 1996. Contrasting rates of spread for introduced species in terrestrial and marine systems. Ecology 77:1680-1686.

Grosholz, E.D. 2002. Ecological and evolutionary consequences of coastal invasions. Tr. Ecol. Evol. 17: 22-27.

Grosholz, E.D. 2005. Recent biological invasion may hasten invasional meltdown by accelerating historical introductions. Proc. Nat. Acad. Sci. USA 102:1088-1091.

Grosholz, E.D. and G.M. Ruiz. 1995. The spread and potential impact of the recently introduced European green crab, *Carcinus maenas*, in central California. Mar. Biol. 122:239-247.

Grosholz, E.D. and G.M. Ruiz. 1996. Predicting the impact of introduced marine species: Lessons from the multiple invasions of the European green crab. Biol. Conserv. 78:59-66.

Grosholz, E.D., S. Drill, L. McCann, and K. Bimrose. 2021a. Engaging community scientists in the management of an invasive marine pest. California Agriculture 75: 40-45.

Grosholz, E.D., S. Lovell, E. Besedin and M. Katz. 2011. Modeling the impacts of the European Green Crab on commercial shellfisheries. Ecol. Appl. 21:915-924.

Grosholz, E.D., P.G. Olin, B. Williams, and R. Tinsman. 2002. Reducing predation on Manila clams by nonindigenous European green crabs. Journal of Shellfish Research.

Grosholz, E.D., G.M. Ruiz, C.A. Dean, K.A. Shirley, J.L. Maron, and P.G. Connors. 2000. The impacts of a nonindigenous marine predator in a California bay. Ecology 81: 1206-1224.

Grosholz, E.D., G. Ashton, M. Bradley, C. Brown, L. Ceballos-Osuna, A. Chang, C. de Rivera, J. Gonzalez, M. Heineke, M. Marraffini, L. McCann, E. Pollard, I. Pritchard, G. Ruiz, B. Turner and C. Tepolt. 2021b. Stage-specific overcompensation, the hydra effect and the failure to eradicate an invasive predator. Proc. Nat. Acad. Sci. USA 118(12): e2003955118.

Hanks, R.W. 1961. Chemical control of the green crab, *Carcinus maenas* (L.). Proceeding of the National Shellfisheries Association 52:75-84.

Hansen, B. K., M. W. Jacobsen, A. L. Middelboe, C. M. Preston, R. Marin, 3rd, D. Bekkevold, S. W. Knudsen, P. R. Moller and E. E. Nielsen. 2020. Remote, autonomous real-time monitoring of environmental DNA from commercial fish. Sci. Rep. 10:13272.

Hampton, S., Griffiths, C. 2007. Why *Carcinus maenas* cannot get a grip on South Africa's wave-exposed coastline. Afr. J. Mar. Sci. 29:123–126.

Hardege, J.D. and J.A. Terschak. 2011. Identification of Crustacean Sex Pheromones. Chemical Communication in Crustaceans, eds. T. Breithaupt and M. Thiel. Springer, New York, pp.373-392.

Harvey, J. B. J., J. P. Ryan, R. Marin, C. M. Preston, N. Alvarado, C. A. Scholin and R. C. Vrijenhoek. 2012. Robotic sampling, in situ monitoring and molecular detection of marine zooplankton. J. Exp. Mar. Biol. Ecol. 413:60-70.

Hendry, A.P., M.T. Kinnison, M. Heino, T. Day, T.B. Smith, G. Fitt, C.T. Bergstrom, J. Oakeshott, P.S. Jørgensen, M.P Zalucki, G. Gilchrist, S. Southerton, A. Sih, S. Strauss, R.F. Denison, and S.P. Carroll. 2011. Evolutionary principles and their practical application. Evol. Appl. 4(2):159–183.

Hidalgo, F.J., P.J. Barón, P. J. and J.M. Orensanz. 2005. A prediction come true: The green crab invades the Patagonian coast. Biol. Invas. 7:547–552.

Hollenbeck, C. M., Portnoy, D. S., Garcia de la serrana, D., Magnesen, T., Matejusova, I., and Johnston, I. A. 2022. Temperature-associated selection linked to putative chromosomal inversions in king scallop (*Pecten maximus*). Proc. Roy Soc. B. 289:20221573.

Howard, B.R., F.T. Francis, I.M Côté, and T.W. Therriault. 2019. Habitat alteration by invasive European green crab (*Carcinus maenas*) causes eelgrass loss in British Columbia. Biol. Invas. 21:3607–3618.

Howard, B.R., K.S.P. Gale, A. Davis, D.A. Lyons, C. DiBacco, E. Grason, P.S. McDonald, S.J. Green and T.W. Therriault, T.W. 2022. Evaluation of methods for identification of early detection monitoring sites based on habitat suitability for invasive European Green Crab in the Salish Sea, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/057.vii + 54 p.

Hunt, C.E. and S. Behrens Yamada. 2003. Biotic resistance experienced by an invasive crustacean in a temperate estuary. Marine Bioinvasions: Patterns, Processes and Perspectives. J. Pederson, ed. Springer Dordecht, pp. 33-43.

Jensen, K.T. and J.N. Jensen. 1985. The importance of some epibenthic predators on the density of juvenile benthic macrofauna in the Danish Wadden Sea. J. Exp. Mar. Biol. Ecol. 89:157-174.

Jeffery, N W, DiBacco, C., Wringe, B. F., Stanley, R. R. E., Hamilton, L. C., Ravindran, P. N., & Bradbury, I. R. 2017. Genomic evidence of hybridization between two independent invasions of European green crab (*Carcinus maenas*) in the Northwest Atlantic. Heredity 119:154–165.

Jeffery, N.W., I.R. Bradbury, R.R.E. Stanley, B.F. Wringe, M. Van Wyngaarden, J. B. Lowen, C.H. McKenzie, K. Matheson, P.S. Sargent and C. DiBacco. 2018. Genomewide evidence of environmentally mediated secondary contact of European green crab (*Carcinus maenas*) lineages in eastern North America. Evol. Appl. 11:869–882.

Jeffery, N.W, C. DiBacco, M. Van Wyngaarden, L.C. Hamilton, R.R.E. Stanley, R. Bernier, J. FitzGerald, K. Matheson, C.H. McKenzie, P.N. Ravindran, R. Beiko, and I.R. Bradbury. 2017. RAD sequencing reveals genomewide divergence between independent invasions of the European green crab (*Carcinus maenas*) in the Northwest Atlantic. Ecol. Evol. 7:2513–2524.

Kang, B., A.D. Myracle, and D.I. Skonberg. 2019. Potential of recovered proteins from invasive green crabs (Carcinus maenas) as a functional food ingredient. J. Sci. Food Agricul. 99:1748-1754.

Keller, A. G., E. W. Grason, P. S. McDonald, A. Ramon-Laca and R. P. Kelly. 2022. Tracking an invasion front with environmental DNA. Ecol Appl 32: e2561.

Kelley, A.L., de Rivera, C.E., Buckley, B.A. 2011. Intraspecific variation in thermotolerance and morphology of the invasive European green crab, *Carcinus maenas*, on the west coast of North America. Journal of Experimental Marine Biology and Ecology 409, 70–78.

Kelley, A.L., de Rivera, C.E., Buckley, B.A. 2013. Cold tolerance of the invasive *Carcinus maenas* in the east Pacific: molecular mechanisms and implications for range expansion in a changing climate. Biol Invasions 15, 2299–2309.

