Marine Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring fishery

John Driscoll *, Peter Tyedmers

School for Resource and Environmental Studies Dalhousie University 6100 University Ave, Suite 5010 Halifax, Nova Scotia Canada B3 H 3J5

ARTICLE INFO

Article history:
Received 31 July 2009
Accepted 14 August 2009

Keywords:
Fisheries management
Fuel
Greenhouse gas
Trawl
Purse seine
Herring

ABSTRACT

Commercial fisheries are heavily dependent upon the combustion of fossil fuels and as such contribute to increased atmospheric concentrations of greenhouse gases and the concomitant impact on the world's climate. The fuel use and greenhouse gas intensity of a fishery is a function of several variables. One that has not been previously investigated is the role of fisheries management. Using historical gear-specific fuel use and landings data, we employ scenarios to examine the potential impact that recent changes in the management of the New England fishery for Atlantic herring (*Clupea harengus*) may have on fishery-related fuel use and greenhouse gas emissions. Specifically, we consider the direct effect of the seasonal ban of midwater trawling in favor of purse seine and fixed gears within Atlantic herring fishing Area 1A. We also evaluate the indirect effect of reductions to the Area 1A total allowable catch of Atlantic herring on the regional supply of bait and the resulting potential need to import bait herring from Canada. Our results indicate that because of the five-fold lower fuel intensity of purse seining, relative to midwater trawling (21 L/ton versus 108-118 L/ton), the seasonal ban on midwater trawling has the potential to markedly reduce overall fuel use and greenhouse gas emissions associated with the herring fishery. These results indicate that management decisions can strongly influence energy demands and resulting greenhouse gas emissions of fisheries. We urge those involved with fisheries management to take this into account when developing policy and management measures.

1. Introduction

The fuel that a fishery uses and the greenhouse gas (GHG) emissions that result are important yet underappreciated aspects of its environmental and economic sustainability. While fishermen have long been concerned with the costs of fuel inputs, and consumer demand for information related to GHG emissions is increasing, fisheries policy and management decision-making processes largely overlook these issues. This must change if fisheries management is to better align with policies to address climate change and help guide fisheries in the face of increasing fuel prices and consumer concern regarding GHG emissions.

Fishing operations emit GHGs primarily as a waste product of fossil fuel combustion and secondarily through the provision of fuels, ice, gear, and other necessities, and the construction and maintenance of vessels [1–4]. Consequently, a vessel or fleet's GHG intensity (the total GHG emissions associated with a fishery per unit of catch landed) is strongly related to its fuel intensity (the fuel used per unit of catch landed).

Several factors are known to influence the fuel intensity of commercial fisheries. These include the abundance and characteristics of the target species, vessel and engine size, fleet size and the degree of its overcapitalization, trip length and distance traveled to fishing grounds, and the gear used [2–11]. For example, vessels using seines to target nearshore stocks of schooling small pelagic species may use well under 100 liters of diesel per metric ton landed, while trawlers and longliners targeting high value species have been documented to burn over 2000 liters per metric ton [5,8,10–12]. Mitchell and Cleveland [6] found that the carbon intensity (there defined as the amount of carbon dioxide (CO_2) released for each kilocalorie of seafood produced) of the New Bedford, Massachusetts fleet increased almost 530% between 1968 and 1988. This increase mirrored an increase in fleet-wide fuel intensity over the same period, which the authors attributed to fleet overcapacity and a reduction in target species stocks.

One factor that has not been investigated to date is the impact that fisheries management decisions may have on fleet fuel use and GHG emissions. Fisheries management decisions often affect fleet characteristics, fishing effort, and fishing practices, and by extension, management decisions may influence fuel use patterns. Therefore, while fisheries management decisions have to date been made largely without regard to potential impacts on fleet fuel use (beyond nominally considering economic concerns of

---

* Corresponding author. Tel.: +1 250 973 6580; fax: 1 250 973 6581.
E-mail addresses: john.driscoll@dal.ca (J. Driscoll), Peter.tyedmers@dal.ca (P. Tyedmers).

0308-597X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpol.2009.08.005

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005

vessel owners), these decisions may have a non-trivial impact on fuel use intensity and GHG emissions.

Here we examine the potential impact of two recent fisheries management decisions on fuel use and GHG emissions in the New England fishery for Atlantic herring (*Clupea harengus*). Specifically, we model a number of hypothetical scenarios to evaluate the potential effects of the seasonal Purse Seine/Fixed Gear Only provision of Amendment I to the Atlantic Herring Fishery Management Plan [13] implemented in 2007, and of the reduced Total Allowable Catch (TAC) for the 2007–2009 Atlantic herring fishery in Herring Management Area 1A [14].

1.1. US fisheries for atlantic herring

1.1.1. History

Commercial fisheries for Atlantic herring have been vigorously prosecuted since the 1890s [15]. Commercial landings have varied greatly in the decades since fossil-fuel-based fishing methods became widespread in the mid-20th century (Fig. 1). A large fleet of foreign-owned vessels depleted offshore stocks in the western north Atlantic during the 1960s and early 1970s, and by 1977 US Atlantic herring landings had crashed [16]. Following a nadir in the early 1980s, US landings have rebounded to average over 90,000 metric tons per year since 1995 [17].

