Net negative nutrient yields in a bait-consuming fishery

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Abstract

Efforts to achieve sustainable food systems are impeded by inefficiencies associated with the use of agricultural land and resources to grow feed for animals, rather than food for direct consumption by people. In contrast, the unspoken assumption about fisheries, which are a key source of protein and micronutrients, is that they are inherently net-positive producers of food, as they appear to require no intentional inputs of resources that could otherwise be directly consumed by people. However, this assumption may not hold true for all fisheries. One such fishery is the Maine fishery for American lobster (Homarus americanus), which for decades has used substantial amounts of Atlantic herring (Clupea harengus) as bait in its traps. Here, we evaluate the Maine lobster fishery’s production of a suite of nutrients both before and after consideration of its use of Atlantic herring as bait. Despite several sources of uncertainty, our results indicate that the Maine lobster fishery has likely been a net consumer of multiple nutrients in recent years. This stems from both the scale of herring bait use in the lobster fishery, and from herring’s comparatively high edible biomass yield and nutrient content. To our knowledge, this is the first example of a fishery consuming more nutrients, through bait, than it produces through landings. Identifying and addressing such inefficiencies will ensure that fisheries contribute to sustainable food production.

1. Introduction

The global food system is a primary driver of large-scale environmental change. Land use change (primarily driven by agriculture) and direct exploitation of marine species have been identified as the primary drivers of negative impacts on terrestrial and marine ecosystems, respectively (Diaz et al. 2019). Against this backdrop, the continued use of resources to produce animal-derived food products has come under criticism for relative inefficiency. The use of crops to feed animals is estimated to result in the loss of vast amounts of dietary energy that could, in theory, be used to support billions of people (Foley et al. 2011, Cassidy et al. 2013, West et al. 2014). Aquaculture operations that require inputs of fishmeal and fish oil have faced similar criticisms (Naylor et al. 2000), and much effort has gone into improving this aspect of the industry (Kok et al. 2020, Naylor et al. 2021). In contrast, criticisms of inefficiency in fisheries have tended to focus on clear-cut examples of post-capture waste (e.g. the highly visible issue of incidental catch and discarding of marine species). Fisheries catches remove vast quantities of nutrients from aquatic ecosystems (Hicks et al. 2019), and they appear to do so without requiring inputs of resources that could otherwise directly support peoples’ diets (e.g. the resources used for animal feeds). To date, however, a potentially analogous situation has remained unexplored: the use of edible species as bait. Here, we explore the nutrient yield consequences of bait use in a major fishery.

The USA’s fishery for American lobster (Homarus americanus; hereafter referred to as ‘lobster’) is among the nation’s most lucrative fisheries, accounting for approximately 1.3% of the USA’s total landed biomass and receiving 9.4% of the USA’s total commercial fisheries landed value during the years assessed in this study (2006–2017) (NOAA Fisheries 2021a). Lobster landings are dominated by the Maine trap
fishery, which provided approximately 82.6% of USA lobster landings over this time period (NOAA Fisheries 2021a). This fishery experienced an extended period of generally increasing catches from the late 1980s onward (figure 1). The most recent assessment indicates that the lobster stock in the Gulf of Maine and Georges Bank region was near record-high abundance as of 2018, with exploitation essentially equal to the target (ASMFC 2020).

The Maine lobster fishery uses substantial amounts of bait. For decades, the primary bait used in this fishery was domestically-caught Atlantic herring (Clupea harengus, hereafter referred to as ‘herring’) (Stoll et al 2021). The extent of herring bait use in this fishery is such that it has provided a subsidy to lobster biomass production (Grabowski et al 2010). In addition to bait, herring are processed into a variety of food types for people (e.g. frozen/salted, kippers, and sardines; ASMFC 2022). The herring stock has declined in recent years (NEFSC 2018), and is currently considered to be overfished, with spawning biomass of approximately 29% of the level associated with maximum sustainable yield (NMFS 2022). The stock is not considered to be undergoing overfishing as of 2022, however (NMFS 2022).

