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Reducing effort in the U.S. American lobster (*Homarus americanus*) fishery to prevent North Atlantic right whale (*Eubalaena glacialis*) entanglements may support higher profits and long-term sustainability

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ABSTRACT

North Atlantic right whales (*Eubalaena glacialis*) feed and migrate in areas of the inshore and offshore trap fishery for American lobster (*Homarus americanus*) in the Northeast U.S. In addition to a recent increase in lethal and sub-lethal interactions with Canadian snow crab gear, entanglement in both Canadian and U.S. lobster trap gear threatens the continued existence of this endangered species. The U.S. National Marine Fisheries Service is considering a number of measures to prevent right whale entanglement bycatch that could impact lobster fishing effort. The U.S. lobster fishery in Maine expends approximately 7.5 times as much effort as the Canadian fishery in Lobster Fishing Area 34, where Canadian fishers catch about 3.7 times more lobster per trap than their counterparts in Maine. From 2007 to 2013 in Maine, lobster landings doubled as the number of traps fell 10.5% and landings per trap increased by about 125%. The state of Massachusetts has achieved record high landings since trap/pot seasonal closures have been implemented to protect right whales, especially within the Statistical Reporting Areas most affected by the closures. Therefore, a negative economic impact should not be assumed with effort reduction. In fact, reducing effort may serve to increase fishing profits while supporting the protection of endangered North Atlantic right whales and the long-term sustainability of the lobster fishery.

1. Background

The United States' National Marine Fisheries Service (NMFS) is preparing new regulations designed to reduce bycatch of endangered North Atlantic right whales (*Eubalaena glacialis*) in the American lobster (*Homarus americanus*) fishery. Entanglement in fixed fishing gear, which, in U.S. waters, is dominated by gear from the American lobster fishery, is the leading cause of mortality among North Atlantic right whales [1,2] and has important sublethal impacts on the species' ability to recover [3]. Many of the measures NMFS is considering could lead to a reduction in fishing effort. Myers et al. [4] showed how reducing effort would benefit both the U.S. lobster industry and the North Atlantic right whale by improving efficiency in the fishery and removing lines that pose an entanglement risk. Here we extend that concept by exploring how overcapacity and effort reduction are connected to American lobster landings and revenue in the U.S. fishery.

1.1. The U.S. American lobster fishery

The American lobster fishery is the United States' most valuable fishery by gross revenue,[1] bringing in over US $670 million in landings 2016 [5]. It is based in the Northeast, especially the states of Maine, Massachusetts, New Hampshire, and Rhode Island, and is fished using fixed trap/pot fishing gear. Trap/pot fishing gear consists of a baited trap or string of traps (referred to as a trawl) on the seafloor connected to a surface buoy with a vertical buoyline or "endline." The surface buoy and endline serve to mark the location of the trap or trawl for the owner and other fixed and mobile fishing gear (i.e. scallop dredge and bottom trawl) operators operating in the area, as well as to allow the traps to be hauled up through the water column. The rope connecting traps in a

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[1] Highest gross revenue does not necessarily reflect highest profit or net revenue; fisheries operating with overcapacity are likely to have lower net revenues than those operating at optimal efficiency.

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trawl is referred to as "groundline."

Since 2007, NMFS has required fishers in most areas to use sinking or neutrally buoyant groundline due to the potential for floating groundline to entangle North Atlantic right whales [6]. However, North Atlantic right whales and other protected species—including humpback, fin, sei, and minke whales and loggerhead and leatherback sea turtles—are known to become entangled in trap/pot endlines [7,8] (Fig. 1). Entanglement involvement with endlines has been the most commonly identified right whale interaction since the sinking groundline rule went into effect [9]; since 2007, line consistent with endlines has been recovered from entangled whales about ten times more often than line consistent with groundline [10]. The U.S. American lobster fishery employs an estimated 912,300 vertical endlines during peak fishing months—many of which are within the North Atlantic right whale's designated Critical Habitat Area [11,12] (Figs. 2 and 3). The rope used for endlines has become substantially stronger over recent decades as manufacturing techniques have evolved, likely contributing to an increase in right whale entanglement severity and mortality as whales are less able to break free of entangling line and gear [13].

The Atlantic States Marine Fisheries Commission (ASMFC) [14] has divided the U.S. lobster stock into three biological areas: the Gulf of Maine, Georges Bank, and southern New England (Fig. 4). The Gulf of Maine stock accounts for greater than 90% of U.S. lobster landings and is primarily an inshore fishery [15]. The Georges Bank stock has represented an average of 5% of total U.S. landings over the last several decades and is mainly an offshore fishery [15]. The Gulf of Maine and Georges Bank stocks are heavily fished, especially in the fall, but stock abundance is also high [15]. The southern New England stock historically contributed the second highest lobster landings, but dramatic declines in recent years lowered the contribution of this stock to just 2% of the U.S. total in 2013 [15]. During this time the offshore component of the southern New England fishery has grown as the inshore fishery collapsed. The southern New England stock is listed as severely depleted [15].

The U.S. American lobster fishery has experienced robust landings growth in recent decades, with peak landings in 2016 of over 72,000 metric tons (nearly 160 million pounds) valued at more than $670 million [5]. Landings value has also shown consistent growth. Total U.S. American lobster landings weight increased by 2.78 times from 1992 to 2016, while landings value increased by 2.24 times when adjusted for inflation (4.03 times nominal value)[2] (Fig. 5).

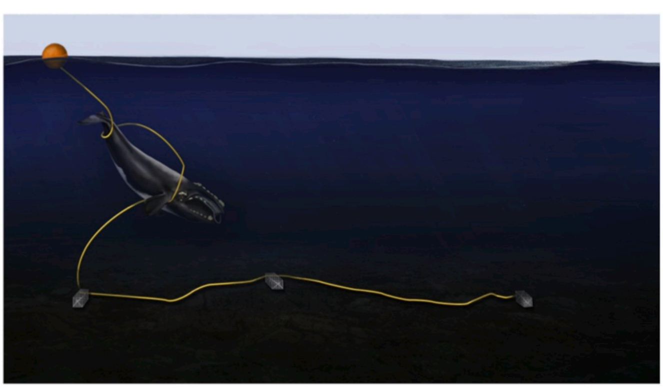

Fig. 1. Illustration of a North Atlantic right whale entangled in vertical endline, showing the surface buoy, endline, and string of traps or "trawl" connected by sinking groundline. Credit: Natalie Renier, Woods Hole Oceanographic Institution.

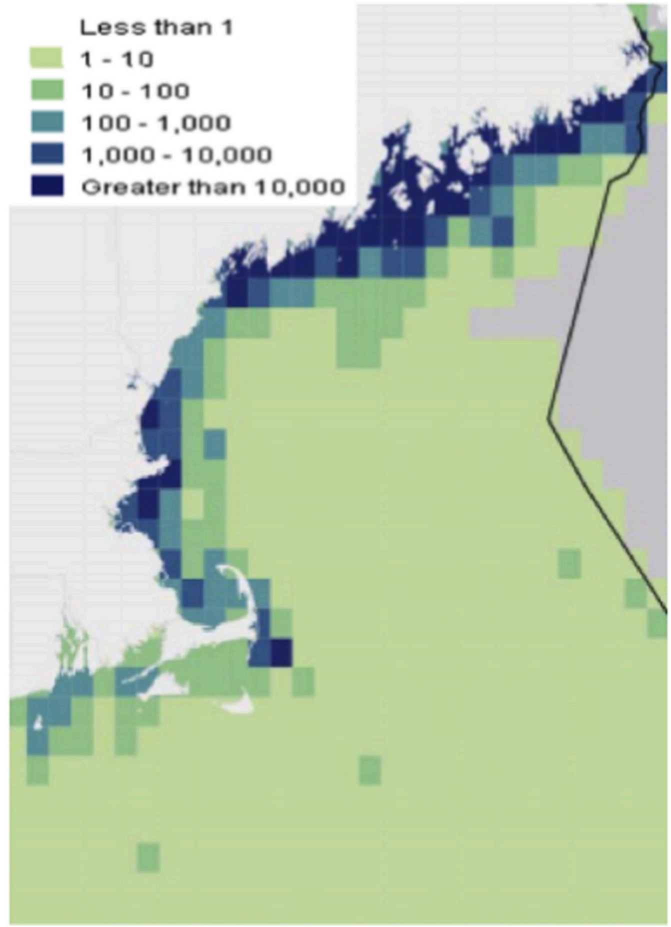

Fig. 2. (left): Map of estimated commercial trap/pot endline density (number of endlines per 100 square nautical miles) in September in the Northeast U.S. using 2016 and 2017 fisheries data. The total number of commercial trap/pot endlines in use in the Northeast region in September is estimated to be 920,500, 912,300 of which are used to catch lobster.
Source: NMFS co-occurrence model 2019 [12]; https://www.greateratlantic.fisheries.noaa.gov/protected/whaletrp/trt/meetings/April%202019/apr_16_risk_reduction_decision_tool_webinar_full_slide_deck.pdf

This growth in landings has not been driven by increased participation in the fishery: the total number of participants has fallen from an estimated 13,000 in 1997 to 8,485 in 2019 [17,18]. Fishers can be licensed to harvest in state-managed waters (zero to three miles from shore), federally managed waters (three or more miles from shore), or both. For example, 27% of fishers with commercial Massachusetts state licenses also have federal licenses [92]. However, in 1999 NMFS indefinitely extended a moratorium on issuing new federal licenses in an effort to control overfishing and rebuild lobster stocks [20]. The number

[2] Lobster has been shown to be price inelastic at the retail-store level [100], meaning that higher prices should lead to higher profits because demand will decrease less than the relative increase in price. However, this is not necessarily reflected in ex-vessel landings value, which is the value fishers receive when selling their catch (primarily to lobster dealers). For example, in the summer of 2012 in Maine a glut of soft-shelled lobsters caused prices to plummet, leading some fishers to voluntarily pause harvesting to reduce supply.

Fig. 3. (right): Map of North Atlantic right whale designated critical habitat area in the Northeast U.S.
Source: [11]; available at https://www.fisheries.noaa.gov/resource/map/north-atlantic-right-whale-critical-habitat-map-and-gis-data.

of federal licenses has since fallen from 3313 to 2103 in 2018 [15,21].

Fewer fishers are now bringing in much higher revenue, although costs (especially fuel and bait) have not remained stagnant. Although the gross value of the fishery is high, profitability is variable and especially dependent on fuel and bait costs and ex-vessel price. Previous studies have shown that while net returns in the fishery are positive, profit margins are slim and the return to owner-operator labor is often below the prevailing wage that could be earned in alternative professions [22]. Although real landings value has increased by approximately 60% since the most recent of these studies (2005–2016) (Fig. 5), input costs and ex-vessel price have also changed. For example, the real price of diesel fuel varied from approximately US $3.20 in 2005 to over $4 from 2011 to 2014 to a low of $2.50 in 2016 [23], and real ex-vessel price per pound fell from US $2.37 in 2005 to $2.10 in 2016 [5].[3] Therefore, the extent to which the recent lobster landings boom has been reflected in net profits is unclear.

Instead of increased participation, rising water temperatures in the northwest Atlantic Ocean appear to be contributing to increased recruitment in the Gulf of Maine stock and may be an important driver of recent high landings [15]. Water temperature strongly influences lobster life history, and in recent years the Gulf of Maine has experienced longer time periods within the optimal temperature range for lobsters of 12°–18 °C [15]. However, strong growth in the U.S. American lobster fishery should not necessarily be expected to continue. When water temperatures increase beyond their optimal range, lobsters experience stressful conditions that can cause a number of health issues, disease, and poor recruitment [15]. Together with heavy fishing pressure, ocean warming has been an important factor in the collapse of the southern New England stock; many portions of the inshore environment in southern New England now experience prolonged time periods where water temperature exceeds 20 °C [15]. The Gulf of Maine is among the most rapidly warming bodies of water in the world [24,25], so current high levels of recruitment may not be sustained. In the most recent stock assessment from 2015, three of the five young of year indicators for the Gulf of Maine—which help indicate future sustainability of the stock—were low [15]. Oppenheim et al. [26] have also predicted that Gulf of Maine lobster landings will decline to near-historical levels (i.e. a 65 to 75% decrease) within the next decade as the lobster population continues to shift poleward in a warming ocean.