For centuries prior to and after European settlement in what became the New England states, fixed gear types, such as stop seines and weirs, that targeted inshore juvenile Atlantic herring were the dominant means of Atlantic herring fishing. Weirs and stop seines caught the majority of domestic Atlantic herring landings as recently as 1981 (Fig. 2). Vessels using mobile gears began targeting the recovering offshore stocks in the early 1980s [19]. Over the past twenty years, vessels using purse seines, paired midwater trawl nets, and midwater otter trawl nets have appeared and flourished in quick succession. Today, vessels using these three gear types dominate the Atlantic herring fishery, and fixed gear fishing has largely gone by the wayside in the United States (Fig. 2).

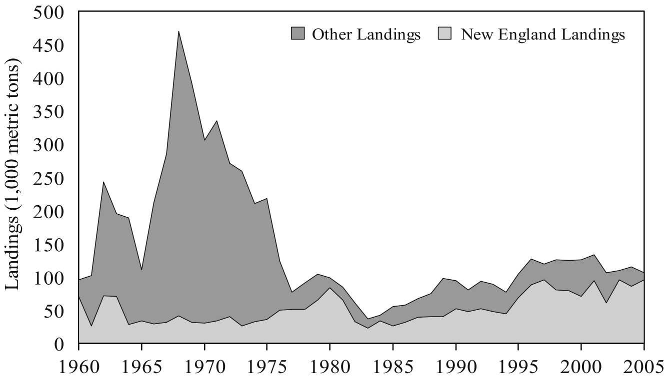

Fig. 1. Annual landings of Gulf of Maine and Georges Bank Atlantic herring by all nations and by the New England states, 1960-2005. Source: [18].

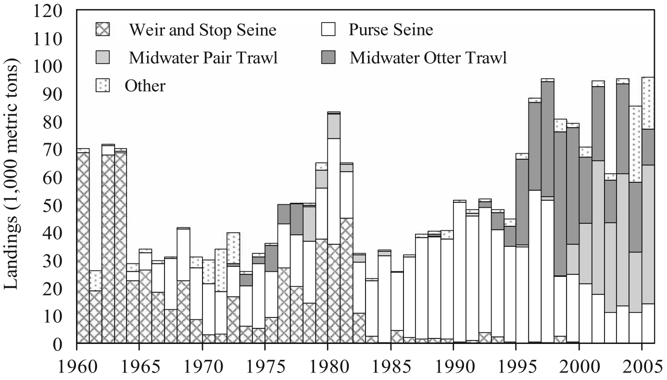

Fig. 2. Annual Atlantic herring landings in New England by gear type, 1960-2005. Source: [18].

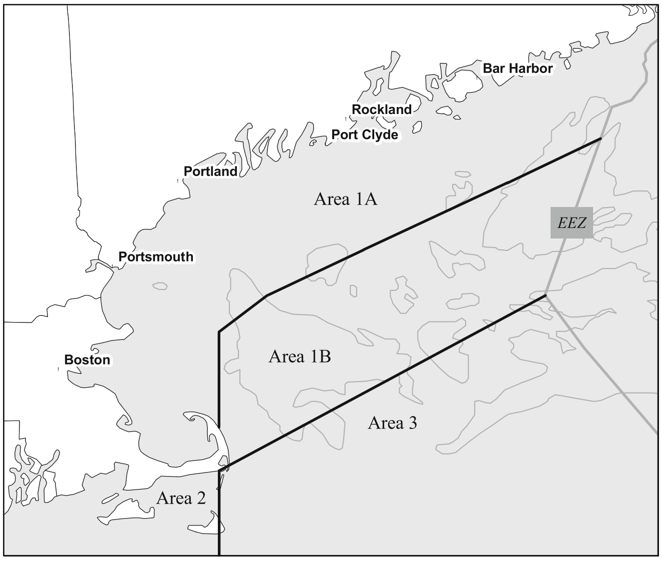

Fig. 3. Atlantic herring management areas in the Gulf of Maine and on Georges Bank. Source: Raymond Jayncke, Charles MacMichael, and J.D.

1.1.2. Management

Atlantic herring stocks are co-managed by the New England Fishery Management Council (NEFMC) and the Atlantic States Marine Fisheries Commission (ASMFC). Management plans are approved by the National Marine Fisheries Service (NMFS) and ASMFC [20]. The guiding management document is the Atlantic Herring Fishery Management Plan (FMP). The US portion of the Gulf of Maine is divided into three Atlantic herring Management Areas, with Area 1 further subdivided into Areas 1A and 1B (Fig. 3). Each Area has a seasonal TAC, and fishing is stopped when reported landings have reached 95% of that Area's TAC [14].

1.1.3. Effects of recent management decisions

Despite the apparent health of the Atlantic herring stock and fishery at the turn of the 21st century, concerns were raised regarding the increased role of midwater trawlers in the fishery. Specifically, groundfish fishers were frustrated by the bycatch of groundfish in midwater tows, and tuna fishers and whale watchers accused large trawlers of breaking apart schools of Atlantic herring in nearshore waters and thus driving both tuna and whales further offshore in their search for prey [21]. These concerns were addressed, at least in part, by Amendment I to the Atlantic Herring Fishery Management Plan, which was implemented by NMFS in 2007. Among the 15 measures implemented by Amendment I, one of the most important was the decision to create a Purse Seine/Fixed Gear Only Area. The Purse Seine/Fixed Gear Only Area measure bars Atlantic herring fishing with midwater trawl gear in Area 1A (Fig. 3) from June 1 through September 30 of each year [21]. Midwater trawl fishing is allowed in Area 1A from October 1 through May 31 of each year.