Klassen, G.J. and Locke, A. 2007. A biological synopsis of the European green crab, *Carcinus maenas*. Can. Manuscr. Rep. Fish. Aquat. Sci. 2818, vii+75pp.

Kouba, A., F.J. Oficialdegui, R.N. Cuthbert, M. Kourantidou, J. South, E. Tricarico, R.E. Gozlan, F. Courchamp, and P.J. Haubrock. 2022. Identifying economic costs and knowledge gaps of invasive aquatic crustaceans. Sci. Tot. Environ. 813: 152325.

Kuris, A.M. and K.D. Lafferty. 1992. Modeling crustacean fisheries: effects of parasites on management strategies. Can. J. Fish. Aquat. Sci. 49:327-336.

Kuris, A. M. and C. S. Culver. 1999. An introduced sabellid polychaete pest infesting cultured abalones and its potential spread to other California gastropods Invertebrate Biology 118: 391-403.

Lafferty, K.D. and A.M. Kuris. 1996. Biological control of marine pests. Ecology 77:1989-2000.

Legeay, A. and J.-C. Massabuau. 2000. Effect of salinity on hypoxia tolerance of resting green crabs, *Carcinus maenas*, after feeding. Mar. Biol. 136:387-396.

Lehnert, S. J., DiBacco, C., Jeffery, N. W., Blakeslee, A. M. H., Isaksson, J., Roman, J., Wringe, B. F., Stanley, R. R. E., Matheson, K., McKenzie, C. H., Hamilton, L. C., and Bradbury, I. R. 2018. Temporal dynamics of genetic clines of invasive European green crab (*Carcinus maenas*) in eastern North America. Evol. Appl. 11:1656–1670.

Lohrer, A.M. and R.B. Whitlatch. 2002. Interactions among aliens: Apparent replacement of one exotic species by another. Ecology 83:719-732.

Lovell, S.J., S.F. Stone and L. Fernandez. 2006. The economic impacts of aquatic invasive species: A review of the literature. Ag. Res. Econ. Rev. 35:195-208.

Lyons, D.A., J.B. Lowen, T.W. Therriault, D. Brickman, L. Guo, A.M. Moore, M.A. Peña, Z. Wang, and C. DiBacco. 2020. Identifying marine invasion hotspots using stacked species distribution models. Biol. Invas. 22: 3403-3423.

Malyshev, A. and P.A. Quijon. 2011. Disruption of essential habitat by a coastal invader: new evidence of the effects of green crabs on eelgrass beds. ICES J. Mar. Sci. 68:1852-1856.

Matheson, P., and McGaughran, A. 2022. Genomic data is missing for many highly invasive species, restricting our preparedness for escalating incursion rates. Sci. Rep.12:1–8.

Matheson, K., C.H. McKenzie, R.S. Gregory, D.A. Robichaud, I.R. Bradbury, P.V.R. Snelgrove and G.A. Rose. 2016. Linking eelgrass decline and impacts on associated fish communities to European green crab *Carcinus maenas* invasion. Mar. Ecol. Progr. Ser. 548: 31-45.

McConaugha, J.R., 1992. Decapod larvae: dispersal, mortality, and ecology - a working hypothesis. Am. Zool. 32, 512–523.

McDonald, P.S., G. Jensen, and D.A. Armstrong. 2001. The competitive and predatory impacts of the nonindigenous crab *Carcinus maenas* (L.) on early benthic phase Dungeness crab *Cancer magister* Dana. J. Exp. Mar. Biol. Ecol. 258: 39-54.

McGaw, I.J. and E. Naylor. 1992. Salinity preference of the shore crab *Carcinus maenas* in relation to coloration during intermoult and to prior acclimation. J. Exp. Mar. Biol. Ecol. 155:145-159.

McGaw, I.J. C.L. Reiber, and J.A. Guadagnoli. 1999. Behavioral physiology of four crab species in low salinity. Bio. Bull. 196:163-176.

McKenzie, C.H., Matheson, K., Sargent, P.S., Piersiak, M., Bernier, R.Y., Simard, N., and Therriault, T.W. 2022. Trapping methods for invasive European green crab in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/063. iv+ 47p.

McKenzie, J. L., Chung, D. J., Healy, T. M., Brennan, R. S., Bryant, H. J., Whitehead, A., and Schulte, P. M. 2019. Mitochondrial ecophysiology: assessing the evolutionary forces that shape mitochondrial variation. Integr. Comp. Biol. 59:925–937.

Meehl, G.A., Zwiers, F., Evans, J., Knutson, T., Mearns, L., Whetton, P. 2000. Trends in extreme weather and climate events: Issues related to modeling extremes in projections of future climate change. Bulletin of the American Meteorological Society 81, 427–436.

Menge, B.A. 1983. Components of predation intensity in the low zone of the New England rocky intertidal region. Oecologia 58: 141-155.

Menge, B.A. 1995. Indirect effects in marine rocky intertidal interaction webs: patterns and importance. Ecol. Monogr. 65: 12-74.

Miyata, K., Y. Inoue, Y. Amano, T. Nishioka, M. Yamane, T. Kawaguchi, O. Morita and H. Honda. 2021. Fish environmental RNA enables precise ecological surveys with high positive predictivity. Ecol. Indicat. 128.

Mohamedeen, H., and R.G. Hartnoll. 1989. Larval and postlarval growth of individually reared specimens of the common shore crab *Carcinus maenas* (L.). J. Exp. Mar. Biol. Ecol. 134, 1–24.

Moore, A.C. and O.J. Schmitz. 2021. Do predators have a role to play in wetland ecosystem functioning? An experimental study in New England salt marshes. Ecol. Evol. 11:10956-10967.

Moro, D., Byrne, M., Kennedy, M., Campbell, S., & Tizard, M. 2018. Identifying knowledge gaps for gene drive research to control invasive animal species: The next CRISPR step. Glob. Ecol. Conserv. 13:e00363.

Nagaraj, M. 1993. Combined effects of temperature and salinity on the zoeal development of the green crab, *Carcinus maenas* (Linnaeus, 1758)(Decapoda: Portunidae). Sci. Mar 57:1-8.

Neckels, H.A. 2015. Loss of eelgrass in Casco Bay, Maine, linked to green crab disturbance. Northeast. Natur. 22: 478-500.

Nunes, P. and J. van den Bergh. 2004. Can people value protection against invasive marine species? Evidence from a joint travel cost-contingent valuation survey in the Netherlands. Environ. Res. Econ. 28:517-532.

O'Connor, N.J.. 2014. Invasion dynamics on a temperate rocky shore: from early invasion to establishment of a marine invader. Biol. Invas. 16:73-87.

Oye, K. A., Esvelt, K., Appleton, E., Catteruccia, F., Church, G., Kuiken, T., Lightfoot, S. B. Y., McNamara, J., Smidler, A., and Collins, J. P. 2014. Regulating gene drives. Science 345:626–628.

Pearman, J. K., U. Ammon, O. Laroche, A. Zaiko, S. A. Wood, M. Zubia, S. Planes and X. Pochon. 2020. Metabarcoding as a tool to enhance marine surveillance of nonindigenous species in tropical harbors: A case study in Tahiti. Environmental DNA 3:173-189.