1.2. North Atlantic right whales

Once numbering in the tens of thousands [27], at the end of 2018 there were an estimated 409 North Atlantic right whales remaining [1,28]. The population grew slowly from a low of approximately 270 animals in 1990 to 482 in 2010, but has since declined rapidly [28] (Fig. 6). Only approximately 90 reproductive-aged females remain in the population [28,36]. NMFS has calculated Potential Biological Removal (PBR) for North Atlantic right whales at 0.9, meaning that less than one animal can be killed each year due to human activity while still allowing the population to recover [7]. With continued high rates of anthropogenic mortality, the population could be functionally extinct within several decades [37].

North Atlantic right whales are protected under the U.S.'s Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA) and Canada's Species at Risk Act. In addition to the legal imperative to protect this species, North Atlantic right whales are also highly valued by the public and provide vital ecosystem services. In a survey of American households, participants indicated that they were willing to pay an average of US $72 every year for ten years for the recovery of North Atlantic right whales, and US $39 annually for them to be downlisted from endangered to threatened [38]. Large whales such as right whales are also increasingly recognized for their important role in sequestering carbon from the atmosphere into the deep sea and in mixing and transporting nutrients to support primary productivity in marine ecosystems [39–41]. A recent estimate placed the value of an average individual large whale at over US $2 million in terms of carbon sequestration, fisheries productivity enhancement, and ecotourism [42].

Entanglement in fishing gear and vessel strikes are responsible for all diagnosed adult North Atlantic right whale mortalities since 1970; no adults are known to have died of natural causes in almost fifty years (though many mortalities are not observed or diagnosed) [2,32]. Entanglement was the cause of death in 72% of diagnosed adult mortalities since the population has been in decline (from 2010 to 2018), but only 35% from 2000 to 2009 [2,32]. The incidence of fatal vessel strikes has fallen substantially since the 2008 Ship Strike Rule was implemented on the U.S. East Coast [43], though vessel strikes have caused high numbers of right whale mortalities since 2017 particularly in Canada's

[3] A time series of bait input costs is difficult to obtain due to the potential for fishers to switch bait types in response to changes in price and availability.

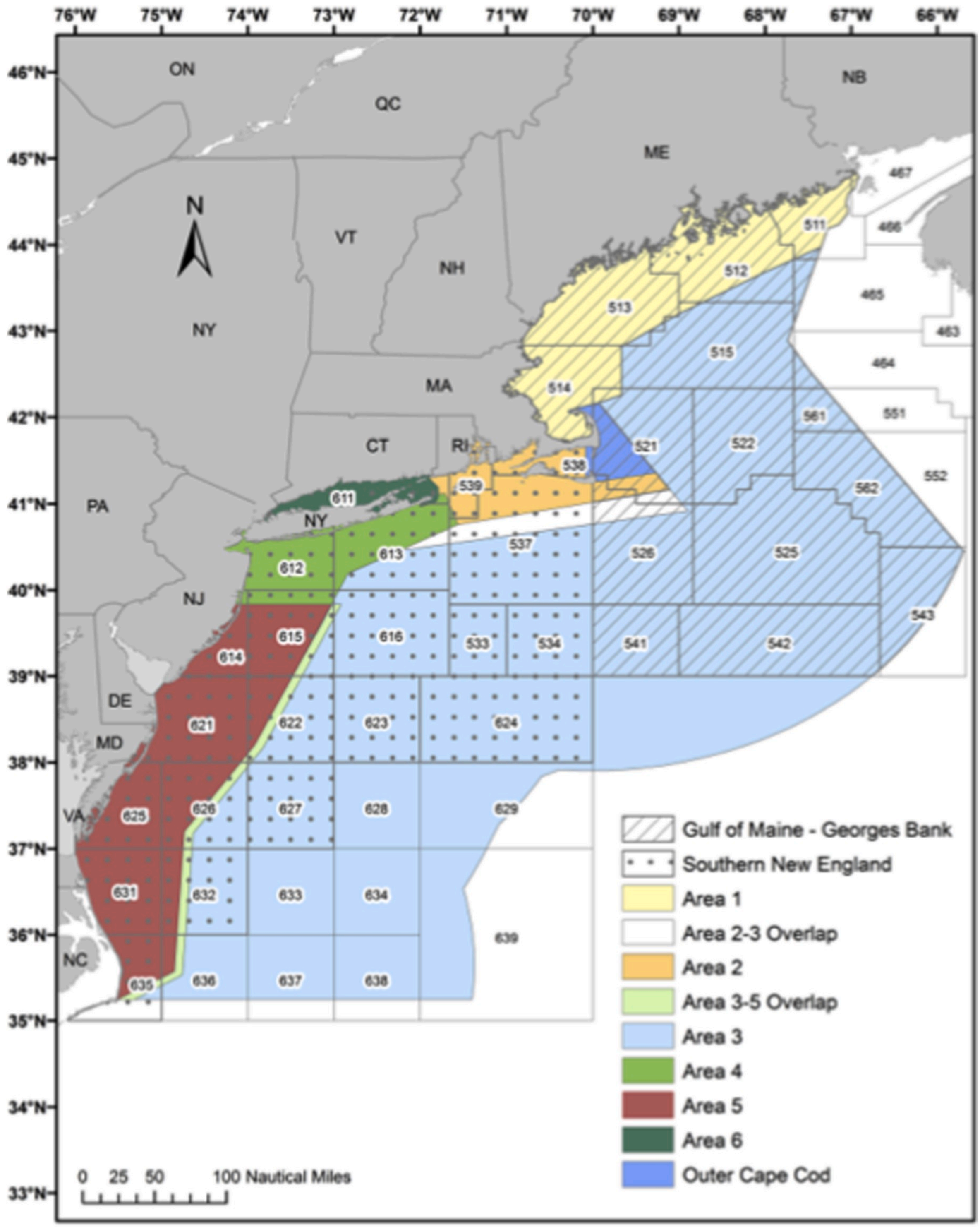

Fig. 4. Map of Lobster Management Areas showing Gulf of Maine - Georges Bank and southern New England lobster stock areas, and NMFS Statistical Reporting Areas.
Source: Atlantic States Marine Fisheries Commission, Map of Stock Assessment and Management Areas [14]; available at http://www.asmfc.org/uploads/file//58f8cd9aLobsterManagement_StockArea_Map_Nov2016.JPG

Gulf of Saint Lawrence [1].

Entanglement is very common among North Atlantic right whales: in a 2012 study, 83% of right whales showed scars from entanglements and an estimated 26 percent—or approximately 100 animals—are entangled each year [44]. Right whale serious injuries and mortalities in U.S. waters from entanglement alone—excluding entanglements known to be caused by Canadian gear—have exceeded PBR every year except for two since 2000 [45]. In their most recent ESA Section 7 consultation on the impacts of the American lobster fishery, NMFS stated that U.S. lobster fishing gear is likely to kill 3.25 animals annually [46].

North Atlantic right whales are broadly distributed on the continental shelf from Florida to Newfoundland and can be found in areas likely to overlap with trap/pot fisheries throughout the year [47,48]. Rope taken off entangled whales has been tracked to fisheries

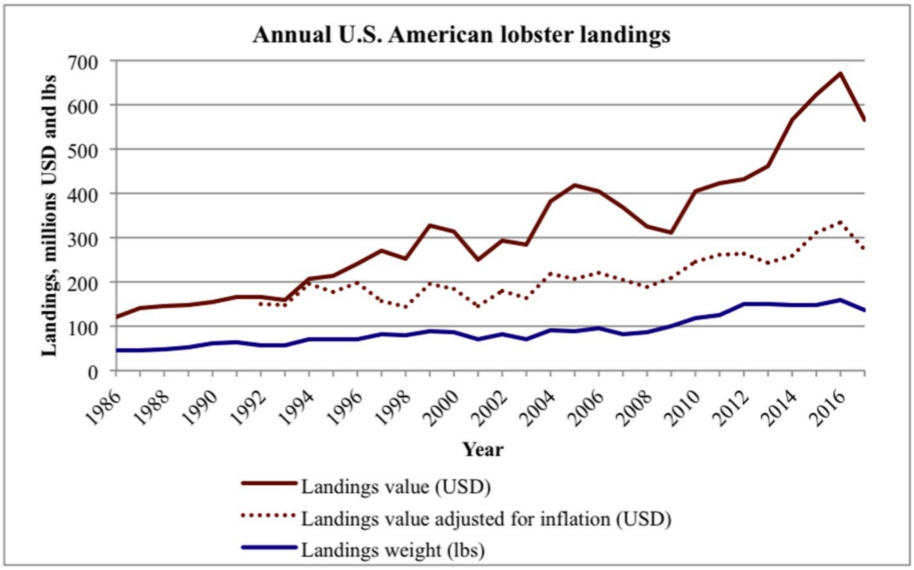

Fig. 5. U.S. annual commercial lobster landings weight and value (nominal and adjusted for inflation) from 1986 to 2017. Inflation adjustment was made using the Producer Price Index (PPI) for Unprocessed Shellfish indexed to December 1991 (PPI not available for 1986 to 1991). Landings data from National Marine Fisheries Service (NMFS) Annual Commercial Landing Statistics 2019 [5]; PPI from U.S. Bureau of Labor Statistics [16].

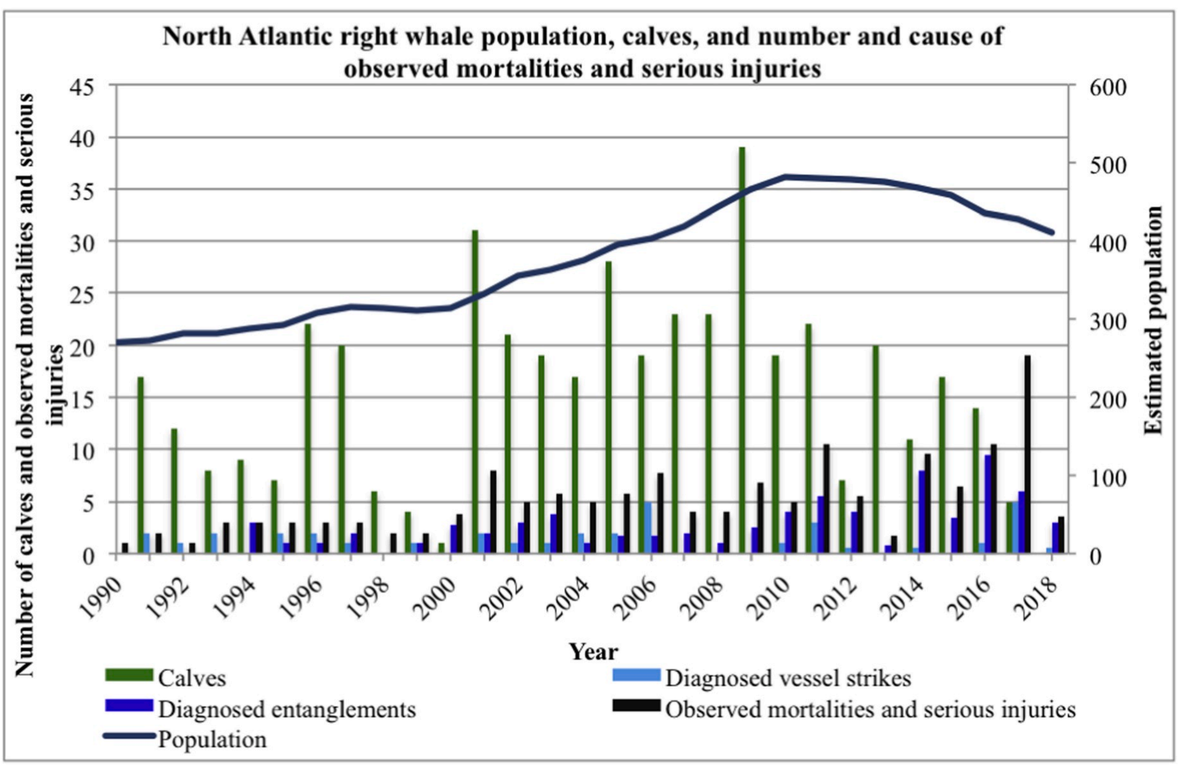

Fig. 6. Estimated North Atlantic right whale population, number of calves, observed mortalities and serious injuries, and diagnosed cause of death or serious injury. Diagnosed entanglements have increased significantly since the population has been in decline.
Data from Ref. [7,28–34]; available https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901 and NOAA Northeast Fisheries Science Center (unpublished) [35]; available at https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901.

throughout these areas [36] (Fig. 7). However, fishing gear from most right whale entanglements is not traced back to a particular area [45], likely due at least in part to a lack of gear marking throughout significant portions of the U.S. and Canadian fisheries, such as most of inshore Maine.