This provision of Amendment 1 significantly alters the structure of the entire New England Atlantic herring fishery.

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005

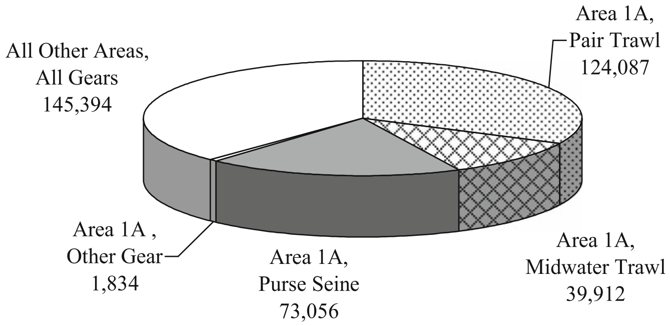

Fig. 4. Total Atlantic herring landings (metric tons) for 2002-2005 for Area 1A (by gear type) and Areas 1B, 2, and 3. Source [14].

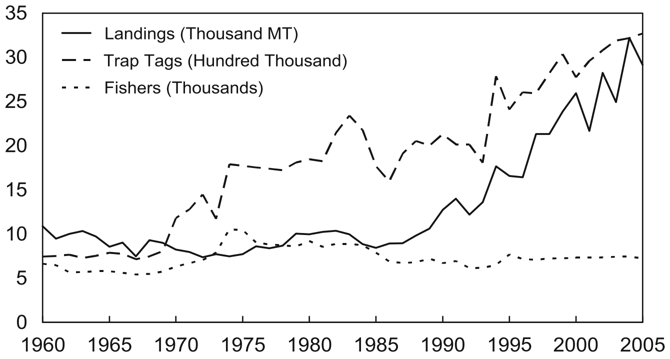

Fig. 5. Maine lobster fishers, trap tags issued, and landings, 1960-2005.Source: [25].

During the years preceding the implementation of Amendment I, landings from Area 1A accounted for the majority of US Atlantic herring landings (Fig. 4). Approximately 70% of those Area 1A landings were taken with paired midwater and single midwater trawl gear (Fig. 4).

While Amendment I grants the midwater fleet access to Area 1A after September 30, the June–September TAC for the fishery may be nearly or completely reached by that point in the year [14]. Thus, Amendment I effectively bars two of the three dominant fishing gears from the most productive fishing grounds during the traditional Atlantic herring fishing season.

Although the Gulf of Maine Atlantic herring stock is not considered overfished, there are concerns regarding potential overestimation of stock biomass, and underestimation of mortality due to predation and fishing [14]. In response, the Area 1A TAC has been reduced, from 60,000 metric tons in 2006 to 50,000 metric tons in 2007, and to 45,000 metric tons for the 2008 and 2009 peak seasons [14].

Reductions in the 1A TAC may have important ramifications for the fishery for American lobster (*Homarus americanus*) [22]. In recent years, approximately 60% of the New England Atlantic herring catch has been destined for use as bait in the lucrative trap fishery for American lobster [23]. An analysis of the 2006 Maine lobster fishery, by far the region's largest, estimated that Atlantic herring made up 87% of the bait used by those lobster fishers who landed over 2,000 pounds of lobster during that year [24]. When adjusted for the fish content of salted Atlantic herring, approximately 2.2 metric tons of Atlantic herring were used as bait per metric ton of lobster landed in Maine [24]. For this reason, demand from the lobster industry is understood by Atlantic herring industry stakeholders to be a primary driver of Atlantic herring fishing activity [19]. This demand is not expected to abate, as the Maine lobster fishery has shown steady increases in landings and total trap ownership for much of the past forty years, even though the number of fishers has remained relatively steady and the current recession has apparently softened lobster prices (Fig. 5).

As Area 1A has traditionally accounted for the majority of New England Atlantic herring landings (Fig. 4) and by extension herring used as lobster bait throughout the region, recent Atlantic herring management decisions have the potential to alter the manner in which herring is supplied to the lobster bait market. Specifically, if the purse seine fleet has sufficient capacity, they have the potential to catch a far greater share of the Area 1A TAC than they did prior to Amendment 1. Furthermore, it is reasonable to expect that any shortcomings in the supply of Atlantic herring to the lobster bait market as a result of reductions in the Area 1A TAC will be met by bait dealers purchasing Atlantic herring from other sources or through the substitution of other forms of bait.