Pasko, S. and J. Goldberg. 2014. Review of harvest incentives to control invasive species. Manag. Biol. Invas. 5: 263-277.

Pershing, A.J., M.A. Alexander, D.C. Brady, D. Brickman, E.N. Curchitser, A.W. Diamond, L. McClenachan, K.E. Mills, O.C. Nichols, D.E. Pendleton, N.R. Record, J.D. Scott, M.D. Staudinger, and Y. Wang. 2021. Climate impacts on the Gulf of Maine ecosystem: A review of observed and expected changes in 2050 from rising temperatures. Elementa: Sci. Anthrop. 9:1.

Pringle, J. M., Blakeslee, A. M. H., Byers, J. E., and Roman, J. 2011. Asymmetric dispersal allows an upstream region to control population structure throughout a species' range. Proc. Nat. Acad. Sci. USA 108:15288–15293.

Proctor, C. 1997. Possible impacts of *Carcinus maenas* on Tasmanian mariculture and fisheries. Proceedings of the First International Workshop on the Demography, Impacts and Management of Introduced Populations of the European crab, *Carcinus maeans*, Centre for Research on Introduced Marine Pests, Hobart, Tasmania, Technical Report 11.

Qiao, H., W. Liu, Y. Zhang, Y.Y. Zhang, and Q.Q. Li. 2019. Genetic admixture accelerates invasion via provisioning rapid adaptive evolution. Mol. Ecol. 28(17):4012–4027.

Raposa, K., J. Goldstein, K. Grimes, J. Mora, P. Stacey, and R. McKinney. 2019. A comparative assessment of salt marsh crabs (Decapoda: Brachyura) across the National Estuarine Research Reserves in New England, USA. J. Crust. Biol. 2019:1-9.

Rayner, G., and, I.J. McGaw. 2019. Effects of the invasive green crab (*Carcinus maenas*) on American lobster (*Homarus americanus*): Food acquisition and trapping behaviour. Journal of Sea Research. 144: 95-104.

Reise, K. 1978. Experiments on epibenthic predation in the Wadden Sea. Helgol. Wiss. Meeresunters. 31:55-101.

Reise, K. 1985. Tidal flat ecology. An experimental approach to species interactions. Springer-Verlag, Berlin. 191 pp.

Rewitz, K., B. Styrishave, M.H. Depledge, and O. Anderson. 2004. Spatial and temporal distribution of shore crabs *Carcinus maenas* in a small tidal estuary (Looe Estuary, Cornwall, England). J. Crust. Biol. 24:178-187.

Rius, M., and J.A. Darling. 2014. How important is intraspecific genetic admixture to the success of colonising populations? Trend. Ecol. Evol. 29(4):233–242.

Roman J. 2006. Diluting the founder effect: cryptic invasions expand a marine invader's range. Proc. R. Soc. B 273:2453–2459.

Ropes, J.W. 1968. The feeding habits of the green crab *Carcinus maenas* (L.). J. Exp. Mar. Biol. Ecol. 67:183-201.

Rossong, M.A., P.J. Williams, M. Comeau, S.C. Mitchell, and J. Apaloo. 2006. Agonistic interactions between the invasive green crab, *Carcinus maenas* (Linnaeus) and juvenile

American lobster, *Homarus americanus* (Milne Edwards). J. Exp. Mar.Biol. Ecol. 329: 281–288.
Roux, L. M. D., D. Giblot-Ducray, N. J. Bott, K. H. Wiltshire, M. R. Deveney, K. M. Westfall and C. L. Abbott. 2020. Analytical validation and field testing of a specific qPCR assay for environmental DNA detection of invasive European green crab (*Carcinus maenas*). Environmental DNA 2:309-320.
Ruiz, G.M., J.T. Carlton, E.D. Grosholz, and A.H. Hines. 1997. Global invasions of marine and estuarine habitats by non-indigenous species: Mechanisms, extent, and consequences. Am. Zool. 37:621-632.
Ruiz, G.M., W.C. Walton, E.D. Grosholz, L. Rodriguez, R.E. Threseher, and C. Proctor. 1998. Increased individual size associated with invading populations of the crab *Carcinus maenas* in North America and Australia.
Šargač, Z., Giménez, L., González-Ortegón, E., Harzsch, S., Tremblay, N., Torres, G., 2022. Quantifying the portfolio of larval responses to salinity and temperature in a coastal-marine invertebrate: a cross population study along the European coast. Mar Biol 169, 81.
See, K.E. and B.E. Feist. 2010. Reconstructing the range expansion and subsequent invasion of introduced European green crab along the west coast of the United States. Biol. Invas. 12:1305–1318.
Spitzner, F., Giménez, L., Meth, R., Harzsch, S., Torres, G., 2019. Unmasking intraspecific variation in offspring responses to multiple environmental drivers. Mar Biol 166, 112.
St-Hilaire, S., J. Krause, K. Wight, L. Poirier, and K. Singh. 2016. Break-even analysis for a green crab fishery in PEI, Canada. Manag. Biol. Invas. 7:297-303.
Strasser, M. and C.-P. Günther. 2001. Larval supply of predator and prey: temporal mismatch between crabs and bivalves after a severe winter in the Wadden Sea. J. Sea Res. 46:57–67.
Suarez, A.V., and N.D. Tsutsui. 2008. The evolutionary consequences of biological invasions. Mol. Ecol. 17(1):351–360.
Sunnucks, P., H.E. Morales, A.M. Lamb, A. Pavlova, and C. Greening. 2017. Integrative approaches for studying mitochondrial and nuclear genome co-evolution in oxidative phosphorylation. Front. Gen. 8:1–12.
Tan, E.B.P. and B.F. Beal. 2015. Interactions between the invasive European green crab, *Carcinus maenas* (L.), and juveniles of the soft-shell clam, Mya arenaria L., in eastern Maine, USA. J. Exp. Mar. Biol. Ecol. 462:62-73.
Tepolt, C., and S. Palumbi. 2015. Transcriptome sequencing reveals both neutral and adaptive genome dynamics in a marine invader. Mol. Ecol. 24:4145–4158.
Tepolt, C.K. and S.R. Palumbi. 2020. Rapid adaptation to temperature via a potential genomic island of divergence in the invasive green crab, *Carcinus maenas*. Front. Ecol. Evol. 8:580701.
Tepolt, C. K. and G.N. Somero. 2014. Master of all trades: thermal acclimation and adaptation of cardiac function in a broadly distributed marine invasive species, the European green crab, *Carcinus maenas*. J. Exp. Biol. 217:1129–1138.

Tepolt, C.K., E.D. Grosholz, C.E. de Rivera, and G.M. Ruiz. 2022. Balanced polymorphism fuels rapid selection in an invasive crab despite high gene flow and low genetic diversity. Mol. Ecol. 31:55–69.

Tepolt, C., J.A. Darling, M.J. Bagley, J.B. Geller, M.J. Blum, and E.D. Grosholz, E. D. 2009. European green crabs (*Carcinus maenas*) in the Northeastern Pacific: genetic evidence for high population connectivity and current-mediated expansion from a single introduced source populations. Diver. Distrib. 15:997–1009.

Tettlebach, S.T. 1986. Dynamics of crustacean predation on the northern bay scallop, *Argopecten irradians irradians*. Ph.D. dissertation, University of Connecticut.

Tigano, A., and V.L. Friesen. 2016. Genomics of local adaptation with gene flow. Mol. Ecol. *25*:2144–2164.

