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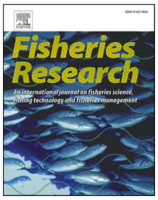

Shrinking shrimp - Investigating the weight loss of northern shrimp *Pandalus borealis* following boiling

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ABSTRACT

Reported landings from commercial fisheries are a main source of information on the removed biomass of a species and/or stock from the sea. In many fisheries, however, on-board processing to meet market demand causes a discrepancy between the landed weight and original live weight, necessitating the use of correction factors during data preparation for stock assessment and advice. One such fishery is for northern shrimp (*Pandalus borealis)* in the Skagerrak, Kattegat and northern North Sea. In this fishery, large, often female shrimp are boiled in salt water while on-board to maximise sale prices and scientists currently use a correction factor of 1.13 to account for the weight loss of shrimp from boiling. Here, we investigated this correction factor by conducting a weight loss experiment on-board the Swedish shrimp fishery between 2022 and 2024. We estimate that shrimps lose 10.26 % of their weight during boiling which corresponds to a correction factor of 1.11. Further, we find that weight loss likely varies on a seasonal basis, with more weight being lost during Q2 and Q3 compared to Q1 and Q4, potentially due to changes in the biology of the species as well as environmental conditions. Our findings suggest that the current correction factor used in the assessment of the stock should be reduced for the Swedish fishery and should preferably vary based on when the shrimp are caught. The experimental methodology used here could also be used to estimate weight loss in other shrimp fisheries.

1. Introduction

Commercial catch data, alongside scientific survey data and biological knowledge, are the primary information used in stock assessment models to estimate the current and past status of a fish stock (Hilborn and Walters 1992; Cadrin and Dickey-Collas 2015). This estimated stock status is then used as the basis of scientific advice, whereby a Total Allowable Catch (TAC) is advised for the next year based on the estimated impact of fishing on the stock, the stock's current state in relation to its reference points as well as a stock's current management strategy (ICES, 2023a).

Data on commercial catches is typically collected from logbooks or landing declarations, with fishers reporting the weight of their catch (by species and location) once it has been landed. Landed weights can then be allocated to certain stocks and countries, and compared to the annual TAC for that stock. In most of the world's major fisheries, fish are caught, stored on-board in some way (typically on ice) and subsequently landed after a short period of time (typically hours or days). Within this process, it is generally expected that the landed weight will be comparable to the original live weight (i.e., the weight of the fish just after it was removed from the sea). However, this is not the case in all fisheries. In fact, there are many cases when the species caught are processed on-board prior to landing to meet market demand. Examples of this include the gutting, beheading and filleting of larger fish as well as the removal of tails and claws or the boiling on-board of certain crustaceans. In such cases, correction factors need to be applied to the landed weight to obtain the original live weight.

One such fishery is for *Pandalus borealis* (shrimp) in the Skagerrak and Kattegat and northern North Sea in the Norwegian deep (ICES, 2024a, 2024b). In this fishery, larger shrimps are boiled on-board to meet market demand and achieve higher sale prices in Sweden and Norway, and to a lesser extent in Denmark (ICES, 2022). In Sweden in particular, larger shrimp boiled in salt water are seen as a delicacy, and are often served fresh at dinner parties and are peeled by hand by guests. These boiled shrimp often have a minimum carapace length larger than 18 mm, with scientific samples taken from on-board the Swedish fishery

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indicating a median size of around 21 mm. *Pandalus* are protandric hermaphrodites (Bergström, 2000) and, in this stock, are thought to change sex from male to female at around age 2, with an estimated length at which 50 % have changed sex (L50) of 18.15 mm based on data dating back to 1986 (ICES, 2022). This means that a many of the boiled shrimp will be female, and a proportion may not have had chance to reproduce as females prior to capture.