1.1.4. Relationship of management decisions and fleet-wide fuel use and emissions

Either of these occurrences, or combinations thereof, have the potential to affect fuel use and GHG emissions associated with each unit of Atlantic herring, both landed and utilized, in New England. To explore the potential scope of these impacts, we modeled four potential post-Amendment I scenarios using historical, gear-specific fuel input and landings data from New England Atlantic herring fisheries and similar data from a likely substitute of herring for lobster bait. They are:

- o Scenario 1: 100% TAC, 100% Effort In this scenario, the purse seine fleet takes 100% of the reduced Area 1A TAC with the same fuel intensity as demonstrated by pre-Amendment I purse seine vessels. Nothing is left for trawlers to catch in Area 1A and no lobster bait substitutes are required.
- o Scenario 2: 100% TAC, 80% Effort The purse seine fleet takes 100% of the reduced Area 1A TAC, but in the absence of fishing pressure from the midwater fleet, purse seine fishing effort is decreased 20% from pre-Amendment I performance. Nothing is left for trawlers to catch in Area 1A and no lobster bait substitutes are required.
- o Scenario 3: 70% TAC, 100% Effort; 30% TAC Taken By Midwater Fleet In this scenario, the purse seine fleet lacks the capacity to catch the entire Area 1A TAC during the seasonal gear closure. Thus, 30% of the summer TAC is taken by the midwater fleet following October 1. Both fisheries operate at their historic fuel use intensity and no lobster bait substitutes are required.
- o Scenario 4: 100% TAC, 100% Effort; Market Replacement of Landings Shortfall As in Scenario 1, the purse seine fleet takes 100% of the reduced Area 1A TAC with 100% of their pre-Amendment 1 effort. The lower Area 1A TAC, however, fails to supply the local market for lobster bait. Lobster bait dealers fill market demand by importing 15,000 metric tons of Atlantic herring from Canadian dealers reflecting the difference between the old Area 1A TAC (60,000 metric tons) and the new TAC (45,000 metric tons).

Although it is unlikely that any of the four scenarios outlined above accurately presage the future, they do encompass a range of conditions that may unfold as a result of the recent changes in US Atlantic herring management. As such, our results should be of interest to managers, policy-makers and stakeholders in this fishery as well as those with an interest in the energy and environmental performance of fisheries in general and the potential role that management decisions may play.

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005

2. Methods

At-sea observer recorded catch, landings, discard and fuel use data for pair trawl, single vessel midwater trawl, and purse seine Atlantic herring trips, taken from 1995 to 2006 were obtained from the National Marine Fisheries Service's Northeast Fisheries Sampling Branch. Data were not restricted to only those trips taken in Area 1A, rather, they are indicative of typical fleet-wide fuel use and landings while targeting herring. Importantly, observer data from one pair trawl trip is for one of the two paired vessels; thus, two trips may be recorded for two vessels towing one net. Consequently, there would be no overlap in the catch or fuel use data recorded by the two observers. Due to the complexity of the pair-trawling process and the potential that an incomplete representation of the fishery could arise where only one vessel carried an observer, data were only used for those trips in which both vessels carried an observer. The data did not include fuel use information for non-fishing 'carrier vessels', which are sometimes used to transport excess catch from the fishing grounds to the dock. Fuel use, catch and landings data were converted to metric units and average gear-specific fuel use intensity values calculated.

Estimates of fuel inputs associated with the acquisition of substitute lobster bait sourced from Canada is based on an analysis of a Nova Scotia-based purse seine fishery for Atlantic herring destined for use as lobster bait [26]. Further, it was assumed that these substitute bait herring were frozen using an energy requirement of 328 kWh of electricity per metric ton, the average electricity use reported for two large Nova Scotia bait dealers [26]. It was also assumed that this substitute herring bait was transported by tractor trailer a total one-way distance of 945 km from Halifax, Nova Scotia to Portland, Maine.

Table 1
Summary of at-sea observer reported catch, landings, discards, and fuel use for sampled trips targeting Atlantic herring in U.S. waters in 1995, 1999, 2000, 2001, and 2003–2006.

	Purse seine	Midwater trawl	Pair trawl (per vessel)
Total trips in sample	84	96	184
Total catch (metric tons)	7,014	8,408	13,296
Landed (metric tons)	6,884	8,210	12,668
Atlantic herring	6,882	7,842	12,600
Atlantic mackerel	2	308	32
Alewife	0	36	16
Discarded at sea (metric tons)	130	198	627
Atlantic herring	121	116	337
Other species	9	83	291
Spiny dogfish	8	50	43
Haddock	0	9	3
Atlantic mackerel	0	5	3
Total fuel use (L)	143,800	850,352	1,481,545

Models of total GHG emissions associated with the extraction, refinement, transport and combustion of diesel fuel, along with the transport and freezer storage of bait from Canada were constructed using SimaPro 7.1.4 software (PRé Consultants; Amersfoort, The Netherlands) and emissions factors found in associated databases. SimaPro software and its associated datasets are typically employed to facilitate modeling potential contributions to a wide range of environmental impacts associated with the "life cycle" flows of material and energy inputs required to provide a good or service (for applications to fisheries, see [1–4]). However, it can also be used, as we have here, to model contributions to individual concerns such as greenhouse gas emissions.

Estimates of total fleet-wide and weighted average fuel consumption and associated GHG emissions were based on gear-specific catch proportions as of 2005. Scenarios were modeled by assigning historic average fuel, other resource inputs (e.g. electricity for imported bait freezer storage, transport etc) and emissions values, in proportion to modeled parameters.