Thresher, R.E. (editor). 1997. Proceeding of the first international workshop on the demography, impacts, and management of introduced populations of the European crab, *Carcinus maenas.* Technical Report #11, Centre for Research on Introduced Marine Pests, CSIRO. Hobart, Australia. 101 pp.

Thresher, R.E., M. Werner, J.T. Hoeg, I. Svane, H. Glenner, N.E. Murphy, and C. Wittwer. 2000. Developing the options for managing marine pests: specificity trials on the parasitic castrator, *Sacculina carcini*, against the European crab, Carcinus maenas, and related species. J. Exp. Mar. Biol. Ecol. 254:37-51.

Thresher, R., C. Proctor, G. Ruiz, R. Gurney, C. MacKinnon, W. Walton, L. Rodriguez, and N. Bax. 2003. Invasion dynamics of the European shore crab, *Carcinus maenas*, in Australia. Mar. Biol. 142:867-876.

Torchin, M.E., K.D. Lafferty, and A.M. Kuris. 2001. Release from parasites as natural enemies: increased performance of a globally introduced marine crab. Biol. Inv. 3:333-345.

Torres, G. and L. Giménez. 2020. Temperature modulates compensatory responses to food limitation at metamorphosis in a marine invertebrate. Funct. Ecol. 34:1564–1576.

Torres, G., G. Charmantier, D. Wilcockson, S. Harzsch and L. Giménez. 2021. Physiological basis of interactive responses to temperature and salinity in coastal marine invertebrate: Implications for responses to warming. Ecology and Evolution 11:7042–7056.

Trussell, G.C., P.J. Ewanchuck and M.D. Bertness. 2003. Trait-mediate effects in rocky intertidal food chains: predator risk cues alter prey feeding rates. Ecology 84:629-640.

von Ammon, U., S. A. Wood, O. Laroche, A. Zaiko, S. D. Lavery, G. J. Inglis and X. Pochon. 2019. Linking Environmental DNA and RNA for Improved Detection of the Marine Invasive Fanworm Sabella spallanzanii. Front. Mar. Sci. 6.

Walton, W.C. 2000. Problems, predators, and perception: Management of quahog (hardclam), *Mercenaria mercenaria*, stock enhancement programs in southern New England J. Shell. Res. 20:127-134.

Walton, W.C., C. MacKinnon, L.F. Rodriguez, C. Proctor, and G.A. Ruiz. 2002. Effect of an invasive crab upon a marine fishery: green crab, *Carcinus maenas*, predation upon a venerid clam, *Katelysia scalarina*, in Tasmania (Australia) J. Exp. Mar. Biol. Ecol 272:171-189.

Webber, B. L., Raghu, S., and Edwards, O. R. 2015. Opinion: Is CRISPR-based gene drive a biocontrol silver bullet or global conservation threat? Proc. Nat. Acad. Sci. USA 112:10565–10567.

Wedell, N., Price, T. A. R., and Lindholm, A. K. 2019. Gene drive: Progress and prospects. Proc. Roy. Soc. Biol. Sci. 286(1917).

Westfall, K. M., T. W. Therriault and C. L. Abbott. 2019. A new approach to molecular biosurveillance of invasive species using DNA metabarcoding. Glob. Chg. Biol. 26: 1012-1022.

Westfall, K. M., T. W. Therriault and C. L. Abbott. 2022. Targeted next-generation sequencing of environmental DNA improves detection of invasive European green crab (*Carcinus maenas*). Environmental DNA 4: 440-452.

Welch, W. R. 1968. Changes in abundance of the green crab, *Carcinus maenas* (L.), in relation to recent temperature changes. Fishery Bulletin 67:337–345.

Whiteley, N.M. 2011. Physiological and ecological responses of crustaceans to ocean acidification. Mar. Ecol. Prog. Ser. 430: 257–271.

Whitlow, W.L., N.A. Rice and C. Sweeney. 2003. Native species vulnerability to introduced predators: testing an inducible defense and a refuge from predation. Biol. Invas. 5:23-31.

Williams, S. L. and E. D. Grosholz. 2008. The invasive species challenge in estuarine and coastal environments: marrying management and science. Estuar. Coast 31:3-20.

Williams, S. L., I. C. Davidson, J. R. Pasari, G. V. Ashton, J. T. Carlton, R. E Crafton, R. E. Fontana, E. D. Grosholz, A. W. Miller, G. M. Ruiz, and C. J. Zabin. 2013. Managing multiple vectors for marine invasions in an increasingly connected world. Bioscience 63:952-966.

Williams, L., Nivison, C., Ambrose, W., Dobbin, R., & Locke WL, V. 2015. Lack of adult novel northern lineages of invasive green crab *Carcinus maenas* along much of the northern US Atlantic coast. Mar. Ecol. Prog. Ser. 532:153–159.

Yamada, S.B. 2001. Global Invader: The European Green Crab. Oregon Sea Grant. 140 pp.

Yamahara, K. M., C. M. Preston, J. Birch, K. Walz, R. Marin, S. Jensen, D. Pargett, B. Roman, W. Ussler, Y. Zhang, J. Ryan, B. Hobson, B. Kieft, B. Raanan, K. D. Goodwin, F. P. Chavez and C. Scholin. 2019. In situ Autonomous Acquisition and Preservation of Marine Environmental DNA Using an Autonomous Underwater Vehicle. Front. Mar. Sci. 6.

Yates, M. C., A. M. Derry and M. E. Cristescu. 2021. Environmental RNA: A revolution in ecological resolution? Tr. Ecol. Evol. 36: 601-609.

Zarrella-Smith, K.A., J.N. Woodall, A. Ryan, N.B. Furey, and J.S. Goldstein. 2022. Seasonal estuarine movements of green crabs revealed by acoustic telemetry. Mar. Ecol. Progr. Ser. 681:129-143.

APPENDICES

Appendix A. Definitions

Most definitions were taken from the Invasive Species Policy within the Department of the Interior Departmental Manual (https://www.doi.gov/sites/doi.gov/files/elips/documents/524-dm-1-508.pdf) and from definitions in the Model Process: Aquatic Invasive Species Rapid Response Fund document produced in 2023 by the ANSTF Rapid Response Work Group.

Aquatic invasive species: An invasive species that resides within fresh, estuarine, or marine waters.

Biofouling: Biofouling, or biological fouling, is the accumulation of microorganisms, plants, algae, or small animals on surfaces that have a mechanical function (i.e. ship or submarine hulls, grates, etc.) causing structural or other functional deficiencies. There are two phases or types of biofouling: microfouling and macrofouling.

Catch Per Unit Effort (CPUE) is an indirect metric of the abundance of EGC in relation to a defined geographic area and time scale. It is used to indicate the amount of effort undertaken to collect a given number of EGC. For EGC emergency management data consistency purposes, CPUE must be reported and qualified:

- Per 100 traps as calculated to nearest 0.1 CPUE;
- By aggregate or individual trap type; and
- By cumulative Trap set days or Trap check days over the operational period or other defined time span of interest.

Examples:

- 30 EGC caught in 200 shrimp traps and deployed for 1 overnight period then recovered (200 trap set days): 30 ÷ 200 = 0.15 x 100 = 15.0 CPUE.
- 30 EGC caught in 200 shrimp traps and deployed for 3 overnight periods then recovered (600 trap set days): 30 ÷ 600 = 0.05 x 100 = 5.0 CPUE.