As herring have higher edible yield rates (i.e. proportion of total biomass that is composed of edible flesh; FAO 1989), and greater concentrations of many nutrients than lobster biomass (figure 2), the Maine lobster fishery’s consumption of herring bait may represent a scenario in which a fishery consumes substantial amounts of nutrients that could otherwise be available to people. Here, we model several scenarios for the Maine lobster fishery’s gross (i.e. before domestic herring bait is considered) and net yields of protein, the omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), iron, zinc, and vitamin B₁₂, for the years 2006–2017. Based on estimates found in the literature (Grabowski et al 2010, Lehuta et al 2014, Driscoll et al 2015), three herring bait use scenarios were modelled: a ‘best guess’ scenario in which the Maine lobster fishery consumed 70% of the USA’s annual landings of Atlantic herring, and low and high scenarios of 60% and 80%, respectively. In addition, three lobster edible yield rate sub-scenarios were modelled: a ‘best guess’ of 18%, and low and high estimates of 15% and 21%, respectively. Our analysis ends in 2017 because significant catch limits were enacted for the domestic herring fishery beginning in 2018 (85 FR 26874 2020), which soon led to sharp reductions in herring available for bait (Stoll et al 2021). Unless noted otherwise, all results discussed pertain to ‘best guess’ scenarios.

2. Materials and methods

2.1. Data

Maine lobster landings data were obtained from Maine’s Department of Marine Resources (Maine DMR 2018). Atlantic herring landings data were obtained from the National Marine Fisheries Service (NOAA Fisheries 2021b). The Atlantic herring edible yield rate estimate was obtained from a publication of the United Nations Food and Agricultural Organization (FAO 1989). Nutrient content rates for lobster (raw) and herring (raw) were obtained from a United States Department of Agriculture Database (USDA 2018). Data and sources for recommended dietary allowance are shown in supplementary materials.

2.2. Scenario model of domestic herring bait use

There is no single time series of data for the Maine lobster fishery’s bait use. In lieu of direct estimates, three domestic herring bait use scenarios were modelled for the years 2006–2017: a ‘best guess’ scenario in which the Maine lobster fishery used 70% of annual USA Atlantic herring landings, and low and high-use
scenarios of 60% and 80%, respectively. These scenarios were derived from the literature (Grabowski et al. 2010, Lehuta et al. 2014, Driscoll et al. 2015, Stoll et al. 2021).

Driscoll et al. (2015), using surveys of Maine lobster license holders (n = 83), reported that Maine lobster fishers in the 2006 fishery used Atlantic herring at rates that would have equalled approximately 73% of the 2006 USA Atlantic herring landings (Driscoll et al. 2015). Grabowski et al. (2010) estimated that ‘about 70%’ of Atlantic herring were used as bait in New England lobster fisheries (Grabowski et al. 2010). From these two sources, 70% of Atlantic herring landings was considered the ‘best guess’ for the average annual herring use in the Maine lobster fishery since 2006.

However, this may be an underestimate for this period overall. It is notable that the 2006 estimate (in which the Maine lobster fishery was estimated to use approximately 73% of that year’s Atlantic herring landings) was also the year of the highest herring landings in recent decades (NOAA Fisheries 2021b); thus, the proportion of herring destined for use as lobster bait may be higher in years when herring landings were lower. Indeed, (Lehuta et al. 2014) stated that the Gulf of Maine lobster fishery may have consumed up to 80% of annual herring landings in the years after 2007 (Lehuta et al. 2014). Thus, 80% of annual USA Atlantic herring landings was used as the high-use scenario.