The boiling of large shrimp takes place on-board immediately after capture, and generally involves the placement of shrimp in boiling (temperatures near 100℃) extra-salted seawater for several minutes, albeit the temperature, salinity and boiling duration will likely differ between vessels and trips. The boiled shrimp are subsequently cooled and packed, and the packed weight is reported, either in logbooks on-board vessels or in landings declarations onshore. Boiling in hot salty water is expected to cause a reduction in weight through the loss of water and proteins (Benjakul et al., 2008, Martínez-Alvarez et al., 2009; Manheem et al., 2012), meaning the weight reported might not reliably reflect the original live weight.

To counteract for the loss of weight due to boiling, several corrections are routinely made to both the biological estimates made in the lab and the catch estimates of shrimp used in stock assessment. With regards to the latter, which is the focus of this work, scientists within the International Council for the Exploration of the Sea (ICES) currently use catch data where a correction factor has been applied to the boiled fraction of the commercial landings. Specifically, the landed weight of the boiled fraction (i.e., the weight of packed shrimp) is scaled upwards by a factor of 1.13 to account for the potential loss of weight by boiling (ICES, 2023a; 2023b) and has been applied back to 2000 by scientists in Sweden, Denmark and Norway (Ulmestrand et al., 2016). A correction factor of 1.13 corresponds to a weight loss of approximately 11.5 %, and is calculated as follows:

$$correction\ factor = \frac{1}{1 - \frac{weight\ loss(\%)}{100}} \tag{1}$$

The application of the correction factor is, however, not without its complications. For instance, it is routinely applied *post-hoc* (once all the annual landings have been taken and recorded) and the annual TAC is expressed in original live weight and is generally fully utilised by the fishery (ICES, 2023c; 2024a; 2024b). Consequently, when the landings originally reported by the fishers (part of which are boiled) are scaled upwards by 1.13, the estimated total catch often exceeds the annual TAC for the stock. It is also notable that not all shrimp are boiled, and the weight of the raw (i.e. not boiled) shrimp is assumed indicative of original live weight. In the Swedish and Norwegian fisheries, 50–70 % of all catches are boiled at sea, whereas this declines to 35 % in the Danish fishery (ICES, 2024a).

The spawning biomass (defined as the biomass of females) of the shrimp stock in the Skagerrak and Kattegat and northern North Sea in the Norwegian deep has declined substantially over the last 20 years, and has been estimated to be below its biological reference points, including the ICES limit reference point B_{lim}, since 2011 (ICES 2024a, 2024b). This continued low biomass, despite reductions in catch, has led to scrutiny in the stock assessment and the data used it in. One aspect that has been highlighted by scientists is the validity of the current correction factor, with small-scale *ad hoc* investigations by scientists in all three countries suggesting that a factor of 1.13 might be too high (ICES, 2022). To help address this, we carried out a weight loss experiment on-board the Swedish shrimp fishery in years 2022–2024. Specifically, we collected measurements of shrimp weight following capture, boiling and packing, and used them to investigate the following research questions: (1) what is the weight loss of shrimp between capture and boiling? (2) Is there any further weight loss or gain between boiling and packing? And (3) what is the total weight loss between capture and packing? Throughout we also considered differences in temperature, salinity, and boiling duration as explanatory variables, and used the estimated rates of weight loss to test the validity of the current correction factor for the Swedish shrimp fishery.

2. Methods

In accordance with the European Data Collection Framework (DCF), Sweden implements several sampling programs of the Swedish commercial fishing fleet (EU, 2017; European Commission, 2024). Within the DCF, a sampling program is thus already in place for the Swedish shrimp fishery and provides an ideal platform for our on-board weight loss experiment. In brief, this program of data collection aims to sample two Swedish shrimp fisheries: one that operates further offshore (generally larger vessels, using trawls equipped with a shrimp grid and a fish retention tunnel) and one that operates more inshore (generally smaller vessels, with trawls equipped with a shrimp grid but without a fish retention tunnel). Further details on the sampling program and design can be found in ICES (2022) and in Annex 1.1 of the Swedish National Work-Plan 2022–2024 (European Commission, 2024).