Containment: A management intervention aimed to restrict an invasive species to a limited geographical range.

Control: A management intervention aimed at reducing the density and/or distribution of an invasive alien species to an acceptable level.

Early Detection: A process of surveying for, reporting, and verifying the presence of a non-native species before the founding population begins to reproduce or spreads so widely that eradication is no longer feasible.

Eradication: Removal or destruction of an entire population of invasive species.

Interstate organization: Entities established by an interstate compact that is approved by Federal statute; represents two or more states or tribes; and has jurisdiction over, serves as forum for coordinating, or otherwise has a role or responsibility for the management of, any land or other natural resources.

Introduction: As a result of human activity, the intentional or unintentional escape, release, dissemination, or placement of an organism into an ecosystem to which it is not native.

Invasive Species: With regard to a particular ecosystem, a non-native organism whose introduction causes or is likely to cause economic or environmental harm or harm to human, animal, or plant health.

Management: Activities including but not limited to planning (identification and inventory, prioritization, establishing action thresholds), monitoring, prevention, early detection, rapid response, eradication, control, restoration, research, and regulatory approaches used to minimize the threat of invasive species.

Native Species: With respect to a particular ecosystem, an organism, including its seeds, eggs, spores, or other biological material capable of propagating that species, that, other than as a result of an introduction, historically occurred or currently occurs in that ecosystem.

Prevention: The action of stopping invasive species from being introduced or spreading into a new ecosystem.

Range Expansion: increases in the geographic area occupied by a species.

Rapid Response: A process that is employed to eradicate the founding population of a non-native species from a specific location before it begins to reproduce or spreads so widely that eradication is no longer feasible.

Response measures: Approaches or tools that are used to remove or destroy the target species. Response measures may include biological, chemical, manual, or mechanical techniques.

Secondary Spread: Dispersal or transport of invasive species from populations residing outside of their native range.

Species: Defined within this document as a set of animals or plants in which the members have similar characteristics to each other and can reproduce with one another in nature and produce fertile offspring.

Trap set days: When a trap is set intertidally or sub-tidally for the action of capturing EGC for a single overnight period. Overnight trap days are standard trapping protocols based on known EGC feeding activity patterns. If a trap is set and retrieved within a single calendar day, count it as a single trap day, but be aware that it may be later counted as a portion of a trap day for comparability with a standard overnight trap day.

- Total set trap days are counted from the day after a trap is set and includes the day the trap is removed. This metric is mostly a qualitative measure of effort during an operational period or season and may be used to estimate a gross level of potential EGC risk/density to help assess if additional support is needed. Example: 50 traps set on Monday, Aug 8, and retrieved Friday, Aug 12. This would be 50 x 4 = 200 trap days.

Trap check days means the number of days within an operational period that a trap is checked for EGC. This metric is mostly a qualitative measure of effort and may be used to estimate a gross level of potential EGC risk/density to help assess if additional support is needed in a given Coordination Area.

- Total trap check days means the cumulative number of traps checked every day the traps are deployed. If traps are checked every day, total trap check days will be the same as total trap days. Example: 50 traps set on Monday, Aug 8, and retrieved Friday, Aug 12, and checked every day. This would be 50 x 4 = 200 trap check days.

Appendix B. Ongoing Actions and Green Crab Management Plans

Ongoing Actions along the West Coast of North America

Alaska**:** Ongoing actions in Alaska include multi-partner coordination, data sharing, strategic planning, early detection surveillance monitoring, rapid response, control trapping, community-based monitoring, and public outreach. Alaska first detected European green crab in 2022. On July 19, 2022, the Metlakatla Indian Community discovered three crab shells during an Annette Islands Reserve survey. Further investigation found more molts, as well as live and dead crabs. Current management efforts are being coordinated between many partners including NOAA Fisheries and the Metlakatla Indian Community. Green crab are a serious threat for Alaska's tidal habitats. In 2020, the Metlakatla Indian Community began an early detection program, which streamlined monitoring and data collection. No green crabs were found in 2020 or 2021. Early detection work includes molt / carapace surveys and trapping in the intertidal zone, tide pools, and deeper areas. Management actions currently include early detection, surveillance, and control trapping. The Alaska Department of Fish and Game will be expanding trapping efforts in the region. The Metlakatla Indian Community, NOAA Fisheries, and Alaska Department of Fish and Game have built a strong partnership. They provide technical and financial support, technical assistance, and subject matter experts to bolster the community-based monitoring program. An Early Detection and Rapid Response Plan for *Carcinus maenas* in Alaska was completed in 2009 to facilitate the prevention and detection of invasive green crab, and to organize and implement a rapid response after an invasion is detected. The plan utilizes an adaptive approach that can be amended as necessary to deal with biological, logistical, jurisdictional, or other changes that may occur. This plan is currently being updated, and will be tested with a table-top rapid response exercise scheduled to take place in Homer, Alaska in August 2023. Significant public engagement is included as part of early detection surveillance monitoring.

British Columbia, Canada: Ongoing actions include research, modeling, habitat monitoring, control actions, multi-partner coordination, data sharing, strategic planning, early detection surveillance monitoring, and rapid response. Established populations of European Green Crabs have been found on the west coast of Vancouver Island. Since 2018, new detections of European Green Crab have been found on: northern Vancouver Island (Port Hardy); southern Vancouver Island (Esquimalt Lagoon, Witty's Lagoon); the Gulf Islands (Salt Spring Island); Haida Gwaii and, in southern British Columbian waters (Boundary Bay). Fisheries and Oceans Canada is collaborating with many partners including academia, fish harvesters, Indigenous Peoples, conservation groups, community members, provincial and territorial departments, and the United States to provide training on proper identification, sampling methods and data collection standards. Risk assessments for green crab invasion into Canadian waters have been completed, as well as ongoing research investigating eelgrass loss and habitat alteration by green crab invasion in British Columbia. The Salish Sea Transboundary Action Plan for Invasive European Green Crab was completed in 2019, with Washington Department of Fish and Wildlife (WDFW), Department of Fisheries and Oceans Canada (DFO), and Transport Canada as the key regulatory managers. The purpose of the Salish Sea Transboundary Action Plan for Invasive European Green Crab (Plan) is to establish and implement a coordinated and collaborative response to incursions of European green crab that pose a risk of harming or threatening the environmental, economic, or human resources within the shared waters of the Salish Sea. Within the Salish Sea, the range and abundance of EGC is limited, with an established (self-sustaining) population in Sooke Basin, British Columbia. As of October 2018, small numbers of EGC have been found at several other locations in British Columbia and Washington State.

Puget Sound: Coordinated efforts to protect and restore Puget Sound have been ongoing, with MOUs in place with multiple federal agencies since 2008, updated in 2016. The Puget Sound Federal Task Force (PSFTF) was newly codified as the Puget Sound Federal Leadership Task Force under the FY2023 Omnibus. A key purpose of the Puget Sound Federal Task Force is to strengthen the early and ongoing integration of federal activities and capabilities into the Puget Sound Action Agenda and its implementation. Another key purpose of the Puget Sound Federal Task Force is to strengthen intergovernmental coordination of federal actions with tribal governments, and, to contribute to fulfilling federal trust responsibilities. Integrating federal activities into the implementation of the Puget Sound Action Agenda is important because the Action Agenda is the shared vision for Puget Sound protection and recovery. Action items for European green crab were added to the 2022-2026 PSFTF Action Plan, integrating federal activities into this State led effort.