In addition to mortalities, entanglement has serious sublethal impacts on North Atlantic right whales that likely inhibit the species' ability to recover [3]. Right whales can produce up to an estimated 8, 000lbs of force with a single stroke of their flukes [49], so they will often continue to swim while entangled in rope and/or associated traps and buoys. Entangling gear creates substantial drag for a swimming animal, and the energetic demands of an entanglement are comparable to or exceed those of other major life history events such as migration and pregnancy [3,50].

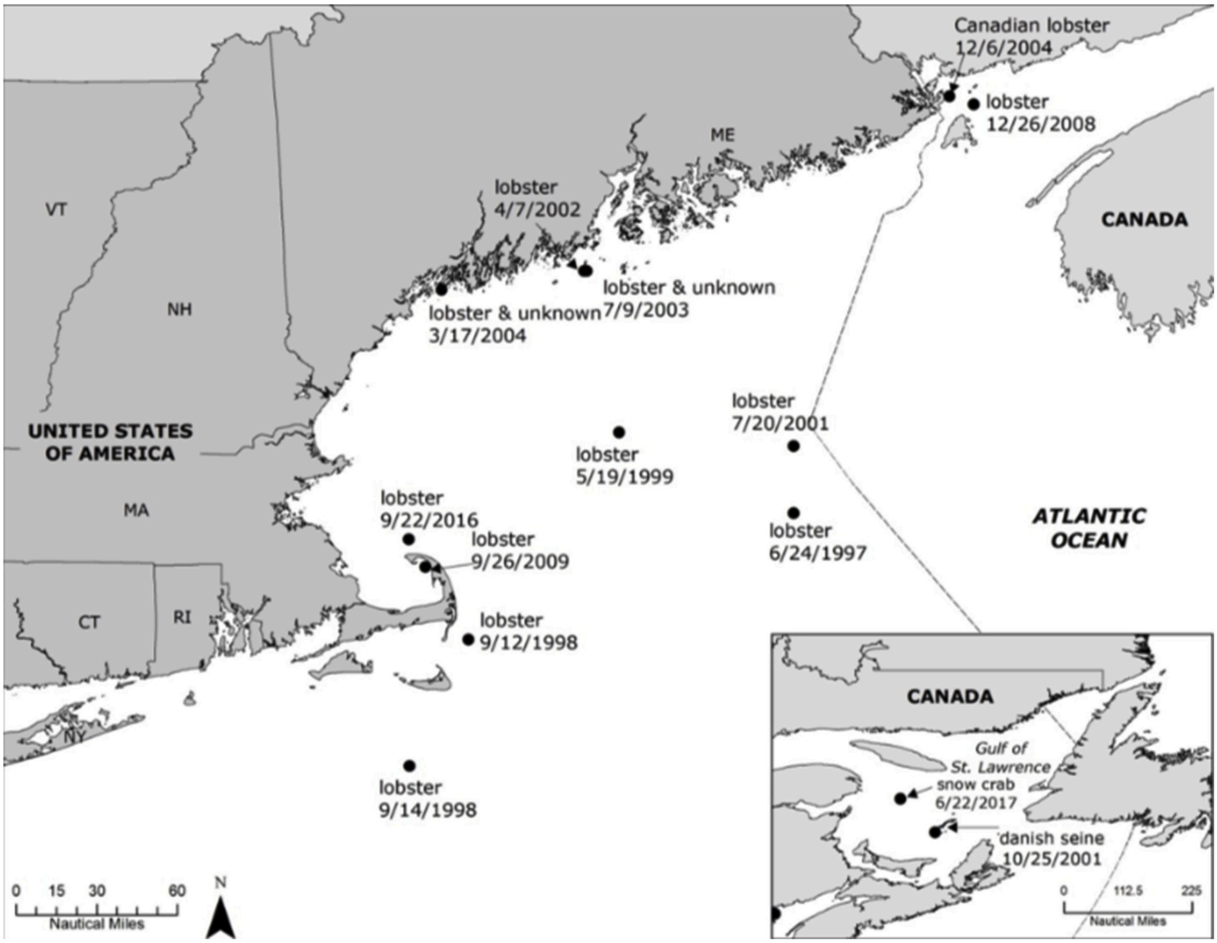

Fig. 7. Map of North Atlantic right whale entanglements from 1997 to 2017 for which the set location and gear type are known and gear was recovered from a whale. Source: [36]

For reproductive females, the energetic costs of entanglement can extend the amount of time needed to recover fat stores following pregnancy, calving and lactation, potentially delaying the female's ability to become pregnant [3]. In recent years, the average calving interval for reproductive females has stretched from three to ten years [1], likely due at least in part to the costs of entanglement on the population. Females have approximately a five percent chance of not becoming entangled during that ten-year period [36].

Entanglement also poses a serious animal welfare concern. The MMPA limits "take" of marine mammals, defined as harassment, hunting, capture, killing or the attempt to harass, hunt, capture or kill, but also specifies that takes must be humane—wherein the term "humane" means "that method of taking which involves the least possible degree of pain and suffering practicable to the mammal involved" [51]. When a right whale becomes entangled, the line and gear can wrap around the animal's body, flukes, flippers and mouth—impeding swimming and feeding, causing chronic infection, emaciation, and damage to blubber, muscle, and bone [2,52–55] (Fig. 8). It can take months to years for a North Atlantic right whale to die of entanglement, during which time it experiences extreme pain and debilitation [52–56]. For example, entanglement is known to have caused fatal scoliosis in a juvenile whale due to the strain of dragging fishing gear as a young animal (Fig. 9) and nearly severed flippers on multiple animals swimming in up to 30 to 50 wraps of constricting rope (Fig. 10) [2].

Fig. 8. Fishing rope furrowed into the lip of Bayla, North Atlantic right whale #3911. A small fragment of plastic-covered mesh was recovered from this entanglement. The mesh size was comparable to that used in lobster traps. Credit: Michael Moore, NMFS Permit 932-1905-00/MA-009526.

Fig. 9. North Atlantic right whale (CALO0901, 3710) with debilitating abnormal curvature of the spine (scoliosis) caused by an entanglement. This injury caused chronic damage to the spine, which ultimately led to the young animal's death. Image credit: University of North Carolina Wilmington; NMFS Permit No. 932–1489.

Fig. 10. a (top: North Atlantic right whale (SC118) with 13 constricting wraps of fishing line around a pectoral flipper that caused a partial amputation. Fig. 10b (bottom): Deep furrow created by fishing line sawing into the humerus of the same whale over time, and the bone's unsuccessful attempt to repair this injury. Image credit: NOAA National Ocean Service Center for Coastal Environmental Health and Biomolecular Research Coastal Marine Mammal Strandings and Assessments Project; NMFS Permit No. 932-1905.

1.3. Regulatory processes concerning the U.S. American lobster fishery and North Atlantic right whales

The U.S. American lobster fishery is cooperatively managed by the states (zero to three miles from shore) and NMFS (three or more miles from shore) under the framework of the ASMFC. State waters regulations are promulgated by the respective government agencies, i.e. the Maine Department of Marine Resources and Massachusetts Division of Marine Fisheries, while complementary federal water regulations are promulgated by NMFS. The ASMFC assesses the fishery according to seven Lobster Management Areas (LMAs) (Fig. 4), of which LMA 1 is the most productive, with 92.5% of total catch in 2012 (the most recent year for which landings by LMA are available) [57]. In cases where state and federal regulations differ, the most restrictive rule applies.

The Atlantic Large Whale Take Reduction Team (ALWTRT), a group of fishers, scientists, conservationists, and state and federal officials, was created in 1996 as mandated by the Marine Mammal Protection Act. The ALWTRT is designed to advise NMFS on steps to reduce incidental take (or killing) of large whales in Atlantic fixed gear (trap/pot and gillnet) fisheries to a level below PBR [17]. Although the ALWTRT is mandated to reduce take of all large whale species affected by the fisheries, in recent years the ALWTRT has focused on North Atlantic right whales due to the urgency of the right whale entanglement crisis and the potential for this species to become extinct in the near future.

Since 1997, NMFS has taken a series of management actions, some of which were recommended by the ALWTRT, to identify and reduce North Atlantic right whale bycatch [36]. These include gear marking requirements, surface weak links, sinking groundlines, trap limits, minimum numbers of traps per endline, and seasonal fishery closures [36]. However, right whale entanglement mortalities and serious injuries have increased substantially over the same period and the population trajectory has reversed from modest growth to rapid decline. Though a number of factors have likely contributed to the rising entanglement mortality rate, including stronger fishing rope [13] and climate change-related shifts in right whale distribution [25], protective measures to date have failed to demonstrably reduce total right whale entanglement risk and mortalities [58]. Between June 2017 and September 2019, 30 North Atlantic right whales were found dead in U.S. and Canadian waters in an Unusual Mortality Event (UME) [48,59]. This UME has brought renewed urgency to the ALWTRT and NMFS rule-making processes.

At the April 2019 ALWTRT meeting, NMFS indicated an intent to develop and implement new rules to reduce North Atlantic right whale bycatch by 60–80% and asked Team members to generate proposals to meet that risk reduction target [60]. At the end of the meeting, the Team reached near-consensus agreement on a suite of measures implemented by state and federal management area [61]. The primary risk reduction measures agreed upon were:

1. Reductions in the number of endlines fished by 18–50%
2. Use of reduced breaking strength (less than 1,700lbs force) endlines

There were notable differences in the recommendations from different caucus groups within the ALWTRT. The fishing industry and state management representatives focused on endline reductions and reduced breaking strength rope, while the conservation non-governmental organization (NGO) members also recommended:

3. Additional time/area fishery closures in North Atlantic right whale aggregation areas
4. Rapid research using and steps toward implementation of ropeless fishing gear (defined as gear that does not use endlines prior to gear retrieval)

Additional seasonal closures and ropeless gear testing and/or implementation were not included in the near-consensus recommendations [61], but are likely to be continually considered as part of ongoing efforts to reduce large whale bycatch in the fishery.

The ALWTRT's near-consensus subsequently withered as members of the Maine ALWTRT caucus withdrew their support [62,63].[4] However, the purpose of the ALWTRT is to make consensus-based recommendations to NMFS, and under the MMPA NMFS is responsible for implementing measures to reduce serious injuries and mortalities to below PBR regardless of whether the Team reaches consensus [51]. NMFS therefore indicated their intent to move forward with regulations [64]. In August 2019, NMFS published a notice of intent to prepare an environmental impact statement and a request for public comments on proposed modifications to the Atlantic Large Whale Take Reduction Plan, which was based on the ALWTRT's risk reduction framework [65]. NMFS is tentatively expected to release a proposed rule including the ALWTRT's recommendations in 2020, with a final rule expected thereafter.

2. Potential impacts of proposed regulations on fishing effort

Each of the major management measures NMFS is considering to reduce right whale bycatch could have an impact on fishing effort, described here by the number of traps or trap days used, as explained below. If the lobster fishery is operating efficiently, then a reduction in effort would likely lead to reduced landings and potentially lower revenue (depending on the extent to which price rises in response to a contraction of supply). In contrast, if the exploitation rate in the lobster fishery is above optimum efficiency, reducing effort would likely allow lobster biomass to build up so that catch rates remain high with substantially reduced operating costs [4,66]. Understanding how effort reduction could impact the fishery is important for federal and state regulators, the fishing industry, and conservation interests.

2.1. Reductions in the number of endlines fished

There are multiple ways in which an endline reduction can be implemented: (1) directly, such as through a vertical endline cap that could be administered similar to trap tags (numbered tags placed on each trap to ensure fishers are compliant with trap limits), and (2) indirectly, such as through a trap limit reduction combined with a set minimum number of traps per trawl. In either case, it is imperative that a vertical endline reduction be implemented as a reduction from the actual number of endlines fished, not from the amount currently allowed under regulations, for such a measure to have the expected entanglement risk reduction benefit for right whales. This is because in many areas of the fishery actual effort is lower than regulations allow. If, for example, the trap limit was reduced from 800 to 600 traps in an area where fishers use 550 traps on average, the measure would have significantly less than a 25% entanglement risk reduction benefit.