Of the few sources found in the literature, none suggest that the Maine lobster fishery used less than 70% of the USA’s annual Atlantic herring landings in the years after 2006. In a recent study, Stoll and colleagues assessed voluntary survey data and found that the share of all lobster bait composed of herring declined from approximately 89% in 2004 to 36% in 2018, a decline of approximately 60% (Stoll et al. 2021). However, during this time, the total amount of herring available for use as bait also declined due to reductions in allowable herring catches and rising prices for the herring that was caught (Stoll et al. 2021). Indeed, from 2006–2017, USA Atlantic herring landings declined by approximately 59% (table 1), mirroring the decline in herring’s share of lobster bait reported by Stoll and colleagues. Thus, there is no indication in the literature that herring’s declining share of total lobster bait, as reported by Stoll and colleagues, resulted in the use of a substantially lower proportion of available herring (i.e. while the total amount of herring bait generally declined from 2006–2017, there is no indication that this represented a reduction in the proportion of available herring that was used as bait). As no sources suggested that the Maine lobster fishery used less than 70% of annual herring landings as bait, and as there was no indication that the declining role of herring in total lobster bait was indicative of declines in the share of available herring used as bait, 60% of total herring landings was assumed to represent an adequately cautious ‘low’ scenario for the years 2006–2017.

Lobster landings and herring landings are shown in table 1.

### 2.3. Nutrient yield estimates

For both herring and lobster, yields of seven nutrients were estimated: protein, the omega-3 fatty acids EPA and DHA, iron, zinc, and vitamin B12.

The yield $Y$ of nutrient $V_i$ derived from species $i$ was determined as shown in equation (1). Total biomass $B_i$ (lobster landings, and herring bait estimates) were converted to edible biomass by the application of edible biomass yield rates ($E_{Ed}$). Nutrient content rates ($E_{V}$) were then applied to these estimates of edible biomass, resulting in estimates of edible nutrient yields.

$$Y_{V_i} = B_i \times E_{Ed,i} \times E_{V_i}$$  

### 2.3.1. Scenario model of lobster edible biomass yield rates

Estimating the nutrient yields of the Maine lobster fishery requires consideration of the fishery’s catches of soft-shell vs. hard-shell lobsters, as the proportion of body weight that is edible can vary substantially between these two molt stages. There are a variety of estimates of the edible biomass yield of lobsters in their soft- and hard-shell states. Soft and hard-shelled lobsters are generally said to have edible biomass yields of 12.5%–18% and 20%–28%, respectively: for example, Dow and colleagues estimated that soft- and hard-shell lobsters yielded 12.5% and 25%, respectively (Dow et al. 1975). There are no published estimates of the proportion of Maine lobster yields that have been composed of soft-shell vs. hard-shell lobsters over time, but the Maine lobster fishery’s primary season occurs when lobsters are in their soft-shell stage (Holland 2011).

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| Year | Maine American lobster landings (t) | USA Atlantic herring landings (t) |
|------|-------------------------------------|-----------------------------------|
| 2006 | 34 176                               | 120 833                           |
| 2007 | 29 019                               | 73 846                            |
| 2008 | 31 710                               | 79 107                            |
| 2009 | 36 820                               | 101 860                           |
| 2010 | 43 640                               | 65 730                            |
| 2011 | 47 593                               | 80 162                            |
| 2012 | 57 752                               | 86 981                            |
| 2013 | 57 973                               | 93 483                            |
| 2014 | 56 393                               | 91 685                            |
| 2015 | 55 639                               | 79 532                            |
| 2016 | 60 154                               | 62 608                            |
| 2017 | 50 759                               | 49 457                            |
In recognition of this uncertainty, three sub-scenarios were modelled for lobster edible biomass yield rate. The 'best guess' sub-scenario was based on an assumption that the Maine lobster fishery's landings during the years 2006–2017 were composed of 70% soft-shell and 30% hard-shell lobsters, and the edible biomass yield rates for soft- and hard-shell lobsters were 15% and 25%, respectively. Combining these two estimates, the 'best guess' edible biomass yield sub-scenario was 18%. From this estimate, low and high rates were set at 15% and 21%, respectively.

2.4. Uncertainty

The final step was to determine the uncertainty in modelled scenario results. Referring to equation (1), \( B_i \) for lobster was obtained from landings statistics (Maine DMR 2018) and was modelled as three scenarios for herring bait, and \( E_{ED} \) for lobster was likewise modelled as three sub-scenarios. Uncertainties in edible nutrient yield estimates \( (Y_i) \) were informed by uncertainty in the edible biomass yield rate \( (E_{ED}) \) for herring and in nutrient content rates \( (E_{i}) \) for herring and lobster.