Washington: Ongoing actions include emergency response, early detection surveillance monitoring, control and removal trapping, multi-partner coordination, data sharing, short-term and long-term strategic planning, and public outreach. In 2021, the Washington Department of Fish and Wildlife (WDFW), tribal co-managers, and partners identified an exponential increase of invasive European green crab (EGC), *Carcinus maenas*, in the Lummi Nation’s Sea Pond within the Salish Sea, and in outer coastal areas including Grays Harbor, Makah Bay, and Willapa Bay. On November 23, 2021, the Lummi Indian Business Council passed a resolution declaring a disaster, and on Dec. 14, 2021, WDFW Director Susewind submitted an emergency measures request under RCW 77.135.090 for EGC response to Governor Jay Inslee. On Jan. 19, 2022, Governor Jay Inslee issued an emergency proclamation (#22-02) to address the exponential increase in EGC populations across Washington’s marine shorelines. The proclamation directed WDFW to eradicate, reduce, or contain EGC in Washington. The Washington State Legislature approved $8,568,000 in emergency funding during the 2022 Supplemental Budget to facilitate increased EGC management efforts. An Incident Command System (ICS) was established. WDFW, Washington Sea Grant (WSG), the Lummi Nation, the Makah Tribe, the Shoalwater Bay Tribe, shellfish growers, federal land managers, and various other entities have continued their ongoing efforts managing EGC populations. Representatives have joined the ICS Multi-Agency Coordination (MAC) group. The MAC group provides a forum to share information, coordinate operations, develop long-term priorities for the EGC emergency, and commit and allocate funding and other resources to enhance emergency measures responses.

Oregon: Ongoing activities include removal trapping, surveillance monitoring, multi-species population monitoring (recruitment, age structure, abundance, distribution), research, habitat monitoring, ocean current modeling, data coordination, multi-partner coordination, and public outreach. Summarized from Yamada et al. 2022: In 1997, the first green crabs were found in Coos Bay, Oregon. A strong year class arrived during the 1998 El Niño, but numbers decreased and remained below 1 per trap per day until the arrival of the 2015-2016 El Niño. Since then, numbers have increased to an average of around 4-6 crabs per trap per day for intertidal sites and ~ 9 per trap per day in the shallow subtidal. Measurable ecological impact is predicted to occur at around 10-20 per trap per day (Grosholz et al. 2011). Between the two major El Niños, recruitment of young green crabs has been sporadic, with many years of recruitment failures. But after the 2015-2016 El Niño recruitment has been good every year. The Davidson Current transporting larvae from California during the winter no longer appears to be the only source of larvae for our coastal estuaries (Behrens Yamada, Fisher and Kosro 2021). Now that the populations in Oregon, Washington and British Columbia have built up, there is evidence for local larval production and seeding from a genetically distinct population on Vancouver Island (Alan Shanks and Carolyn Tepolt, pers. com.).

California: Ongoing activities include removal trapping, surveillance monitoring, multi-species population monitoring, ongoing research, habitat monitoring, ocean current modeling, data coordination, multi-partner coordination, and public outreach. The population of European green crab in western North America became established in San Francisco Bay in 1989-90 and spread northward along the coast. The crab successfully invaded the California embayments of Bolinas Lagoon, Tomales Bay, and Bodega Bay in 1993 and Humboldt Bay, California, in 1995. The present southern extent of the *Carcinus maenas* range is Elkhorn Slough in Monterey Bay, California, where the crabs have occurred since 1994. Long-term removal efforts and associated crab population modeling continues to inform regional trapping and removal efforts.

Regional Coordination: Pacific States Marine Fisheries Commission has supported west-coastwide green crab monitoring. In 2020, PSMFC supported monitoring partners: the Metlakatla Indian Community in Alaska and Dr. Sylvia Yamada, Oregon State University. Data collected by PSMFC-supported researchers has yielded important insight into the abundance and population structure of the green crab in three states. This information is of critical importance as resource managers and the commercial shellfish industry develop management options to address the threat posed by this species. Additionally, PSMFC and its GIS services staff are developing an EGC database for the west coast.

Ongoing Actions along the East Coast of North America

New Hampshire: Ongoing activities include trapping and removal, population monitoring, community outreach, and research. As ocean temperatures have increased, populations of these crabs continue to increase. The most common use of these crabs is as bait. There have been efforts to develop markets and a fishery to help reduce green crab populations. The NH Green Crab Project, has been researching when green crabs molt to explore the feasibility of a soft-shell crab market (similar to blue crabs) and subsequently a potential fishery, including community science data collection on crab presence and life history stages.

Maine: Ongoing activities include population monitoring, removal, habitat monitoring, and research. In Maine, green crabs are among the invasive species the Maine Department of Marine Resources tracks. Surveys were conducted regularly in the 1960s and 1970s. While there is currently no viable commercial market for green crabs, efforts are underway in the private sector to pursue converting green crab protein into a sustainable aquaculture feed for use in Maine and possibly for export. Other research is focused on developing a bait and food market for green crabs. Ongoing long-term intertidal monitoring is occurring in the region, including work in southern and Mid-Coast Maine, exploring habitat impacts and both native and invasive crab species population trends.

Links to Local, State and Regional Plans

NEMESIS – Marine Invasions Summary
The Smithsonian Environmental Research Center's National Estuarine and Marine Exotic Species Information System (NEMESIS) maintains information on marine and estuarine invertebrates and algae introduced to the United States. NEMESIS includes detailed information on about 500 species of marine and estuarine of invertebrates and algae introduced to the United States. Each record contains information on taxonomy, distribution, ecology, and impacts, as well as references. The green crab species page is here:
https://invasions.si.edu/nemesis/species_summary/98734

Salish Sea Transboundary Action Plan for Invasive European Green Crab
(https://wdfw.wa.gov/publications/02045#:~:text=The%20purpose%20of%20the%20Salish,resources%20within%20the%20shared%20waters) February 2019; Author(s): Joan Drinkwin, Allen Pleus, Dr. Thomas Therriault, Renny Talbot, Dr. Emily W. Grason, Dr. P. Sean McDonald, Jeff Adams, Todd Hass, Kate Litle. 55 pp. The purpose of the Salish Sea Transboundary Action Plan for Invasive European Green Crab (Plan) is to establish and implement a coordinated and collaborative response to incursions of European green crab that pose a risk of harming or threatening the environmental, economic, or human resources within the shared waters of the Salish Sea.

Early Detection and Rapid Response Plan for the European Green Crab, Carcinus maenas, in Alaska
https://www.adfg.alaska.gov/static/species/nonnative/invasive/pdfs/european_green_crab_early_detection_rapid_response_plan_alaska.pdf
Timothy M. Davidson, Amy A. Larson, Catherine E. de Rivera. 2009. Aquatic Bioinvasion Research & Policy Institute. A partnership between Portland State University and the Smithsonian Environmental Research Center

ANSTF 2002 National Management Plan for the European Green Crab
https://www3.epa.gov/region1/npdes/schillerstation/pdfs/AR-317.pdf
Green Crab Control Committee, Frederick Kern, Chair. Edited by Edwin Grosholz and Gregory Ruiz (55 pages).