If a direct endline cap were to be pursued, the endline reduction would not necessarily lead to an equivalent reduction in the number of traps fished, because many fishers can add traps to trawls in order to continue fishing their standard number of traps. However, vessel and other equipment constraints would likely limit some individuals from fishing their full trap allocation.[5] For example, fishers operating offshore in LMA3 often already fish long trawls of 20 or more traps and may have a limited ability to add more traps per endline. Fishers who operate on small vessels inshore may not have sufficient mechanical hauling strength to fish longer trawls. Therefore, we expect an endline cap to lead to a reduction in effort that is greater than zero but less than the amount of the endline reduction (for example, a 50% endline reduction will lead to a trap reduction between 0 and 50%).

In contrast, an indirect endline reduction implemented through a trap reduction and minimum number of traps per trawl would have a direct impact on effort, provided that the reduction is from the actual number of traps fished. However, in many areas fishers do not fish the full trap limit and may already exceed minimum trap-per-trawl requirements. Therefore, if trap reductions and minimum trap-per-trawl rules are updated from current regulations rather than set according to actual fishing practices, an indirect endline reduction may have less than the expected effect. For example, a 25% trap reduction paired with a 25% increase in the number of traps per trawl would likely lead to less than the expected 40% reduction in endlines and 25% reduction in number of traps.

2.2. Use of reduced breaking strength (less than 1,700lbs force) endlines

Of the proposed measures, the use of reduced breaking strength endlines has the least clear impact on effort, and may not lead to an appreciable reduction in the number of traps fished. Because right whales can more easily break free of entanglements involving weaker rope, use of fishing rope that breaks at or below a threshold of 1,700lbs of force is expected to lessen the severity of entanglements, though not their incidence [13]. If fishers find that 1,700lb breaking strength rope cannot adequately handle their trawls as currently configured, they may consider reducing the number of traps per trawl so as to reduce the load on the endline when hauling (although there are also requirements on the minimum number of trap per trawl). However, other reconfigurations, such as lengthening the groundline between the first and second traps in a trawl, may similarly reduce the load on the endline without reducing the number of traps per trawl.

2.3. Additional time/area fishery closures in North Atlantic right whale aggregation areas

Seasonal closures would have a direct impact on fishing effort by requiring complete removal of fishing gear from an area for a period of time. The extent to which seasonal closures will impact fishing effort depends on the duration of the closure, season, and area fished. Although fishers are currently allowed to harvest American lobster year-round other than within specific seasonal closures (including Cape Cod Bay and some surrounding areas from February to April and the Great South Channel from April to June), there are significant differences in effort and landings by season. For example, in many areas landings are highest in the fall, while late winter and early spring bring in a significantly lower harvest [15]. However, some fishers keep their gear in the water even when harvest is minimal,[6] and endlines pose the same whale bycatch threat regardless of how much lobster is being harvested.

Neither fishing effort nor right whales are evenly distributed across the fishery; seasonal closures aim to identify areas and periods of highest risk. One particular area of concern discussed at the April 2019 ALWTRT meeting is south of Martha's Vineyard and Nantucket in NMFS Statistical Reporting Area 537 [61]. This area falls outside of right whale designated Critical Habitat Area, but right whales have maintained a near-constant presence in Area 537 over the last three years and have frequently been observed aggregating there in large numbers—sometimes more than 100 individuals [48,61]. Their presence has triggered NMFS to implement a number of successive Dynamic Management Areas, where mariners are asked (but not required) to avoid the area or reduce vessel speed to 10 knots or less [67]. Effort in this area is relatively low, but the offshore lobster industry operating there uses heavy fishing gear [12,61]. Heavy fishing gear is of particular concern

[4] The Atlantic Large Whale Take Reduction Team and Plan is the least successful of the five take reduction processes in the United States [98]. The large size of the team, broad scope of the plan, and regulations that are complex and difficult to enforce may be reasons for its comparative difficulty reaching consensus and crafting effective take reduction measures [98,99].

[5] Most fishers in the U.S. lobster fishery are licensed to use up to 800 traps, though there are important differences by area, especially in LMA3 where fishers may use up to 1945 traps [72].

[6] Marine mammal regulations require that lobster traps be hauled back only once every 30 days [72].

because it is more difficult for right whales to break free of and therefore more likely to cause a severe or fatal entanglement.

2.4. Use of ropeless fishing gear

Instead of leaving an endline in the water continuously, ropeless fishing gear releases a buoy and endline or inflates a lift bag to come to the surface when a fisher sends an acoustic command to retrieve their trawl [68] (Fig. 11). Alternatively, many fishers already use a customized hook to catch the groundline between traps and haul their gear to the surface—called grappling—when the permanent buoy or endline go missing [68]. Both acoustic-release ropeless fishing and grappling have the potential to eliminate entanglement in endlines. However, most acoustic-release ropeless fishing systems and virtual trap-marking systems are still in the research and development phase, and concerted effort and investment is required before large-scale commercial deployment is feasible [68].

Ropeless fishing gear may take longer to retrieve than traditional methods due to the added time needed to triangulate on gear position using acoustic signals and/or the time needed to grapple [68]. This may be particularly relevant for early adopters of ropeless gear; time costs may go down as fishers become accustomed to different retrieval methods and technologies are iteratively improved. If fishers are not able to haul as many trawls per day when fishing ropeless, ropeless fishing could effectively cause a reduction in effort. Additionally, the upfront costs of transitioning to ropeless fishing gear may be too high for fishers to replace all of their endlines at once. Combining a transition to ropeless fishing gear with an endline or trap reduction could make the upfront investment more feasible.

On the other hand, ropeless fishing could offer a solution for fishers facing an endline reduction: if allowed by federal and/or state regulations,[7] fishers could replace some of their endlines with ropeless retrieval units to meet endline reduction requirements. Fishers using ropeless gear may also be allowed access to areas that would otherwise be closed to trap/pot fishing. Therefore, the potential overall impact of ropeless fishing on effort depends on implementation.

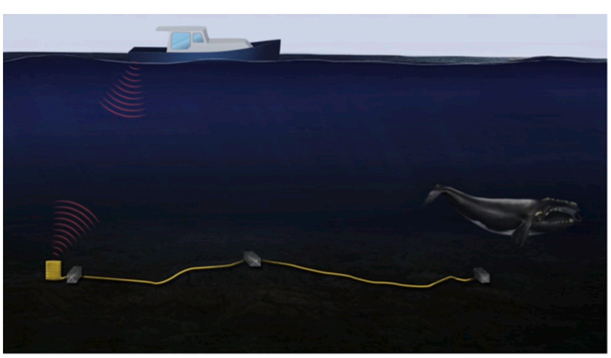

Fig. 11. Illustration of acoustic-release ropeless fishing gear. Upon receiving an acoustic trigger, a buoy and endline attached to a trap at the end of a trawl deploys for retrieval or a lift bag inflates and brings the attached trap and trawl to the surface. Endlines are only used during gear retrieval, or not at all if a lift bag is used. A virtual trap marker visible on a screen in the vessel would replace the marker buoy. Credit: Natalie Renier, Woods Hole Oceanographic Institution.

[7] Current federal and state regulations require the use of surface marking systems that use endlines in the American lobster fishery [72]. However, NMFS and some state agencies have demonstrated interest in supporting ropeless gear development and use.

3. Overcapacity and effort reduction in the U.S. lobster fishery

We examined three case studies to describe how fishing effort has correlated with landings in the U.S. lobster fishery:

A. Comparison of lobster fishing effort on the U.S. (Maine) and Canadian (Lobster Fishing Area 34) sides of the Gulf of Maine in terms of number of traps and season days
B. State of Maine landings and number of traps over time
C. Landings within the Massachusetts Restricted Area seasonal trap/pot closure and Massachusetts statewide landings since the closure was implemented

We used publicly available[8] landings data, price indices, and trap and license counts and the longest available time series up to 1986 in order to show decadal trends.

3.1. Effort and landings in the Gulf of Maine: Maine compared to Lobster Fishing Area 34

We employ a comparison of the lobster fishery on the U.S. and Canadian sides of the Hague Line, the North Atlantic boundary between U.S. and Canadian fishing waters, in 2016 and 2017.[9] U.S. landings data are from state- and federally licensed vessels landing in the state of Maine; Canadian landings are from Lobster Fishing Area (LFA) 34 (Fig. 12). These two areas share similar biological characteristics and have both experienced record landings in recent years following four decades of landings growth [4,5,71]. However, the Maine lobster fishery has a much higher trap limit (800 traps in most inshore areas and up to 1945 in offshore LMA 3) and is allowed to fish year round, whereas LFA 34 is restricted to about one half of the trap limit for most Maine fishers (375–400 traps) and fishing is restricted to a winter season from the last Monday in November to May 31st to control lobster harvest [72,73].

To compare effort in Maine and LFA 34, we compared lobster landings, number of traps, and season days in each area in 2016 and 2017, the two most recent years for which data are available (Table 1). LFA 34 data are provided by fishing season; in this analysis 2016 refers to the 2015/2016 fishing season and 2017 refers to the 2016/2017 fishing season. For the state of Maine, the number of traps is the number of trap tags sold, as published by the state of Maine Department of Marine Resources [74]. For LFA 34, we calculated the number of traps as the trap limit (383[10]) multiplied by the number of licenses (979) [73]. We calculate an indicator of overcapacity in Maine compared to LFA 34 as:

Overcapacity in Maine versus LFA 34 = (number of traps x season days)/landings

In Maine, fishers use nearly eight times as many traps to catch about twice as much lobster as fishers in LFA 34 (Table 1). Since the lobster fishing season in Maine is almost twice as long as that in LFA 34, we calculate that effort in Maine is approximately 7.5 times higher than that

[8] Some data sets used are not publicly published but are available upon request to the relevant state or federal agency.

[9] [Myers et al. [4] also employed a comparison of the U.S. and Canadian lobster fisheries across the Hague Line and found that U.S. effort was about 13 times higher than Canadian. However, Myers et al. [4] compared landings and traps in the U.S.'s Lobster Management Area 1 and Canada's Lobster Fishing Area 34 and calculated effort using different assumptions. We chose to compare the state of Maine and LFA 34 because more recent and complete landings and effort data were available. Therefore, these two studies should not be directly compared, although the conclusion that the U.S. Gulf of Maine fishery is operating at substantial overcapacity holds in both assessments.

[10] The trap limit in LFA 34 is 375 for approximately two thirds of the season and 400 for one third of the season [73]. We therefore used a scaled trap multiplier of 383.

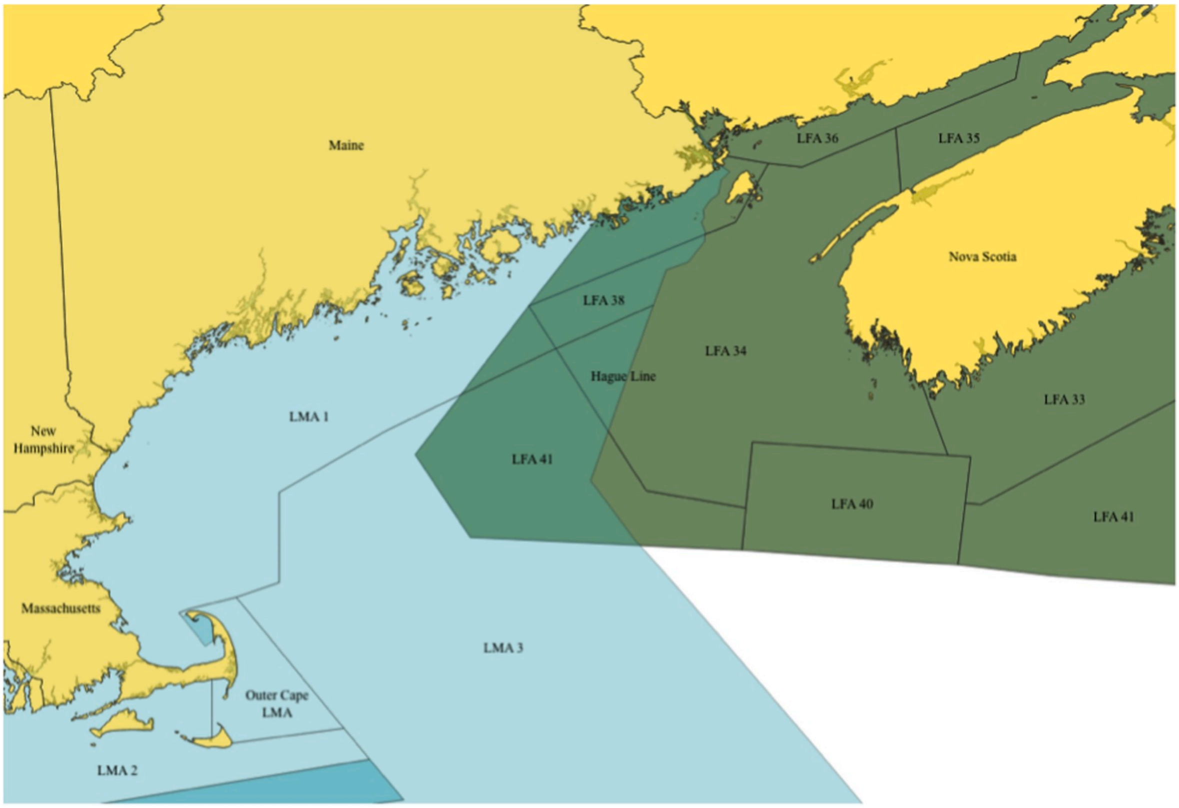

Fig. 12. Map of U.S. Lobster Management Areas (LMAs) and Canadian Lobster Fishing Areas (LFAs) in the Gulf of Maine divided by the Hague Line. Maine landings and effort (primarily from LMA1 and LMA3) are compared to landings and effort in LFA 34. This map shows the U.S. definition of the Hague Line, Canada disputes a small portion encompassing lucrative fishing waters off Machias Seal Island. Map created in QGIS using shapefiles from [69,70].