For the \( E_{ED} \) estimate for herring, there was no accompanying standard error. Using an approach similar to that described by Pauly and Zeller (2016) to generate uncertainty boundaries for historic catch reconstructions, a proxy uncertainty range of ±20% (with an implied 95% confidence level) was assigned after consideration of the quality and agreement of available edible biomass yield estimates for herring. This proxy uncertainty range was converted to a proxy standard error of the mean by first multiplying the \( E_{ED} \) estimate for herring by 0.2 to estimate a proxy 95% confidence interval, which was then divided by 1.96 to give a proxy standard error of the mean.

For the nutrient content rates, standard errors of the mean were available from the USDA database's estimates of nutrient content in herring biomass (raw), but were unavailable for lobster. For lobster, proxy standard errors of the mean were therefore determined for each nutrient via the following process. First, for a given nutrient \( V \), the mean standard error was found over 26 taxa caught in northwest Atlantic fisheries (tables S1 and S2). This was then divided by the mean value of \( V \) across the same 26 species (tables S1 and S2), to give a mean ratio of the standard error to the mean for each nutrient across 26 northwest Atlantic taxa (table S3). This ratio was then multiplied by the associated nutrient content rate \( (E_{i}) \) for lobster (table S3). The resulting proxy standard errors of the mean for lobster nutrient content rates were therefore based on nutrient-specific average ratios of the standard error to the mean for major taxa in the region (supplementary materials).

Using these standard error (SEM) and proxy standard error (PSEM) values, proxy 95% confidence intervals were obtained for each modelled yield \( Y \) of nutrient \( V \) as shown in equation (2):

| American lobster | Atlantic herring |
|------------------|------------------|
| Edible yield     |                  |
| Low scenario: 0.15 | 0.63 (±0.064)    |
| 'Best guess': 0.18 |                  |
| High scenario: 0.21 |                  |
| Protein content  |                  |
| 0.1652           | 0.1796           |
| (±4.86 × 10⁻³)  | (±2.35 × 10⁻³)  |
| EPA content      |                  |
| 1.02 × 10⁻³      | 7.09 × 10⁻³     |
| (±5.65 × 10⁻³)  | (±2.8 × 10⁻⁴)  |
| DHA content      |                  |
| 6.8 × 10⁻⁴      | 8.62 × 10⁻³     |
| (±3.79 × 10⁻⁴)  | (±5.7 × 10⁻⁴)  |
| Iron content     |                  |
| 2.6 × 10⁻⁶      | 1.1 × 10⁻⁵     |
| (±1.85 × 10⁻⁷)  | (±6.825 × 10⁻⁷) |
| Zinc content     |                  |
| 3.53 × 10⁻⁵     | 9.9 × 10⁻⁶     |
| (±1.25 × 10⁻⁶)  | (±7.3 × 10⁻⁷)  |
| Vitamin B₁₂      |                  |
| 1.25 × 10⁻⁸     | 1.367 × 10⁻⁷   |
| (±1.45 × 10⁻⁴)  | (±5.58 × 10⁻⁹) |

Proxy 95% Confidence Intervals

\[
Y_V = 1.96 × Y_V \left( \sqrt{\frac{\sigma_{ED}}{E_{ED}}} \right) + \left( \frac{\sigma_V}{E_V} \right)
\]

where \( E_{ED} \) is the edible biomass yield estimate, \( E_V \) is the estimate of the concentration of nutrient \( V \) in the edible biomass, and \( \sigma \) is the SEM or PSEM. Edible yield rates, nutrient content rates, and associated estimates of uncertainty are shown in table 2.

3. Results

From 2006 to 2017, the Maine lobster fishery's use of domestic herring bait was modelled to be highest in 2006 and declining in the latter years, due to diminishing herring landings (figure 3). The ratio of herring bait: lobster landings declined over this period, from 2.47 in 2006 to 0.68 in 2017 (using the 'Best Guess' bait scenario; table 1).