3. Results

3.1. *Fuel use and emissions by the Atlantic herring fleet, 1995–2006*

At-sea observer collected data were compiled for 84 purse seine trips, 96 single-vessel midwater trawl trips, and 184 paired-trawl vessel trips made in US waters during the years 1995, 1999, 2000, 2001, and 2003–2006. Total reported catch, landings, discards, and fuel use for the three gear types appear in Table 1.

From these data (Table 1), weighted average fuel use intensities per metric ton of landed Atlantic herring for the three fleets were found to range from 21 L/metric ton (L/ton) for purse seiners to 108 and 118 L/ton for single-vessel and paired midwater trawlers, respectively. Applying life cycle GHG emission coefficients to these values, fuel inputs to purse seiners released approximately 65 kg CO_2 equivalent/metric ton (CO_2 eq/ton), while single-vessel and paired midwater trawlers released 337 and 365 kg CO_2 eq/ton, respectively (Table 2). Scaling up to total Area 1A landings in 2005 based on gear-specific landings, indicates that approximately 5.3 million of fuel was burned and the equivalent of 16.5 million kilograms of CO_2 was released in the process of landing just over 59,000 metric tons of Atlantic herring (Table 2). Consequently, the average ton of Atlantic herring landed in Area 1A in 2005 entailed the combustion of approximately 90 L of diesel and resulted in GHG emissions of approximately 280 kg CO_2 eq/metric ton (Table 2).

3.2. *Scenarios*

In the first scenario modeled, in which all of the Area 1A TAC is caught by the purse seine fleet at pre-Amendment 1 fuel efficiency (Scenario 1), the total fuel use associated with the Area 1A TAC would be 945,000 L, and resulting GHG emissions would

Table 2
Estimated 2005 fuel intensity and GHG emissions for landings in pre-Amendment 1 Atlantic herring fishery.

	Purse seine	Midwater trawl	Pair trawl	Total/Average
Area 1A landings (ton)[a]	15,975	10,650	32,541	59,165
Fuel intensity (L/ton)	21[b]	108[b]	118[b]	90
Total fuel burned (L)	336,000	1,150,000	3,840,000	5,326,000
GHG intensity (kg CO_2 eq./ton)	65	337	365	279
Total GHG (kg CO_2 eq)	1,040,000	3,580,000	11,900,000	16,520,000

[a] Area 1A landings data from [14].

[b] calculated from data in Table 1.

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005

Table 3
Landings, fuel use, and GHG emissions for four modeled scenarios.

	Herring (ton)	Fuel use (L)		GHG emissions (kg CO_2 eq)	
		Total	Per Ton	Total	Per Ton
Scenario 1	45,000	945,000	21	2,920,000	65
Scenario 2	45,000	756,000	16.8	2,340,000	52
Scenario 3					
Purse seine	31,500	661,500	21	2,040,000	65
Midwater[a]	13,500	1,560,600	116	4,830,000	358
Total	45,000	2,222,100	49	6,870,000	153
Scenario 4					
Purse seine	45,000	945,000	21	2,920,000	65
Imported	15,000	555,000	37	7,550,000	503
Total	60,000	1,500,000	25	10,470,000	175

[a] Midwater trawl landings modeled as 24% single-vessel midwater trawl-caught and 76% paired-vessel midwater trawl-caught, based upon proportion of Area 1A landings in 2005 (Table 2).

be less than 3 million kg CO_2 eq. (Table 3). If, in the absence of competition with the midwater fleet, the purse seine fleet is able to reduce its average fuel use intensity by 20%, total fuel use and GHG emissions associated with catching the entire Area 1A TAC would be similarly reduced (Scenario 2; Table 3).

If the purse seine fleet operated at the pre-Amendment 1 fuel efficiency but could only take 70% of the Area 1A TAC during the seasonal gear closure, the remaining 30% of the TAC would be available for the midwater fleet following the end of the closure. If the midwater fleet, with its higher fuel use and GHG emissions (Table 2), were to take this remaining 30%, the total fuel use and GHG emissions associated with the entire Area 1A TAC would be over 2 million L and nearly 7 million kg CO_2 eq, respectively (Table 3).

In a final scenario that builds on Scenario 1, we posit that demand from the lobster bait market exceeds the locally available supply of Atlantic herring and bait dealers buy Atlantic herring from other locations. Specifically, we modeled a situation in which demand from the lobster industry results in bait dealers importing an amount equal to the difference between the 2006 and the 2007–2009 Area 1A TACs (15,000 metric tons) from Nova Scotia, Canada. The 45,000 metric tons landed by the Maine purse seine fleet would once again use 945,000 L of fuel and result in emissions of just under 3 million kilograms CO_2 eq (Table 3). However, the 15,000 metric tons of imported Atlantic herring would entail the combustion of an additional 555,000 L of fuel during fishing while emissions from fishing, electricity generation needed to store frozen Atlantic herring, and transportation from Nova Scotia to Maine would yield a total of about 7.5 million kilograms CO_2 eq. Thus, for Scenario 4, total emissions to supply 60,000 metric tons of Atlantic herring amount to almost 10.5 million kilograms CO_2 eq (Table 3). Interestingly, this is still less than the emissions associated with the 60,000 metric tons caught by the mixed purse seine/midwater trawl fleets in the 2005 Area 1A fishery (Table 2). However, the contributions of the higher fuel use in the fishing phase, the electricity used to store the Atlantic herring frozen, and the fuel needed to transport the bait would make the imported 15,000 metric tons disproportionately impactful and would reverse many of the emissions reductions associated with the Area 1A seasonal gear closure (Table 3).