2.1. On-board experiment

Our on-board experiment took place within the Swedish shrimp fishery that operates further offshore using a trawl equipped with a shrimp grid and a fish retention tunnel. Sampling consisted of taking a 1 kg sample at random from the largest fraction of shrimps (i.e. those that had already been sorted and were destined to be boiled) before boiling. The total weight of the sample was then taken (providing the original live weight of the sample; (Fig. 1)) and placed in a steel mesh container that enabled the sample to be boiled at the same time as the rest of catch. The sample was then boiled, removed from the mesh container, and placed in a cooling basket provided by the fishers, which ensured that the sample was cooled in the same manner as the rest of the catch. Within the Swedish shrimp fishery, the cooling of boiled shrimp is done via air cooling and not via other methods such as water cooling (the preferred method within the Norwegian fishery; ICES, 2022). The time spent and location of cooling can, however, differ based on weather conditions, size of the catch, and season, with shrimp spending a varying amount of time cooling on deck versus cooling below deck in a refrigerated space.

The total weight of the sample was measured again approximately 1 hour after boiling (boiled weight) and again just before the fishers packed the catch (packed weight). This packing stage involves placing the shrimp in small cardboard boxes, with boiled shrimp being landed fresh and not stored on ice. It is the packed weight that is then recorded, either in logbooks on-board vessels or in landings declarations onshore, meaning it is the total weight loss between the original live weight and the packed weight that is relevant for the correction factor. Throughout the whole experiment the samples were always kept in close proximity to the rest of the catch and stored in the same manner to ensure consistency in the handling procedure of the catch and the experimental sample.

Due to the fact that boiling procedures are known to vary between vessels, the properties of the boiling process, namely water salinity (%), water temperature (℃ - both at the start and the end of boiling) and boiling duration (minutes) were all logged by scientific observers but controlled by the skippers to match their usual procedure (Table S1). Salinity was also measured by taking a water sample from the boiler directly before the catch and the sample was added. This water sample was then brought back to lab and analysed using a KERN ORA-2SA refractometer.

In total, 23 on-board sampling trips were made between 2022 and 2024 on eight different vessels. Only 1 haul was sampled per trip, with few exceptions (Table S1). Boiled weight was lacking for 2 trips, therefore reducing the sample size from 23 to 21 for the capture to boiled and boiled to packing comparisons. The location and timing of all hauls from which the samples were taken are illustrated in Fig. 2.

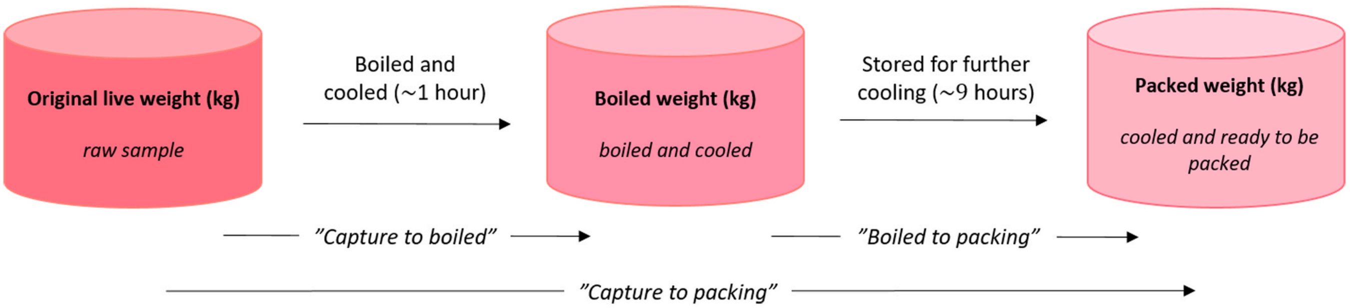

Fig. 1. Infographic of the on-board experiment and sampling procedure used in this study. Weight measurements of a 1 kg sample of *Pandalus borealis* taken from the shrimp set aside to be boiled. Comparisons made in this study are also illustrated.