From 2006 through 2016, gross nutrient yields from the Maine lobster fishery's landings increased by approximately 76%, before declining somewhat in 2017 (figure 4A). This predictably followed the herring bait: lobster landings trend (figure 1). The nutrients embodied in domestic herring bait biomass (figure 4B) were generally greater than the nutrients embodied in the landed lobster biomass (figure 4A). As a result, annual net nutrient yields from the lobster fishery were negative—i.e. the lobster fishery was a net consumer of nutrients—for protein, EPA, DHA, iron, and vitamin B₁₂, for all years during the assessed period of 2006–2017 (figure 4C). For these five nutrients, the lobster fishery's net yields were
consistently negative at all three herring bait estimate scenarios and across three lobster edible yield rate sub-scenarios, and even broad uncertainty bands associated with variability in lobster and herring nutrient content did not result in net positive outcomes (figure 4(C)). Relative to domestic herring bait inputs, the lobster fishery has likely been a net producer of zinc in recent years, however (figure 4(C)).  

4. Discussion

The results of this analysis suggest that for the period 2006–2017 the Maine lobster fishery was a net consumer, rather than producer, for five of the six assessed nutrients. This conclusion can be drawn across reasonable assumptions for annual domestic herring bait inputs and the edible yield rate of lobster landings, and appears to be robust to uncertainty regarding the nutrient yields per unit of edible lobster and herring biomass. Results from the ‘best guess’ herring use scenario (70% of annual USA Atlantic herring landings) is indicated by the solid black line. Shaded areas represent upper and lower estimates of 80% and 60% of landing landings, respectively.

Figure 3. Modelled estimates of domestic Atlantic herring bait use in the Maine lobster fishery, 2006–2017. The ‘best guess’ bait estimate (70% of annual USA Atlantic herring landings) is indicated by the solid black line. Shaded areas represent upper and lower estimates of 80% and 60% of herring landings, respectively.

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Figure 4. (A) Gross nutrient yields from lobster landings, before domestic herring bait nutrient inputs are taken into account. Note that three sub-scenarios are modelled for lobster edible yield rate (21%, 18%, and 15%), indicated by solid lines. Dotted and dashed lines indicate upper and lower confidence intervals, respectively, for the associated sub-scenario estimate, and shaded area represents the full range from lowest to highest confidence interval across all three sub-scenarios. (B) Bait nutrient inputs for three modelled scenarios of domestic herring bait use in the lobster fishery. Shaded region indicates total range of confidence interval values across all three scenarios, informed by uncertainty in edible yield and nutrient content rate. (C) Net nutrient yields (gross lobster yields minus domestic herring bait nutrient inputs) for the three bait scenarios and three lobster edible yield sub-scenarios. For each bait scenario, the solid line indicates the 18% lobster edible yield sub-scenario estimate, and the dotted and dashed lines indicate 21% and 15% lobster edible yield sub-scenario estimates, respectively. Shaded area represents total confidence interval range across all scenarios and sub-scenarios. The dashed grey line indicates net neutral nutrient yield (i.e., lobster nutrient outputs equal herring bait nutrient inputs).

To our knowledge, this is the first demonstration that a fishery may consume more human-available nutrients than it produces. This example may or may not be an outlier among fisheries; additional research on other bait-using fisheries is necessary to understand the degree to which the Maine example is unique or illustrative of a larger trend in bait-using fisheries. To this end, there is a clear need for a significant improvement in the information available for bait use in fisheries. To our knowledge, there are no regional or global estimates of bait use in fisheries. Information on bait use in fisheries, where it exists, is often so vague as to be functionally useless, offering little detail on the species composition or amounts of bait used. Considering the attention that is paid to a variety of other fishery-related topics, the dearth of reliable information for bait use is notable.

There is a growing awareness of the importance of fisheries as sources of nutrients for people (Golden et al. 2016, Thilsted et al. 2016, Hicks et al. 2019). As a result, nutrient-informed approaches to fisheries management are being developed (Robinson et al. 2022). To date, the role of bait in fisheries nutrient yields appears to have been overlooked. The results of this study suggest that bait may be an important
consideration, particularly when it is composed of nutrient-dense, highly edible species.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

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