Table 1a
Landings, number of traps, and season days in Maine versus Lobster Fishing Area (LFA) 34 in 2016 (LFA 34's 2015/2016 fishing season). Maine fishers used approximately 7.55 times as much effort as fishers in LFA 34 to harvest the same amount of lobster. Maine landings data from National Marine Fisheries Service [5] and number of traps from Maine Department of Marine Resources [74]. LFA 34 landings, number of licenses, trap limits, and season days from Fisheries and Oceans Canada [73].

Lobster Fishing Effort in Maine versus Lobster Fishing Area 34, 2016			
	Maine	LFA 34	Maine/LFA 34
Landings (metric tons)	60,175	29,151	2.06
Number of traps	2,946,000	375,000	7.86
Season days	365	184	1.98
Overcapacity in Maine versus LFA 34			7.55

Table 1b
Landings, number of traps, and season days in Maine versus Lobster Fishing Area (LFA) 34 in 2017 (LFA 34's 2016/2017 fishing season). Maine fishers used approximately 7.20 times as much effort as fishers in LFA 34 to harvest the same amount of lobster. Maine landings data from National Marine Fisheries Service [5] and number of traps from Maine Department of Marine Resources [74]. LFA 34 landings, number of licenses, trap limits, and season days from Fisheries and Oceans Canada [73].

Lobster Fishing Effort in Maine versus Lobster Fishing Area 34, 2017			
	Maine	LFA 34	Maine/LFA 34
Landings (metric tons)	48,983	22,679	2.16
Number of traps	2,954,000	375,000	7.88
Season days	365	185	1.97
Overcapacity in Maine versus LFA 34			7.20

in LFA 34 to harvest the same amount of landings. Results were comparable from 2016 to 2017, as both areas experienced a drop in landings of about 20%.

It is important to note that many Maine fishers do not actively fish during the full 365-day season, and commonly remove gear for part of the year. However, even if we estimate that Maine fishers use 75% of available fishing days (292 days), relative capacity in Maine is still about 5.5 times that in LFA 34. Additionally, the number of trap tags sold in Maine does not fully account for latent effort; some fishers likely do not use all of the trap tags they purchase. However, the number of trap tags sold is markedly lower than the full trap limit. In 2016 and 2017, the number of trap tags sold averaged 490 and 493 per fisher, respectively [63], whereas the trap limit is 800 in most areas. This indicates that the number of trap tags sold is a better indicator for actual effort than the number of licenses multiplied by the trap limit in Maine. In contrast, the number of traps for LFA 34 calculated here represents the upper bound for this area and assumes all license holders fish the full trap limit.[11] Even if latent effort in Maine is approximately 20% of the number of trap tags sold and Maine fishers actively fish 75% of the year, overcapacity in Maine compared to LFA 34 is 4.5 times.[12]

Data requested regarding number of days actively fished and actual levels of latent effort in Maine have not yet been made available. Additional factors such as distribution of lobsters, bait and trap type, and soak time may also affect relative catch. However, even a much lower overcapacity estimate would indicate that effort reduction measures such as those currently under consideration by NMFS (i.e. an endline cap and possible trap reduction of up to 50%) would likely lead to a more

[11] LFA 34 license holders are issued a yearly set of trap tags which matches the trap limit, they do not select a number of trap tags to purchase each year [73].
[12] 7.5 × .80 x .75 = 4.5 times overcapacity in Maine compared to Lobster Fishing Area 34.

Table 2
Landings per trap in Maine compared to Lobster Fishing Area (LFA) 34 in 2016 and 2017 (LFA 34's 2015/2016 and 2016/2017 fishing seasons, respectively). LFA 34 fishers harvested about 3.7 times as much lobster per trap as Maine fishers. Maine landings data from National Marine Fisheries Service [5] and number of traps from Maine Department of Marine Resources [74]. LFA 34 landings, number of licenses, trap limits, and season days from Fisheries and Oceans Canada [73].

Landings per trap in Maine versus Lobster Fishing Area 34			
	Maine landings per trap (lbs)	LFA 34 landings per trap (lbs)	LFA 34/ Maine
2016	45	171	3.8
2017	37	133	3.6

economically efficient fishery.

Next, we calculated landings per trap in Maine compared to LFA 34 (Table 2). Total landings indicate a fisher's revenue (when multiplied by ex-vessel price), and does not account for cost. In contrast, landings per trap is a stronger proxy for profit than total landings because it partially accounts for costs by standardizing to effort. Bait and fuel are frequently the most significant input costs to harvest lobster, and are closely related to the number of traps used (i.e. each trap is baited, and fishers likely travel farther and use more fuel to haul more traps). To calculate landings per trap, we divided total annual landings by the number of traps from Table 1.

In 2016 and 2017, LFA 34 fishers brought in about 3.7 times as much lobster per trap than Maine fishers (3.8 times in 2016 and 3.6 times in 2017). This calculation of landings per trap does not take season days into account. Again, if latent effort in Maine is approximately 20% of the number of trap tags sold, LFA 34 landings per trap are still three times higher than in Maine, assuming all LFA 34 fishers use the full trap limit.

LFA 34 did not achieve high landings in recent years by increasing effort; the number of lobster licenses and trap limit has remained consistent over time (Fig. 13) [4,75,76]. Therefore, landings per trap (a proxy for profit) in LFA 34 mirrored growth in total landings (Fig. 14). In contrast, the number of traps in Maine rose by over 1 million before tapering off in the mid-2000s (Fig. 13), indicating that Maine fishers likely experienced comparably higher costs and therefore less increase in profit during a similar period of landings growth [74] (Fig. 14). We compared the number of lobster traps in Nova Scotia Maritimes and Maine from 1990 to 2017 to illustrate this concept. Here we switch to Nova Scotia Maritimes because a more consistent time series of the number of licenses is available [76]. LFA 34 is the most significant contributor to total Nova Scotia Maritimes landings. The number of traps in Nova Scotia Maritimes was calculated by multiplying the annual number of licenses by the proportion of licenses per LFA, category, and LFA restrictions from the most recent Integrated Fisheries Management Plan from 2011 [75].

Landings per trap is especially relevant as per trap harvesting costs, especially bait, are expected to rise in the near future. For example, from 2018 to 2019 the U.S. Atlantic herring quota was cut by 80% and is expected to remain low in coming years [77]. Because herring has been the most important American lobster bait, the reduced quota could cause bait shortages and higher prices in the near-term, increasing per trap lobster harvesting costs (though other bait alternatives may mitigate higher costs) [77].

3.2. Maine landings and number of traps over time

Maine is the largest contributor to the American lobster fishery, with fishers in the state bringing in 83.3% of total U.S. catch in 2016 [5]. The Maine Department of Marine Resources maintains a database of historical Maine lobster landings that details the number of traps in the fishery [74].[13] The number of traps used by Maine lobster fishers grew through the late 1980s and 90s to reach a high in 2006 of 3.283 million traps, and has since tapered off (Fig. 15). Landings have shown strong growth throughout, driving the overall growth in the U.S. lobster fishery despite the collapse of the southern New England stock since the late 1990s (Fig. 15) [15].

Although many factors impact landings, historically a reduction in number of traps has not been connected to reduced landings in Maine. Landings per trap have been relatively stagnant in Maine for most of the last three decades, except for a period from 2007 to 2013 when landings per trap grew rapidly year on year. During this period, landings per trap grew 124% from 19.6lbs to 43.8lbs. This growth in landings per trap correlates with a 10.5% decrease in number of traps and a doubling in landings (100.2% increase). As discussed above (section 3A), landings per trap is a better proxy for fishing profit than landings alone. The rate of growth of total landings weight was also faster after trap numbers began to fall: from 2007 to 2016 Maine landings grew by 207%, whereas from 1997 to 2006 landings grew by 160%, and landings grew by 183% in the decade prior. Such a correlation between reducing effort and increasing landings is characteristic of a fishery that has been operating beyond optimal efficiency and may be at risk of overexploitation. These findings are consistent with Holland [78]; which used a profit maximization model to show that reducing fishing effort could contribute to substantially increased profitability in the Maine lobster fishery—and that it may be more profitable to harvest less lobster, even without accounting for increased future catch rates that would be expected by leaving more lobster uncaught.

3.3. Massachusetts landings before and after implementation of the Massachusetts Restricted Area trap/pot seasonal closure

In 2015, NMFS expanded trap/pot seasonal closures in the Massachusetts Restricted Area and the Great South Channel to protect significant aggregations of North Atlantic right whales known to feed in these areas each year (Fig. 16) [46]. The Massachusetts Restricted Area is closed to trap/pot fishing from February 1st to April 30th and the Great South Channel is closed to trap/pot fishing from April 1st to June 30th [46]. In 2017, 2018, and 2019, the Massachusetts Division of Marine Fisheries [84–86] extended the closure in Cape Cod Bay by up to 14 days due to the continued presence of endangered right whales [84–86]. We focus on the Massachusetts Restricted Area closure in this study because it fully covers multiple Statistical Reporting Areas, making it more feasible to discern the change in landings since the closure was implemented, and because the Massachusetts Restricted Area contributes a greater portion of total statewide landings.

The Massachusetts Restricted Area closure primarily impacts Massachusetts-based fishers, especially those fishing Massachusetts' south shore, Cape Cod Bay, and the outer Cape, though the exact number of fishers affected is unclear. In an amendment to the final rule establishing the trap/pot fishery closure published in 2014, NMFS estimated that "slightly more than" 125 fishers would be affected by the Massachusetts Restricted Area closure [46]. The Massachusetts Division of Marine Fisheries (DMF) has identified 172 individuals who previously fished in Statistical Reporting Areas that fall within the Massachusetts Restricted Area during February, March, and April who can no longer do so [87]. Representatives of the fishing industry have recently estimated that 250 fishers are affected [88]. In 2017, there were 1,018 commercial lobster permits licensed in Massachusetts, of which approximately 780

[13] From 1981 to 1995, DMR calculated the number of traps used by estimating the number of active boats and mean traps per harvester. From 1996 to 2016 the number of traps was taken from the number of trap tags sold.