First detection of the invasive European green crab Carcinus maenas (Linnaeus, 1758) on Lummi Nation reservation tidelands (2019)
https://www.lummi-nsn.gov/userfiles/845_MuellerJefferson2019FirstEGCdetectionatLummi.pdf
Mueller, K. W., and N. T. Jefferson. 2019. Harvest Management Division Technical Report, December 2019, Lummi Natural Resources Department, Bellingham, Washington. Pp. 74 + iv, including appendices

Northwest Treaty Tribes - Makah Tribe Update (June 2022)
https://nwtreatytribes.org/makah-tribe-gets-early-hit-of-invasive-european-green-crab/
Tiffany Royal and Adrianne Akmajian. The Makah Tribe's European green crab invasion has hit yet another alarming benchmark, with more than 1,200 crab captured within the first two months of the trapping season.

Appendix C. Plan Evaluation Measures

European Green Crab Action Items and Evaluation Measures		
Goal 1. Prevention to minimize the likelihood of future introductions		
Item #	**Action Item**	**Evaluation Measures**
1.1	Assess and mitigate living industry pathways	Measureable reduction of AIS in industry, including bait, live seafood, etc.
1.2	Assess and mitigate shipping pathways	Reduction of AIS in ballast and hull fouling
1.3	Investigate and mitigate miscellaneous pathways	Reduction of AIS miscellaneous pathways (e.g. mobile marine infrastructure)
Goal 2. Monitoring to support early detection and inform management strategies		
Item #	**Action Item**	**Evaluation Measures**
2.1	Coordinate and expand monitoring networks	Involvement of partners in central monitoring network
2.2	Expand the development and use of new tools for early detection and population monitoring	Creation of new eDNA and qPCR methods
2.3	Understand scales of dispersal and predict sources of new invasions	Development and refinement of oceanographic models
		Population genomic identification of sources and scales of dispersal
Goal 3. Rapid response to coordinate management strategies and actions for new invasions		
Item #	**Action Item**	**Evaluation Measures**
3.1	Develop an effective Rapid Response strategy	Creation of specific RR plan with partners
3.2	Coordinate with existing Incident Command systems (ICS)	Identify partners for RR plan
Goal 4. Emergency management to coordinate management strategies and actions for rapidly expanding populations		
Item #	**Action Item**	**Evaluation Measures**
4.1	Conduct emergency management strategies and actions for rapidly growing or spreading populations	Conduct emergency response actions at priority sites
		Creation of listing of priority sites for emergency action
		Quantification of risk and ecosystem/human elements under threat
Goal 5. Containment and control of established populations to minimize impacts		
Item #	**Action Item**	**Evaluation Measures**
5.1	Reduce populations to minimize impacts	Reduce EGC populations to functional eradication targets
		Analysis of data to establish thresholds for reduction
5.2	Use of additional methods	Development of biological control, attraction pheromones, etc.
Goal 6. Eradication of new or established populations to eliminate impacts		
Item #	**Action Item**	**Evaluation Measures**
6.1	Conduct eradication of local population	Eradicate local population using pemitted methods
Goal 7. Research to understand invasion risks and to improve or develop new management strategies		
Item #	**Action Item**	**Evaluation Measures**
7.1	Improve and expand detection methods	Development of more effective larval collection techniques for *C. maenas*
		Development of eDNA metabarcoding approaches
		Development of robotic sampling and detection
		Creation of environmental RNA methods
		Improve capture methods for early life stages
7.2	Improve models for predicting risk of future invasion	Creation of model that predicts big or small recruitment years
		Development of habitat suitability for both coasts
7.3	Develop new genetic and genomic tools for management	Research into gene drive approaches
		Development of reference genome
		Identification of genomic variation associated with fitness traits
7.4	Develop a better understanding of ecological interactions	List of location specific impacts and relative risk
Goal 8. Economic analysis to quantify tradeoffs among management strategies		
Item #	**Action Item**	**Evaluation Measures**
8.1	Conduct an economic analysis of management strategies	Economic analysis that can compare and guide management options
Goal 9. Outreach education to explain management strategies		
Item #	**Action Item**	**Evaluation Measures**
9.1	Develop audience-specific messages	Identify specific audiences for communications
		Establish digital library of outreach materials for different groups
		Use best methods including social media for communication
9.2	Engage and educate community scientists and volunteers	Local networks of comm sci/ volunteers actively participating
9.3	Measure success of the targeted information	Conduct online surveys to assess effectiveness of messages
Goal 10. Data management for effective coordination and distribution		
Item #	**Action Item**	**Evaluation Measures**
10.1	Develop database network on both coasts	Creation of central database at PSMFC with new records vetted by SI
10.2	Data tools for rapidly distributing information to participants	Establishment of USGS EDRR network for updates and alerts
10.3	Compile a database listing monitoring/management groups	Comprehensive listing names and contacts for all organiuzations
Goal 11. Adaptive management to evaluate and modify plan implementation		
Item #	**Action Item**	**Evaluation Measures**
11.1	Institute an EGC Advisory Committee Group to facilitate plan implementation	Semi-annual meetings with advisory comm members
		Successful establishement of data hub and products
		New funding awards for high priority actions

Appendix D. Trapping Protocol

The following represents a summary of methods typically used for detecting and monitoring EGC populations using available trapping methods. Detailed discussions of many other aspects of trapping methodology can be found in McKenzie et al. 2022.

To monitor and detect invasions by *Carcinus,* scan shorelines for molts and trap following protocols consistent with those used in the National Estuarine Research Reserve System, including Katchemak Bay Research Reserve (KBRR) and the National Marine Sanctuary Program (de Rivera et al. 2005). Use a combination of baited collapsible Fukui box traps and modified minnow traps, which effectively catch *Carcinus* and are easy to deploy and transport. These characteristics make Fukui box traps and modified minnow traps the ideal tools to sample green crabs in areas with limited wave energy (i.e. mudflats) or when there is limited storage space for equipment (i.e. when sampling from a small boat, float plane, or kayak). Deployment of both types of these traps is recommended since each trap is more effective at catching different sizes of green crabs. The larger box traps are effective for adult green crabs (especially males) while minnow traps, modified with expanded openings, are more effective at catching young-of-the-year and small adult crabs (30-55 mm in carapace width, light green coloration), especially females.

Collapsible Fukui box traps (60 x 45 x 20 cm, with two 40 cm openings and 12 mm mesh) are strongly recommended and are available for order online through Fukui North America: http://www.fukuina.com/fishtraps/square_multi_species_marine_trap.htm. Less expensive versions are available from Memphis Net and Twine: http://www.memphisnet.net/product/2847/traps_fish_collapsible. Minnow traps (vinyl-coated or galvanized steel or plastic tapered cylinders, 42 cm long, 23 cm diameter, with openings on either side and ~10 mm mesh; are available locally in most sporting stores and should be modified to have an opening on one side large enough for smaller adult green crabs (5.0 ± 0.5 cm diameter opening).