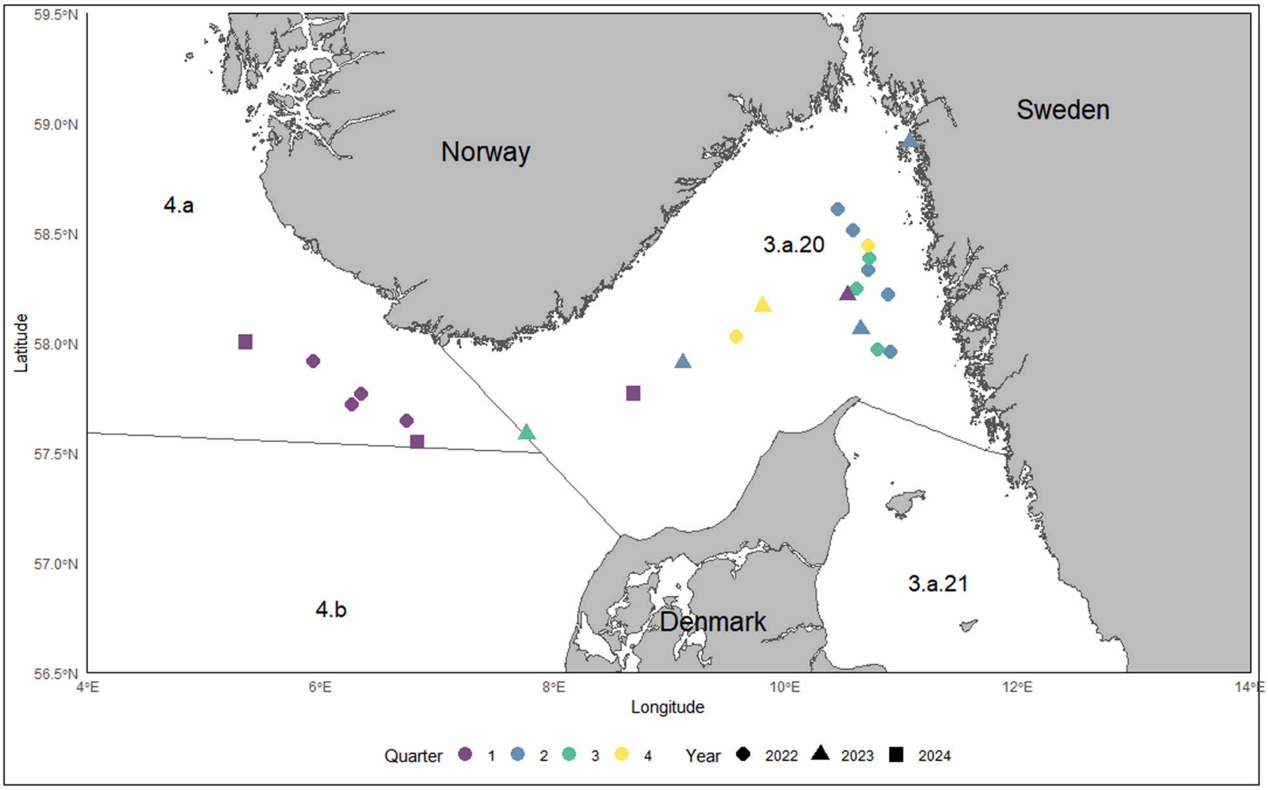

Fig. 2. Location and timing of hauls from which on-board samples were taken during the years 2022 (circle), 2023 (triangle) and 2024 (square). The season of the year (quarters 1–4) in which each sample was collected is also shown. ICES divisions of 4.a (northern North Sea), 4.b (central North Sea), 3.a.20 (Skagerrak) and 3.a.21 (Kattegat) as well as the three countries that commercially fish the stock (Norway, Sweden and Denmark) are labelled.