4. Discussion

From data gathered by at-sea observers monitoring Atlantic herring trips across Herring Management Areas, it is clear that purse seining is far more energy efficient than midwater trawling, regardless of configuration, when targeting Atlantic herring in US waters (Table 2). Although it is unclear why such a difference should exist, it is consistent with previous findings that show purse seining for pelagic, schooling species to be relatively energy efficient in relation to other fishing methods [5,7,8]. Interestingly, however, this marked difference in fuel inputs to purse seining and trawling for small pelagics is not observed in a recent analysis of energy inputs to Norwegian fisheries [11]. There, both forms of fishing consumed about 105 L/metric ton (90 kg fuel/1,000 kg fish landed) when fishing for herring and other small pelagic species [Table 3 in 11]. This result, however, might reflect the limited resolution that is possible when undertaking analyses of a nation's fisheries or it could result from fundamental differences in the relative accessibility of herring to purse seiners and trawlers in Norwegian versus US waters. More detailed analyses of fish availability and fishing behaviors between fleets would have to be undertaken to better understand this difference in relative performance.

Although the five-fold difference in the energy intensity of purse seining and trawling for Atlantic herring in US waters may appear extreme, others have found comparable differences in the energy performance of different gear sectors within a fishery. In his analysis of energy inputs to Danish fisheries, Thrane [10] found beam trawlers burned in excess of five times the amount of fuel per metric ton of flatfish caught as did vessels deploying Danish seine nets. Similarly, Ziegler and Valentinsson [4] found that trawlers targeting Norway lobster (*Nephrops norvegicus*) in Swedish waters consumed four times the energy as did creel (trap) fishing boats per ton of Norway lobster landed. While such large differences in energy performance between gears within a fishery seem remarkable, it attests to the fact that fuel costs, while never trivial, have clearly not dominated decision-making amongst skippers and vessel owners. Given the scale of fuel subsidies enjoyed by many fishing fleets, this is perhaps not too surprising [27]. However, in light of the recent spike in oil prices and the likelihood high prices will return as the global recession eases, it is hard to imagine that such large differences in energy performance will persist.

In terms of scale of direct fuel inputs, the fuel intensities of the US purse seine and midwater trawl Atlantic herring fisheries are similar to those reported for other fisheries for small, pelagic species in the North Atlantic (Fig. 6). Moreover, it is important to note that at 21 L/metric ton landed, the purse seine fishery for Atlantic herring is amongst the lowest energy input commercial fisheries yet described [2,5,7–12,28].. Indeed, the fuel intensity of the contemporary New England purse seine fishery for Atlantic herring is markedly lower than the 33 L/metric ton (284 kcal/kg) quantified for the Maine fishery for Atlantic herring of the mid-1970s [12]. This improvement may potentially be a result of the substantial increase in stock abundance that has occurred over the past 30 years [16].

Turning to the future and the potential effect of recent changes in the management of Atlantic herring in US waters, our results clearly indicate that if the entire Area 1A TAC is caught by purse seine vessels operating at their recent historic fuel intensity (Scenario 1) or at a reduced fuel intensity due to decreased competition with midwater trawl vessels (Scenario 2), both total and average fuel use and GHG emissions will be substantially reduced relative to the pre-Amendment 1 fishery (Table 2). The potential for reductions in fuel intensity due to reduced competition with the midwater fleet appear to be good [29] despite the low fuel inputs currently enjoyed by the purse seine fleet. However, even if average fuel inputs to purse seiners increase as vessels pursue schools in deeper water and further from port in efforts to take the entire Area 1A TAC, it is highly improbable that

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005

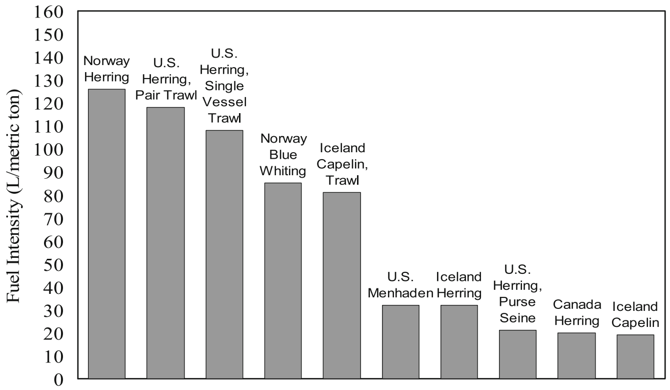

Fig. 6. Fuel intensities (L/ton) of fisheries for small pelagic species. All data are for purse seine fisheries, unless noted otherwise. Source for all data except US Atlantic herring fisheries: [7].

these inputs would approach those of the midwater trawl fleet. In the event that purse seiners licensed to fish Area 1A are unable to catch the entire TAC during the seasonal gear closure, the use of midwater trawl vessels to catch the remaining TAC (Scenario 3) will lessen the potential fuel use and GHG emissions reductions that are possible (Table 3).