These traps should be deployed at low tides, slightly submerged in habitats with structure or types of habitats known to harbor green crabs (e.g. deep channels, adjacent to saltmarshes, eelgrass beds (*Zostera marina*), rocky riprap). It is generally recommended that traps be deployed at 1.0 ft below MLLW if traps are deployed from shore. Fukui and minnow traps should be alternately deployed at least 20-30 m apart. At least 5 of each trap type should be deployed per site, with the spacing modified to fit the extent of the site. Traps can be tethered to a pole or structure and, in areas with strong currents, anchored with rocks or rebar to avoid loss and movement in currents. Traps should lay flat against the substrate and be anchored well enough to allow benthic epifauna to enter. Deploying traps from boats may be a more feasible method if the surrounding areas are dominated by mucky unconsolidated sediment or otherwise inaccessible. This can be accomplished by attaching weighted traps individually to buoys or along a line using long line (halibut) clips. Fresh or frozen fish or in commercial bait containers or perforated plastic tubs can be used as bait. Commercial bait containers are small perforated capsules (15 x 8 cm, with 5 mm holes) that allow the odors of the bait to diffuse yet restrict access to the bait by the trapped species. Oily fish such as herring or sardines appear to be preferred bait. Traps should be retrieved after 24 hours, but can remain deployed for up to 3 days. All captured green crabs should be sealed in containers, frozen, and preserved; identification should also be confirmed by an expert. Subsequent to confirmation, the crab may be disposed of on dry land after trapping.

The mortality of bycatch has been low using these methods and can be minimized by following a few precautions. Fastening a zip tie to each opening will reduce the aperture size in Fukui traps and thereby reduce incidental mortality of mammals, birds, and larger fish. The mortality of small bycatch species (such as crustaceans and small fish) in traps placed in the intertidal may be reduced by placing both types of traps in water filled depressions and by checking them as soon as the tide retreats the day following deployment.

A variety of other traps are used by various researchers to capture green crabs including pitfall traps and traps/structures that crabs would enter for refuge (habitat traps, piles of bags filled with oyster shells), and other types of baited box traps. Pitfall traps are 5-gallon buckets that are buried flush with the sediment and filled with water; they are passive traps designed to collect crabs as they walk across the surface. Pitfall traps, however, must be constantly maintained and monitored as they can rapidly fill with sediment and otherwise continuously catch benthic epifauna. The aggregation of epifauna in these buckets can promote predation by motile predators such as large fish or even raccoons. We also suggest marking pitfall traps to reduce the chance that a person may unwittingly step into one and hurt themselves. Habitat traps are unbaited traps that attract crabs due to the shelter and habitat aspects offered by the traps. For example, this can include any form of trap that provides shelter such as a Fukui or another box trap filled with algae and eelgrass or pipe traps (bounded lengths of PVC piping with one closed end). If an area of high water flow or energy must be sampled, use a more robust and weighted box trap to prevent damage or loss of the Fukui or minnow traps. Sturdy box traps constructed of PVC piping and hardware cloth appear to be robust to high flow areas and the powerful claws of cancrid crabs that can damage Fukui traps. However, areas with large numbers of cancrid crabs also appear less likely to harbor populations of *Carcinus* (Hunt and Behrens Yamada 2003).

Additional techniques to detect green crabs include beach seines, trawls, snorkel surveys (Grosholz et al. 2000) and by shoreline surveys for crab molts and individuals. Beach seines are particularly effective in detecting young-of-the-year green crabs (Larson et al., unpublished), but their use also has a variety of difficulties such as high levels of bycatch, long processing times, and the inability to be used in areas with lots of structure such as submerged aquatic vegetation and woody and rocky debris. Boat trawls were not an effective method of detecting *Carcinus* at one site (Bodega Harbor, CA), since *Carcinus* is not typically found in deeper waters. Snorkel surveys can be used quantitatively (along a transect) or qualitatively to detect green crabs,but are less efficient than trapping. The efficacy of these methods varies and is further evaluated in

Shoreline (walking) surveys for molts and individuals of *Carcinus*, however, are a relatively minimal cost-effective method of detecting populations of *Carcinus*. The high tide mark, where flotsam and jetsam accumulate, and shallow water should be examined for *Carcinus* molts. Crab molts are identified by the same number of spines but are often bleached in appearance. Quick qualitative shoreline surveys in other regions have been successful in detecting adult and juvenile *Carcinus* and other non-native species, even in areas where live ones have not yet been trapped (Davidson et al. 2009, Davidson and de Rivera unpublished). Heterogeneous intertidal habitats such as rocks, woody debris, and algae can harbor individuals of *Carcinus*. Rock turning, in particular, can be effective when the habitat is composed of muddy sand to sandy mud, with smaller rocks that are shallowly embedded. Monitors should be attentive while in the field; many meters of shoreline can be examined for molts and individuals of *Carcinus* and other non-native species while traveling to the trapping locations.

Where to monitor

Based on the wide physiological tolerances, documented habitat use, and survey data of *Carcinus*, monitoring for green crabs should focus on the low-intertidal to shallow subtidal zones of wave sheltered bays and estuaries. However, if large densities of cancrid crabs are present, then *Carcinus* may be found in high intertidal to mid intertidal zones. *Carcinus* should be sampled in areas with physical structure such as cobble/rock beds, shell beds, woody debris, and amongst vegetation (algae, eelgrass, saltmarsh plants) or in depressions or tidal channels. Exposed areas and areas with colder, more saline water with large populations of cancrid crabs do not appear to harbor large populations of *Carcinus* (Grosholz and Ruiz 1996; de Rivera and Larson, unpublished). Similarly, surveys by Hunt and Behrens Yamada (2003) revealed that the highest densities of *Carcinus* were found in the middle areas of the estuary between river miles 2 to 7.4, which do not harbor large populations of *Cancer productus*. Behrens Yamada and Gillespie (2008) predict green crabs may be found in the highest densities in estuaries with low salinity.

Effort

The CPUE of green crabs, a proxy for density, varies greatly among estuaries on the west coast. Central California and British Columbia harbor green crab densities that appear much larger than in Oregon and Washington. One of the premier challenges of ecology and conservation biology is determining an adequate number of samples or effort necessary to detect rare species; the analog of this problem in invasive ecology is detecting a rare invader. Determining the number of samples necessary to detect a rare species can often be aided through a statistical power analysis, but without having accurate estimates of the variance of the present population, such an analysis is not possible. However, examining the effort required to detect these relatively small populations of *Carcinus* in some embayments may allow us to determine a baseline estimate of the effort required to detect a small population of *Carcinus* in other estuaries. In addition, studies by de Rivera and Larson (unpublished) will reveal how CPUE of *Carcinus* changes with population size once population levels are verified. Populations of *Carcinus* in Oregon, Washington, and Humboldt Bay, California have been consistently low in the years following their initial large scale invasion in 1997-98. The CPUE in these embayments was less than 1 per 100 traps (per 24 hours) in Gray's Harbor, Washington and Humboldt Bay, California. During the survey of Humboldt Bay, Grosholz (unpublished data) deployed 144 traps and only caught a single green crab. Thus, it would appear deploying around 100-150 traps in a location may provide a minimal effort to detect low populations of *Carcinus*. If the number of traps available is limited, traps may be redeployed over the course of several days. Ideally, of course, deploying more traps would be preferred if logistically and economically feasible. Many of these estimates were based on traps deployed at preferred or likely locations to find green crabs given their habitat preferences and environmental constraints and during the spring and summer.

Trapping effort should be focused on these preferred habitats, as well as hotspots for other potential vectors such as aquaculture facilities, and during the late summer and at least once a year, because the population is unlikely to recruit in large numbers at multiple times a year. By late summer, crabs in all locations should be large enough to be retained in baited traps.