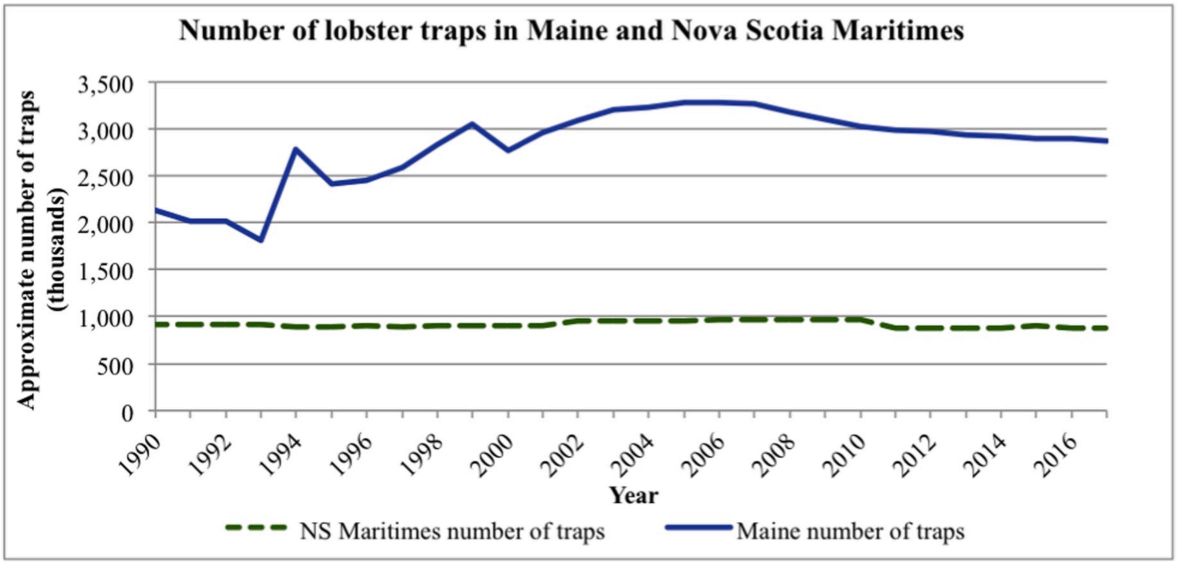

Fig. 13. Estimated number of lobster traps in Maine versus Nova Scotia (NS) Maritimes from 1990 to 2017. Maine number of traps showed uneven growth until reaching a peak of 3.283 million traps in 2006 and has since tapered off slightly, while NS Maritimes number of traps has remained relatively consistent at approximately 900,000 traps. Data from Maine Department of Marine Resources [74] and Fisheries and Oceans Canada [75,76].

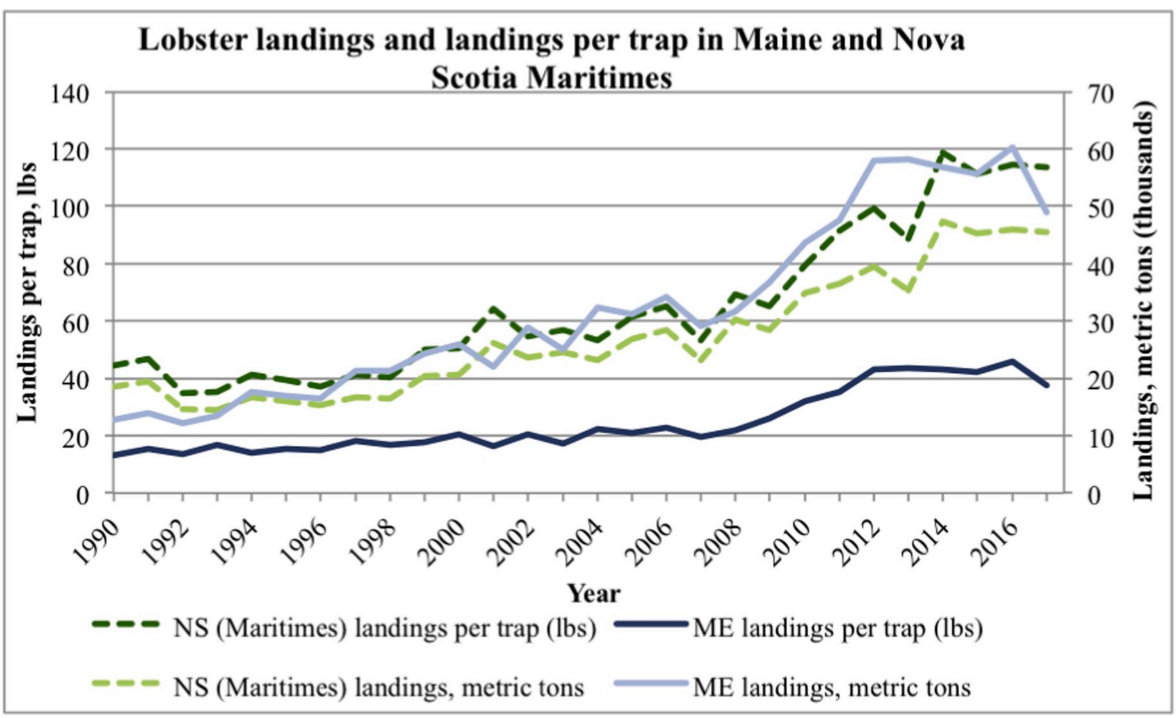

Fig. 14. Maine and Nova Scotia (NS) Maritimes lobster landings and landings per trap from 1990 to 2017. While NS Maritimes landings per trap mirrored landings growth, Maine landings per trap remained relatively stagnant for the majority of this period. Data from the National Marine Fisheries Service [5], Maine Department of Marine Resources [74], and Fisheries and Oceans Canada [71,75,76]; available at https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901.

are actively fished [19]. Therefore, according to these estimates the Massachusetts Restricted Area closure affects between 16 and 32% of Massachusetts' active lobster fishers.

Since the seasonal closures last at least three months, fishers who are impacted often publicly state that they lose at least one quarter of their income each year due to the closures [89,90]. Some fishers claim that the three-month closure effectively becomes five months, causing them to lose closer to 40% of their annual income because it takes about one month to remove their traps before the February 1st start date and another month to replace them once the fishery reopens [89–91]. However, in the three years for which Vessel Trip Report data are available since the closure was implemented (2015, 2016, and 2017), lobster landings in the Statistical Reporting Areas (SRAs) covered by the closures have continued to grow to record highs (Fig. 17) [92]. Vessel Trip Reports are collected for all commercial vessels fishing in Massachusetts waters [93].

The growth in landings in the Massachusetts Restricted Area is consistent with statewide trends: Massachusetts state landings value reached record highs for all three years for which data are available since the closure was implemented (2015, 2016, and 2017) (Fig. 18) [5].

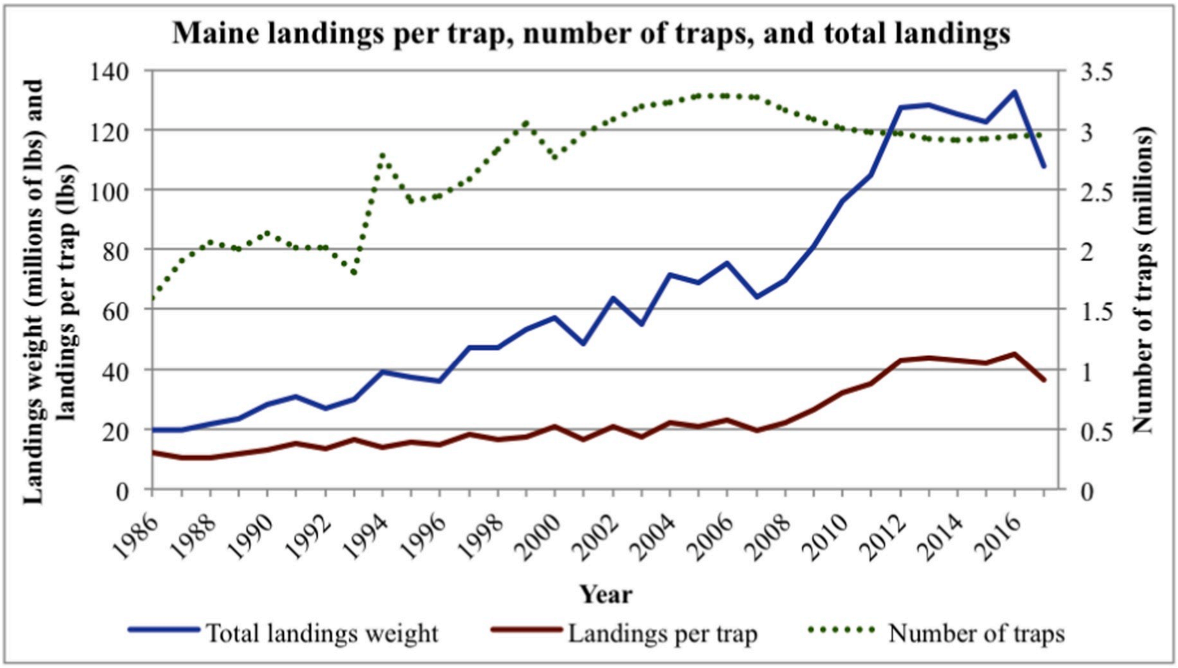

Fig. 15. Maine lobster landings per trap, number of traps (an upper bound indicated by the number of trap tags sold), and total landings weight from 1986 to 2017. Landings per trap were relatively stagnant except from 2007 to 2013, when landings per trap increased substantially year on year, correlating with a decrease in the number of traps and faster rate of growth in total landings. Data from National Marine Fisheries Service [5] and Maine Department of Marine Resources [74]; available at https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901.

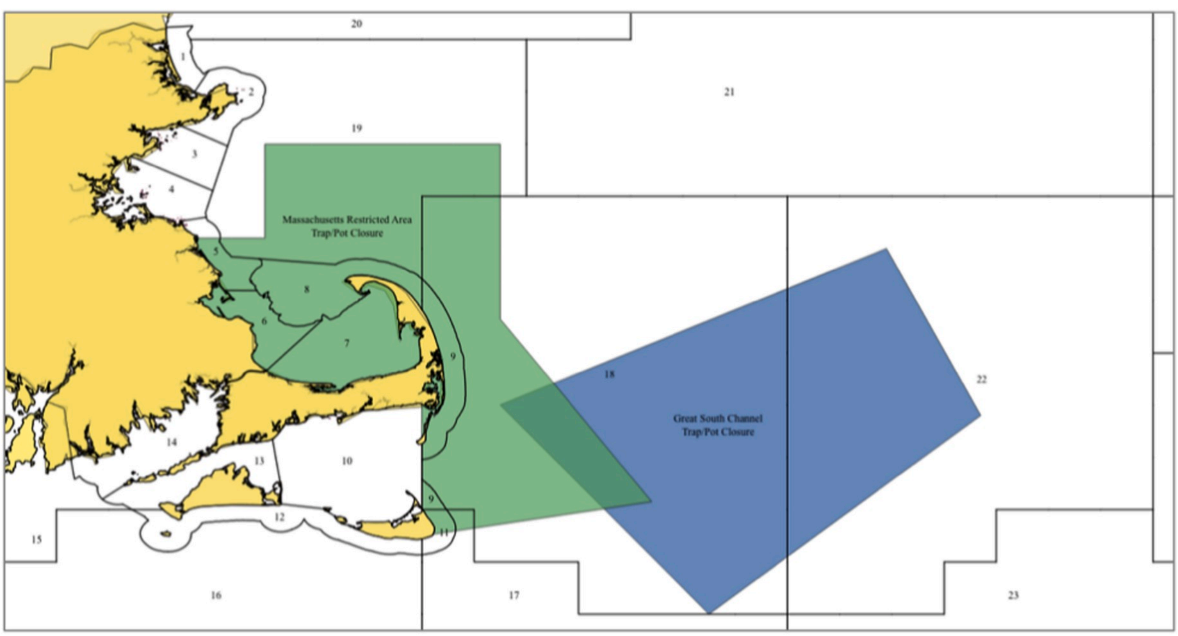

Fig. 16. Map showing the Massachusetts Restricted Area (green) and Great South Channel (blue) Trap/Pot Closures and Massachusetts state lobster harvesting Statistical Reporting Areas (SRAs). Data delineated by state SRAs were used in this analysis; Massachusetts state SRAs differ from federal SRAs and Lobster Management Areas. The Massachusetts Restricted Area closure includes all of SRAs 6, 7, 8, and 9 and most of SRA 5, as well as portions of SRA 18 and 19. The Great South Channel is located within SRAs 18 and 19. Map created in QGIS using shapefiles from NMFS Greater Atlantic Regional Fisheries Office [79]/[80] and MassGIS Bureau of Geographic Information [81–83]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Massachusetts' landings weight also reached an all-time high in 2016, and 2015 and 2017 were the fifth and third highest years on record, respectively (Fig. 18) [5].