2.2. Statistical analysis

Linear mixed effect (LME) models were used to investigate the weight loss of the shrimps. In all models, percentage weight loss was calculated as follows:

$$\textit{Weight loss}(\%) = \frac{(\textit{Original live weight} - \textit{New weight})}{\textit{Original live weight}} \times 100 \tag{2}$$

and was used as a response variable. Year (factor), quarter (factor), temperature, temperature change (Δ°C), salinity and boiling duration were all considered as explanatory variables (Table S1). Specifically, temperature refers to the water temperature at the start of boiling, ranging from 76℃ to 100℃, and temperature change refers to the change in temperature between the start and the end of the boiling process, which spans the boiling duration.

LMEs were used as opposed to more conventional analysis tools (e.g., linear models or simple averages) to statistically account for any unobserved variation associated with trip-level effects (e.g., weather conditions or variables associated with handling and processing not sampled during our experiment) in the random effects distribution of the model. Model fit was assessed via visual inspection of the residuals and other diagnostic tools (e.g. QQ plots). Simple LMEs including only a random intercept term for trip were considered first in order to estimate general rates of weight loss. More complex models were then fit to determine if the observed variability in weight loss could be described by any of the explanatory variables that were collected on-board (e.g., quarter or temperature). During this second part, model selection occurred via a two-step process; (A) the *dredge* function in the MuMIn package (Barton, 2023) was used to reduce the number of models considered and (B) AICc (corrected Akaike Information Criterion) was used to select the most parsimonious model. Only models with a delta AICc (ΔAICc) of less than 4 from the most parsimonious model (i.e., the model with the lowest AIC score) were considered as a ΔAICc > 4

generally indicates a lack of statistical support. AICc was used as opposed to standard AIC as it corrects for low sample size and tends to have smaller biases.

All analysis and visualisation were conducted in R (R Core Team, 2021). LMEs were fit using the *lme4* package (Bates et al., 2015). All plots were generated using the *tidyverse* collection of R packages (Wickham et al., 2019).

3. Results

3.1. Capture to boiled

Analysis via LME modelling indicated an estimated weight loss of 9.21 % between capture (i.e. original live weight) and boiling (Fig. 3; Table 1), albeit substantial variation existed between samples (Table S1). The lowest weight loss observed was 3 % and the highest was 13.8 %. The lowest observation was sampled in March 2022, whereas the highest was sampled in June of the same year.

Model selection via AICc highlighted that the most parsimonious model included a random intercept term for trip and a fixed effect term for quarter (Table S2). This indicated that the weight loss of shrimp between capture and boiling differed on a seasonal basis (Fig. 4). Specifically, the model estimated a weight loss coefficient of 7.4 % in Q1, 10.3 % in Q2, 10.4 % in Q3 and 8.1 % in Q4 (Table 2).

It is also notable that both year and boiling duration were selected as explanatory variables in alternative models, whereas neither temperature nor salinity were found to have statistical support (Table S2). Weight loss was estimated to be higher in both 2022 (9.4 %) and 2023 (9.6 %) than 2024 (8.2 %), albeit the variability across samples and within the number of samples is large (Figure S1). Further, boiling duration was found to have a positive relationship with weight loss between capture and boiling (slope coefficient = 1.2), with a longer time spent being boiled resulting in a greater weight loss (Figure S2).