Turning to the indirect effect that the reduced Area 1A TAC will have on the regional supply of lobster bait, from communications with bait dealers it appears that they would first attempt to meet demand by buying Atlantic herring from other sources. In this situation (Scenario 4), the fuel use and emissions that may be incurred by importing the difference between the 2006 and 2007–2009 TACs (15,000 metric tons), will nearly offset the fuel and emissions reductions gained through the seasonal ban on trawling in Area 1A. An important factor in the impacts of this scenario is the electricity mix for the region in which the Atlantic herring are chilled or frozen. For example, Nova Scotia's energy mix is heavily dependent on coal and oil, both relatively GHG emission intensive sources of electricity [30]. Thus, a ton of Atlantic herring frozen in Nova Scotia will generate more emissions than one stored in a region with a cleaner mix of primary energy sources, and this burden will be passed on to the purchased Atlantic herring. An alternative option that could be pursued by lobster bait dealers and fishermen would be to increase their utilization of other species such as Atlantic menhaden (*Brevoortia tyrannus*). Given reported fuel inputs ranging from 18 to 40 L/metric ton in the purse seine fishery for Atlantic menhaden [8,28] and the relative proximity of sources of Atlantic menhaden to New England, it is unlikely that overall energy inputs and emissions would be higher than those modeled in Scenario 4.

An intriguing and as yet untested scenario that could unfold as a result of the Area 1A ban on midwater trawling is the potential re-emergence of a vibrant fixed gear fishery. Despite accounting for a substantial portion of New England Atlantic herring landings prior to the early 1980s, weirs and stop seines have essentially disappeared from the fishery in recent decades (Fig. 2). And although the energy and emission performance of weir and stop seine fisheries have yet to be assessed, as they are passive gears it is tempting to imagine that they may be able to deliver fish with fuel inputs at or below that which purse seiners require.

Fuel use data were easily accessible for this fishery because fisheries observers in the northeastern United States record skippers' fuel use estimates along with the usual catch and effort information. However, we note that good fuel use data are lacking for many important fisheries in North America. Given the increasing importance of fuel and GHG issues to so many sectors of society, this paucity of data must be addressed. We strongly encourage management agencies to continue to gather fuel use data in fisheries where this currently occurs, or to initiate programs to collect such data where these efforts are currently absent.

5. Conclusion

Two recent management decisions (the seasonal Purse Seine/ Fixed Gear Only Area provision of Amendment 1, and the lowered Area 1A TAC) almost certainly will have consequences for fuel use and GHG emissions in the US Atlantic herring fishery. While the specific outcome has yet to reveal itself, the results of this analysis suggest that the exclusion of midwater trawlers from Area 1A will almost certainly reduce fuel use and GHG emissions associated with the average ton of Area 1A Atlantic herring landed and utilized in the region. However, other factors may conspire to limit these fuel and emissions savings. If the purse seine fleet cannot catch the entire Area 1A summer TAC, or if the reduced 2007–2009 TAC of 45,000 metric tons is not sufficient to meet market demand for lobster bait and bait dealers choose to import energy-intensive bait from elsewhere, the emissions benefits of the seasonal ban on trawling may be substantially reduced. Even with these and other variables accounted for, however, it is unlikely that the fuel use and GHG emissions of the post-Amendment 1 Area 1A Atlantic herring fishery will match or exceed pre-Amendment 1 levels.

Fisheries management decisions can have profound impacts on the fuel intensity and GHG emissions associated with a fishery. In the case described here, management decisions are likely to substantially yet inadvertently reduce both fuel intensity and GHG emissions of the US Atlantic herring fishery. However, other management decisions could just as easily increase a fishery's fuel use and GHG emissions. The impacts of fisheries management on fishery fuel use and GHG emissions have, to date, largely been ignored in policy-setting and decision-making processes. With the inevitable return of high fuel prices and the likely implementation of emissions-mitigation measures currently being considered by governments, fisheries managers should implement measures to assess the potential impacts of their decisions on the fuel use and GHG emissions of managed fisheries. Management decisions can have long-term effects on fleet structure and dynamics, and as such their influence on fleet fuel use and GHG emissions should be taken into account during the decision-making process.

Acknowledgements

This research was supported through a grant from the Lenfest Ocean Program of the Pew Charitable Trusts. The funding body had no role in the study's design, execution, and interpretation, or in the decision to publish results. We gratefully acknowledge the thoughtful feedback that Rob Stephenson and Dan Holland provided on an earlier version of the paper. All remaining limitations are, of course, the sole responsibility of the authors.

References

[1] Ziegler F, Nilsson P, Mattsson B, Walther Y. Life cycle assessment of frozen cod fillets including fishery-specific environmental impacts. International Journal of Life Cycle Assessment 2003;8(1):39–47.
[2] Hospido A, Tyedmers P. Life cycle environmental impacts of Spanish tuna fisheries. Fisheries Research 2005;76:174–86.
[3] Thrane M. LCA of Danish fish products – new methods and insights. International Journal of Life Cycle Assessment 2006;11(1):66–74.
[4] Ziegler F, Valentinsson D. Environmental life cycle assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005

andconventional trawls – LCA methodology with case study. International Journal of Life Cycle Assessment 2008;13:487–97.