Standardizing landings weight to 1990 in the primary SRAs covered by the Massachusetts Restricted Area and the rest of Massachusetts shows that commercial lobster fishers in SRAs 5 to 9 have experienced stronger growth than those in the rest of the state since the closure was implemented. Landings growth in SRAs 5 to 9 continued consistently since the seasonal closure was implemented on February 1st, 2015, but was inconsistent elsewhere (Fig. 19). Notably, landings weight in SRAs 5 to 9 did not drop from 2016 to 2017, in contrast to the rest of Massachusetts and most of the Northeast U.S. When compared to neighboring

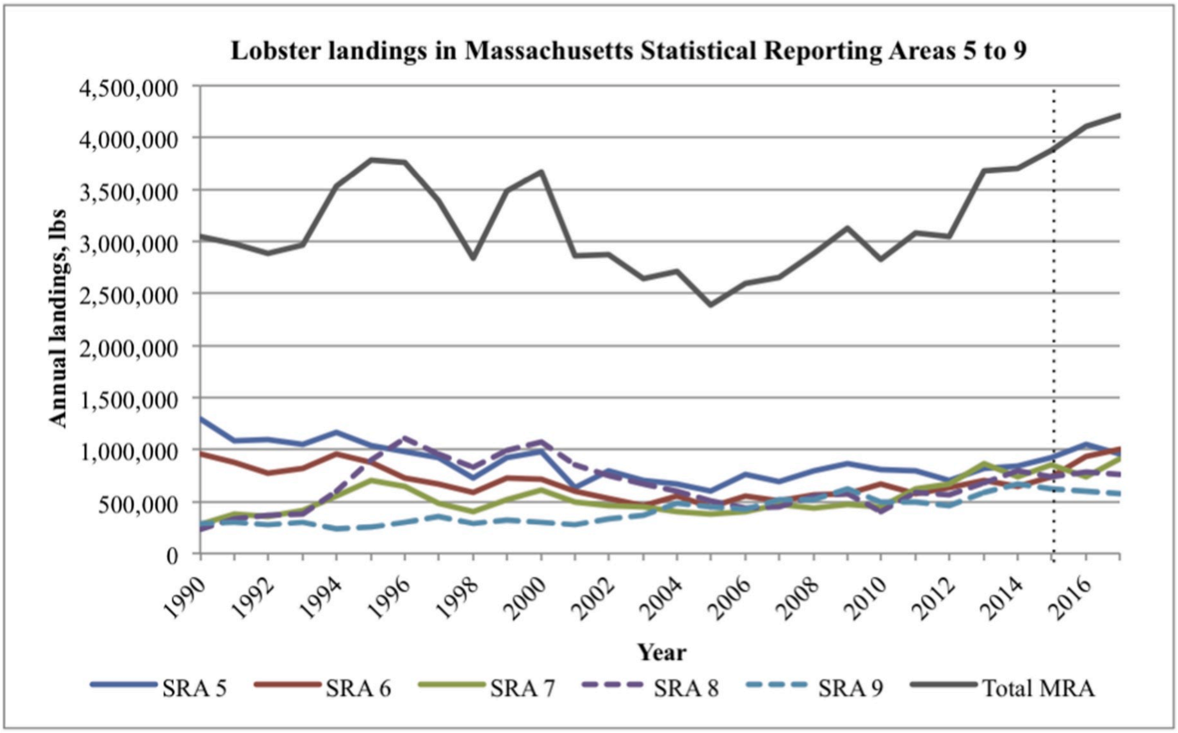

Fig. 17. Annual lobster landings weight, in millions of pounds, for Massachusetts Statistical Reporting Areas (SRAs) 5, 6, 7, 8, and 9 from 1990 to 2017. Vertical line indicates the start of the Massachusetts Restricted Area Trap/Pot Closure in 2015. The Massachusetts Restricted Area Trap/Pot Closure includes all of SRAs 6, 7, 8, and 9, as well as most of SRA 5 and small portions of SRAs 18 and 19. Data from the Massachusetts Division of Marine Fisheries (unpublished) [19]; available at https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901.

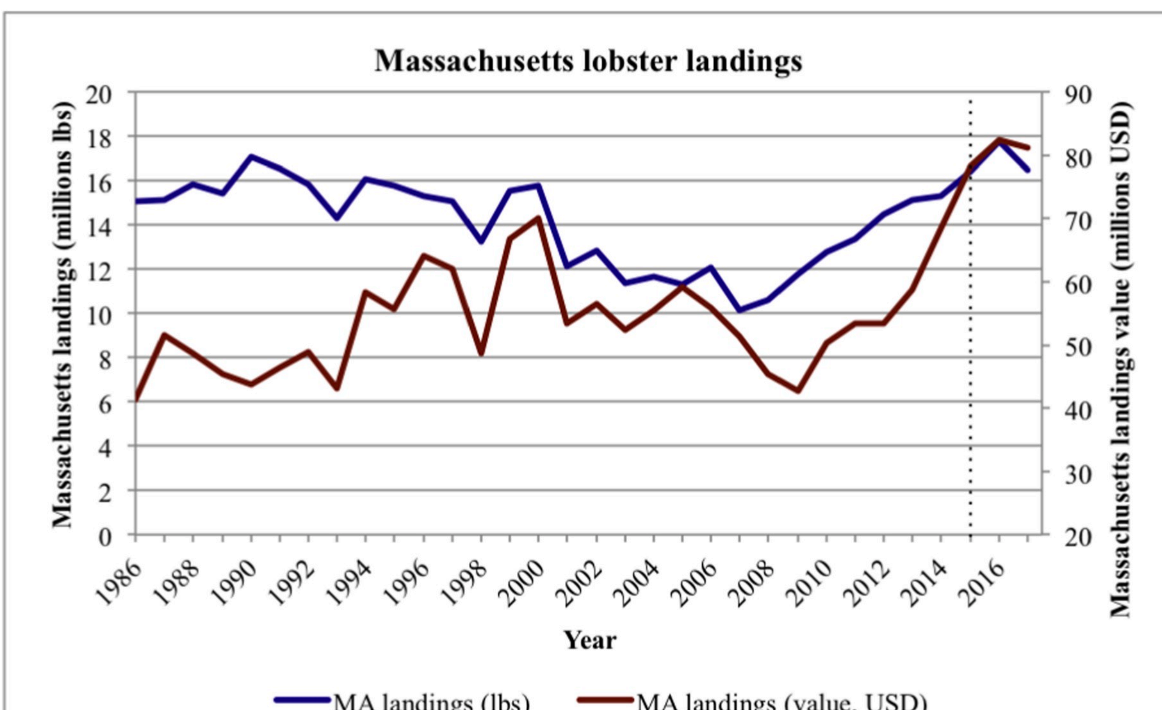

Fig. 18. Massachusetts state landings by weight and value from 1986 to 2017. Vertical line indicates the beginning of the Massachusetts Restricted Area and Great South Channel seasonal trap/pot closures in 2015 (February 1st to April 30th and April 1st to June 30th, respectively). Data from National Marine Fisheries Service [5].

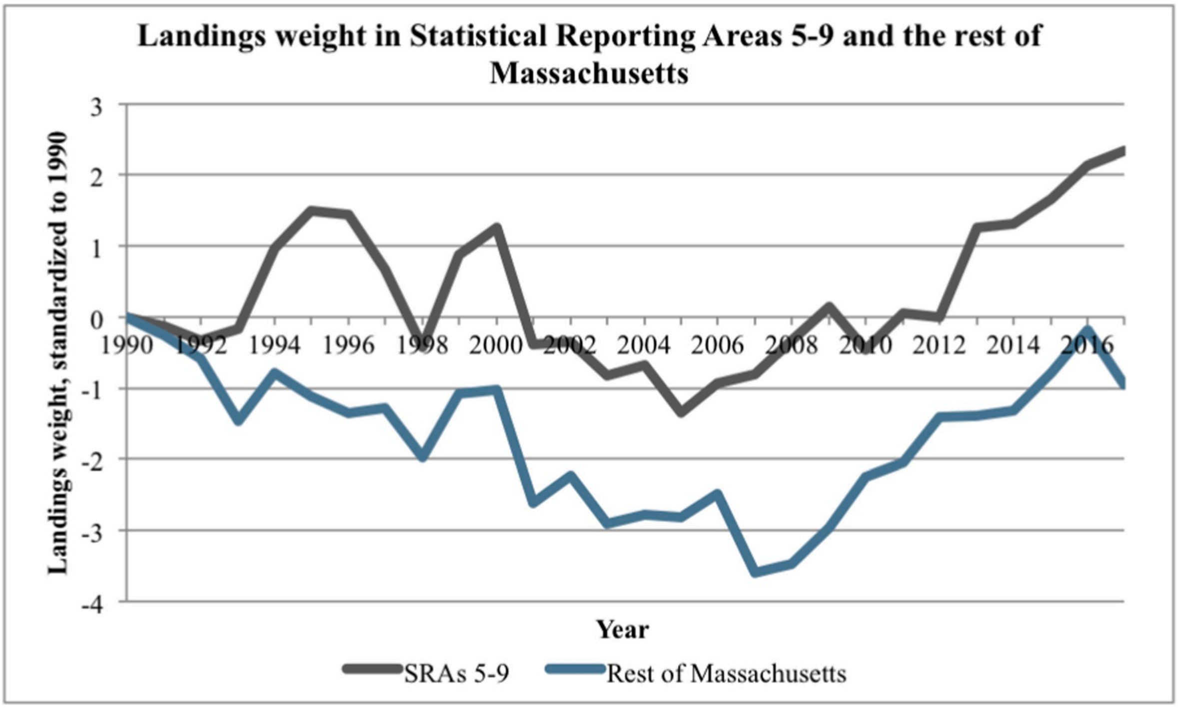

Fig. 19. American lobster commercial landings weight standardized to 1990 landings in the primary Statistical Reporting Areas (SRAs) covered by the Massachusetts Restricted Area (SRAs 5, 6, 7, 8, and 9) and the rest of the state of Massachusetts. The Massachusetts Restricted Area seasonal trap/pot fishery closure took place on February 1st, 2015. Data from Massachusetts Division of Marine Fisheries (unpublished) [19] and National Marine Fisheries Service [5]; available at https://hdl.handle.net/1912/24901, doi:10.26025/1912/24901.

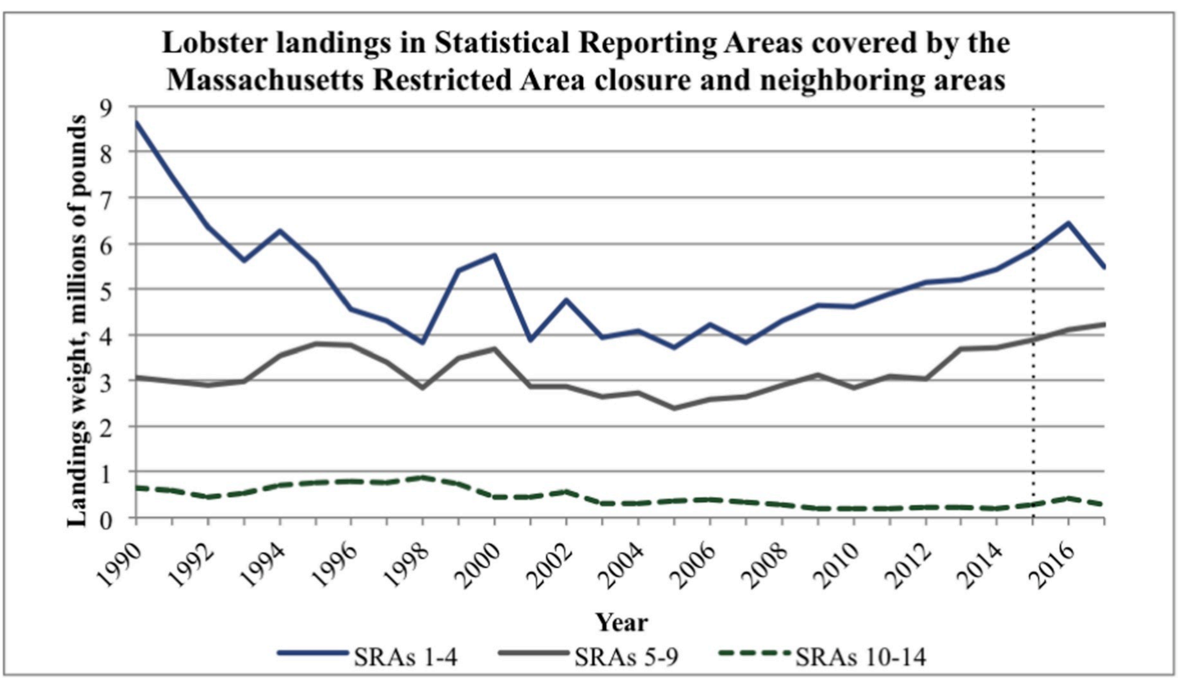

Fig. 20. Lobster landings weight in the Statistical Reporting Areas (SRAs) covered by the Massachusetts Restricted Area (5–9) and to the north (1–4) and south (10–14) from 1990 to 2017. Relative growth in landings in SRAs 5 to 9 was stronger than in neighboring areas since the closure was implemented. Vertical line indicates the start of the three-month closure in 2015. Data from Massachusetts Division of Marine Fisheries (unpublished) [19]; available at https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901.

areas (SRAs 1 to 4 to the north of the Massachusetts Restricted Area and SRAs 10 to 14 to the south), the SRAs covered by the closure have also shown stronger relative growth (Fig. 20).