[5] Watanabe H, Okubo M. Energy Input in Marine Fisheries of Japan. Bulletin of the Japanese Society of Scientific Fisheries/Nippon Suisan Gakkaishi 1989;53(9):1525–31.

[6] Mitchell C, Cleveland C. Resource scarcity, energy use and environmental impact: a case study of the New Bedford, Massachusetts, USA fisheries. Environmental Management 1993;17(3):305–17.

[7] Tyedmers P. Energy consumed by North Atlantic fisheries. In Zeller D, Watson R, Pauly D (ed), Fisheries Impacts on North Atlantic Ecosystems: Catch, Effort and National/Regional Datasets. Fisheries Centre Research Reports, Vancouver, British Columbia, 2001; 9(3): 12–34.

[8] Tyedmers P. Fisheries and energy use. In Cleveland C (ed), Encyclopedia of Energy. Elsevier, San Diego, vol. 2. Elsevier, Amsterdam, 2004:683-693.

[9] Ziegler F, Hansson P-A. Emissions from fuel combustion in Swedish cod fishery. Journal of Cleaner Production 2003;11:303–14.

[10] Thrane M. Energy consumption in the Danish fishery. Journal of Industrial Ecology 2004;8(1-2):223–39.

[11] Schau E, Ellingsen H, Endal A, Aanondsen A. Energy consumption in the Norwegian fisheries. Journal of Cleaner Production 2009;17(3):325–34.

[12] Rawitscher T, Mayer G. Nutritional outputs and energy inputs in seafoods. Science 1977;198(4314):261–4.

[13] NEFMC (2006a). Final Amendment 1 to the fishery management plan (FMP) for Atlantic herring. Accessed January 2009 〈http://www.nefmc.org/herring/index.html〉.

[14] NEFMC (2006b) Proposed Atlantic herring specifications for the 2007-2009 fishing years (January 1, 2007–December 31, 2009). Accessed June 2008: 〈http://www.nefmc.org/herring/index.html〉.

[15] ASMFC, A Atlantic Herring Species Profile. Accessed November 2006: 〈http://www.asmfc.org/〉.

[16] Overholtz W. Atlantic herring. Northeast Fisheries Science Center species synopses 2006. Accessed December, 2008: 〈http://www.nefsc.noaa.gov/sos/spsyn/pp/herring/〉.

[17] ASMFC, B Overview of Stock Status. Accessed March 2008: 〈http://www.asmfc.org/〉.

[18] NMFS (2008) Personal communication from the National Marine Fisheries Service, Fisheries Statistics Division, Silver Spring, MD. Accessed May 2008: 〈http://www.st.nmfs.noaa.gov/st1/index.html〉.

[19] Brandt S, McEvoy D. Distributional effects of property rights: transitions in the Atlantic herring fishery. Marine Policy 2006;3(6):659–70.

[20] Read T, Brownstein T. Considering other consumers: fisheries, predators, and Atlantic herring in the Gulf of Maine. Conservation Ecology 2003;7(1).

[21] USDC. Fisheries of the northeastern United States; Atlantic herring fishery, Amendment I. 15 CFR Part 902, 50 CFR Part 648. Federal Register 2007; 72(47): 11252–11281.

[22] NMFS. Fisheries of the northeastern United States; Atlantic Herring Fishery, Amendment I. Federal Register 2007; 72(47): March 12.

[23] Kanwit K, Schaefer E. The migration and movement patterns of Atlantic herring: an anchor tagging project in the Gulf of Maine and southern New England. Maine Department of Marine Resources Annual Report 2003.

[24] Driscoll, J. Life cycle environmental impacts of Gulf of Maine lobster and herring fisheries management decisions. Master's thesis. Dalhousie University, Halifax, 2008.

[25] Maine DMR. Historical summary of Maine lobster fishery. Accessed April 2008: 〈http://www.maine.gov/dmr/rm/lobster/lobdata.htm〉.

[26] Boyd C. From ocean to market: the life cycle biophysical impacts of the southwest Nova Scotia live lobster industry. Master's thesis. Dalhousie University, Halifax, 2008.

[27] Sumaila R, Teh L, Watson R, Tyedmers P, Pauly D. Fuel price increase, subsidies, overcapacity, and resource sustainability. ICES Journal of Marine Science 2008;65:832–40.

[28] Ruttan L, Tyedmers P. Skippers, spotters and seiners: analysis of the skipper effect in US menhaden (Brevoortia spp). purse-seine fisheries. Fisheries Research 2007;83(1):73–80.

[29] NMFS. Final environmental impact assessment for minimizing impacts of the Atlantic herring fishery on essential fish habitat. Washington, D.C. 2005.

[30] Environment Canada.National inventory report: greenhouse gas sources and sinks in Canada, 1990-2004. The Canadian Government's Submission to the UN Framework Convention on Climate Change 2006.

Please cite this article as: Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring.... Marine Policy (2009), doi:10.1016/j.marpol.2009.08.005