Lobster is not harvested evenly throughout the year, but rather landings are typically low in February, March, and April. This was a significant part of the rationale for amending the Massachusetts Restricted Area closure start date from January 1st to February 1st, which NMFS did before the closure was enacted in 2015 [46]. Although

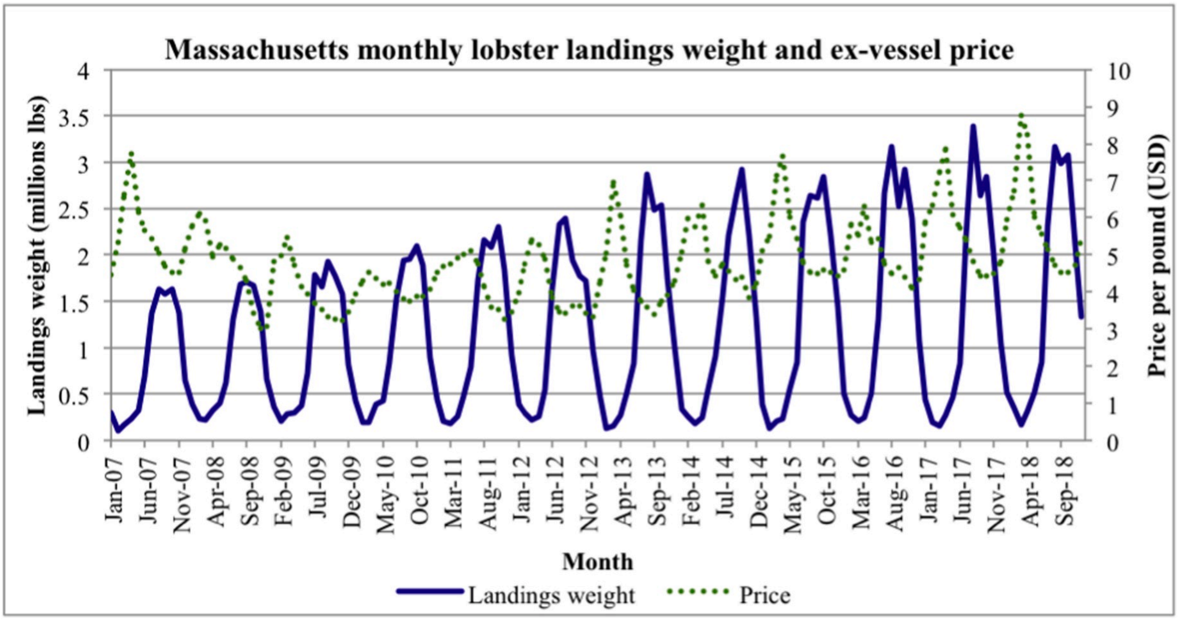

Fig. 21. Massachusetts monthly lobster landings weight and ex-vessel price per pound, January 2007 to December 2018. Price is nominal and not adjusted for inflation. Data from Atlantic Coastal Cooperative Statistics Program [94].

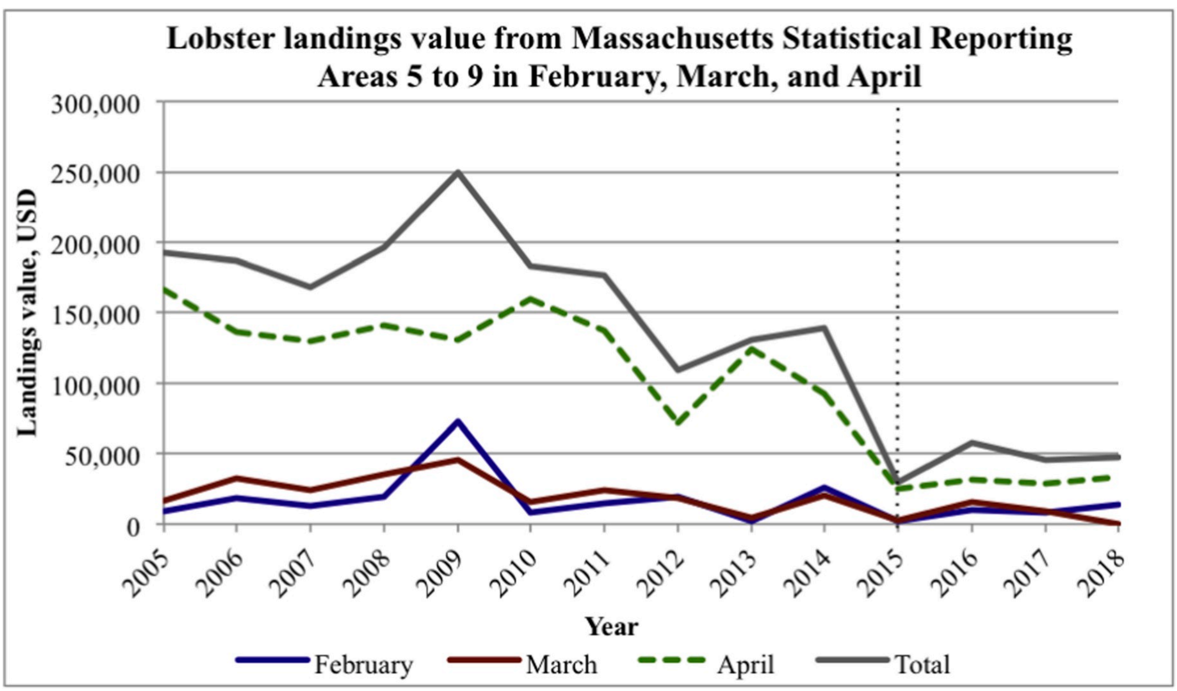

Fig. 22. Lobster landings value in February, March, and April from Massachusetts Statistical Reporting Areas 5 to 9, 2005 to 2018. Landings value from these areas dropped approximately $94,000 from the period immediately before to the period immediately after the closure was implemented. Vertical line indicates the start of the Massachusetts Restricted Area trap/pot closure in 2015. Landings value calculated by multiplying landings weight for each area by average price for Massachusetts for that month and year. Value is nominal and not adjusted for inflation. Data from Massachusetts Division of Marine Fisheries (unpublished) [19]; available at https://hdl.handle.net/1912/24901, DOI 10.26025/1912/24901.

landings during the closure period have historically been very low across the state, low weight is in part compensated for by higher price per pound (Fig. 21) [94]. Fishers who previously may have harvested during the closure months could have experienced a negative economic impact even if they were able to harvest more weight later on, since they would be selling it for a lower price.

However, average lobster landings from February, March, and April in SRAs 5 to 9 changed by only 19,450 pounds from the four-year period immediately before the Massachusetts Restricted Area closure was implemented (2011–2014) to the four-year period immediately after (2015–2018) [19]. When monthly landings weight is multiplied by the average price per pound in Massachusetts for each month, we find that this 19,450 pound difference is equivalent to a change in revenue of about $94,000 for all of SRAs 5 to 9 [19] (Fig. 22). Since the closure was implemented, SRAs 5 to 9 have landed an average of 4.16 million pounds of lobster worth about US $19.35 million annually[14] [5,87]. The change in landings during the closure months is therefore worth only about 0.5% of annual landings from these areas. On the other hand, annual landings from SRAs 5 to 9 have gone up about 587,800 pounds since the closure was implemented [19], an overall increase approximately 30 times greater than the amount lost during the closure months. Overall, the loss in landings during the high-price closure period has therefore been more than compensated for by growth in total landings.

It is important to note that landings by SRA and by state mask individual differences among fishers, some of whom may have lost income due to the closures. This analysis also does not address potential changes in the portions of SRAs 18 and 19 that are covered by the Massachusetts Restricted Area, since finer scale data would be needed to separate landings from the closure portions and the rest of those areas. Additionally, changing local oceanographic conditions affect how much lobster biomass is available to harvest within a specific area [26,95], making it difficult to isolate the impact of the closures.

However, the available evidence does not demonstrate that the Massachusetts Restricted Area closure has had an overall negative economic impact. Instead, landings have reached record highs, and landings from the primary SRAs covered by the Massachusetts Restricted Area showed stronger and more consistent growth than from the rest of the state. The closure may allow for a buildup in lobster biomass that is brought in later in the season, as can occur with effort reduction [4]. Lobsters that otherwise would have been caught during the closure period increase in size (leading to higher landings weight if they are caught later on) and contribute to the reproductive cycle to grow the total stock. Although there is concern that closures may displace fishing effort to waters just outside the closure area, rather than reduce fishing effort, this has not been demonstrated around the Massachusetts Restricted Area closure and is unlikely to occur since fishing effort during the closure period was very low prior to its implementation.

Massachusetts' recent experience with the Massachusetts Restricted Area trap/pot closure suggests that seasonal closures will not necessarily cause landings to drop. The reduction in effort that occurred with the closure did not correlate with a drop in landings. In contrast, landings have continued to rise since the closure was implemented. The hypothesis that the Massachusetts Restricted Area seasonal closure may have supported higher annual fishery landings is also consistent with Oppenheim et al. [26]; in which a model using an annual larval settlement index, local bottom temperature, and disease prevalence indicators predicted that lobster landings in northern Massachusetts would be lower than those actually observed since the closure was implemented. The majority of study sites in northern Massachusetts were covered by the Massachusetts Restricted Area seasonal closure [26].

4. Discussion

Available evidence does not show that landings in the U.S. lobster fishery will necessarily fall with effort reduction. In contrast, in both Maine and Massachusetts an actual or presumed drop in effort has correlated with record high landings, and the significant overcapacity in the Maine fishery compared to Lobster Fishing Area 34 suggests that effort could be substantially reduced and allow fishers to harvest the same landings with lower costs. Therefore, a negative economic impact should not be presumed with right whale bycatch mitigation measures that include or could cause a reduction in fishing effort; the economic impact of effort reduction could in fact be positive.

Although many factors influence total landings, the potential capacity to harvest the same landings with approximately 7.5 times less effort and the correlation between reduced effort and higher landings in the U.S. lobster fishery is typical of a fishery operating with overcapacity, which is likely to lead to an overexploited resource [66]. It is also in line with international fishing trends: effective catch per unit effort—a standard measure of fishing efficiency calibrated to technological advancement—has decreased by approximately 80% in North America from 1950 to 2015, as fishing exploitation has expanded faster than fish stocks can support [96]. Precaution regarding overexploitation is especially important as multiple indicators show that the Gulf of Maine American lobster stock is unlikely to sustain current high abundance levels in the near future [15,26] and as the Gulf of Maine continues to warm at a rapid rate [24,25].

For the U.S. American lobster fishery to continue to be successful for generations, it is in the best interest of fishers to scale back effort in advance of an ecological or economic crisis [97]. As available evidence indicates that the U.S. lobster fishery is currently operating with significant overcapacity, doing so may also support higher profits in the near-term. If fishing effort is scaled back in a manner that reduces the number and strength of vertical endlines, it will simultaneously serve to reduce entanglement risk for North Atlantic right whales. This study provides particular support for a trap reduction implemented in concert with a set minimum number of traps per trawl or an endline cap, as well as seasonal closures. Additional closures in areas of high right whale aggregation could provide significant conservation benefit and may not have a net negative economic impact if overall landings gains exceed losses during the closure period. Other right whale protection measures that may indirectly lead to a reduction in effort, such as ropeless fishing, could also serve to reduce overexploitation in the lobster fishery. Implementing ropeless fishing together with a trap reduction could strengthen this benefit while reducing the upfront cost of technological transition.

After decades of insufficient protections, the U.S. American lobster fishery is facing potentially significant new regulations to protect North Atlantic right whales from entanglement. However, a negative economic impact should not be presumed with such measures; right whale bycatch mitigation measures that include or could cause a reduction in lobster fishing effort may support higher profits and the long-term sustainability of the fishery.

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Declaration of competing interest

None.

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Hannah J. Myers: Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Michael J. Moore:** Conceptualization, Writing - review & editing.

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[14] This value was calculated by multiplying the average annual portion of statewide landings from SRAs 5 to 9 (0.24) by the average landings value for the state of Massachusetts ($80,630,500) from 2015 to 2017.

Appendix A. Supplementary data

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