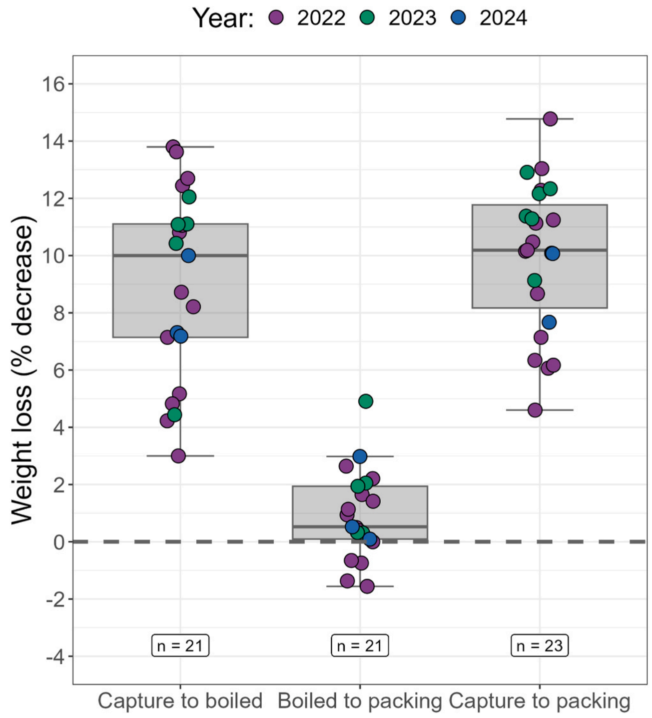

Fig. 3. Weight loss of a 1 kg sample of shrimp measured on-board following capture, boiling and packing. Boxplots describe the median and interquartile range (25th and 75th). Points represent individual samples and are coloured based on which year they were taken: 2022 (purple; n = 14), 2023 (green; n = 6) and 2024 (blue; n = 3). Positive (above the dotted line) and negative (below the dotted line) signify a loss and gain in weight, respectively. The sample size of each comparison is listed.

Table 1
Fixed effect coefficients and confidence intervals (lower = 2.5 % - higher = 97.5 %) for weight loss of shrimp measured on-board following capture, boiling and packing. All values are extracted from the simplest LME model with just a random intercept term for trip. All values have been rounded to two decimal places.

Comparison	Weight loss (%)
Capture to boiled	9.21 (7.66 – 10.81)
Boiled to packing	0.95 (0.23 – 1.67)
Capture to packing	10.26 (9.09 – 11.45)

3.2. Boiled to packing

Analysis via LME modelling indicated an estimated weight loss of 0.95 % between boiling and packing (Fig. 3; Table 1). In four samples, the shrimp gained weight with an average of 1.08 %, whereas in one sample the weight remained unchanged. Amongst those samples that lost further weight between boiling and packing, the weight loss ranged from 0.09 % to 4.9 %.

Model selection via AICc highlighted that the most parsimonious model included a random intercept term for trip and no further exploratory variables (Table S2). That said, models that considered both year and boiling duration do have some statistical support. Weight loss between boiling and packing was found to be highest in 2023 (1.9 %) compared to both 2022 (0.4 %) and 2024 (1.2 %; Figure S1). There was also a negative relationship between boiling duration and weight loss (slope coefficient = −0.44; Figure S2).

3.3. Capture to packing

Analysis via LME modelling indicated an estimated weight loss of 10.26 % between capture and packing (Fig. 3; Table 1), albeit variation existed between samples (Table S1). The lowest weight loss observed was 4.6 % and the highest weight loss was 14.8 %.

Model selection via AICc highlighted that the most parsimonious model included a random intercept term for trip and a fixed effect term for quarter (Table S2). This indicated that the weight loss of shrimp between capture and boiling differed on a seasonal basis (Fig. 4). Specifically, the model estimated a weight loss coefficient of 8.6 % in Q1, 11.4 % in Q2, 10.9 % in Q3 and 9.6 % in Q4 (Table 2). Again, year was also considered an important explanatory variable in alternative models, with the weight loss coefficient estimated at 10.0 % in 2022, 11.2 % in 2023 and 9.3 % in 2024.

4. Discussion

The ICES working group that assesses the northern shrimp stock in the Skagerrak and Kattegat and northern North Sea in the Norwegian Deep, currently uses data where a correction factor of 1.13 (a weight loss of approximately 11.5 % - see Eq. 1) has been applied to the boiled fraction of the catch to account for the weight loss during boiling (ICES 2024a; 2024b). Exactly how this correction factor has been derived is unknown, and has in recent times been questioned by fishers, managers and scientists in Norway, Sweden and Denmark (ICES, 2022). Here we show that this correction factor might be too high using data collected on-board the Swedish shrimp fishery in 2022–2024. Specifically, we estimate a weight loss of 9.21 % between capture and boiling and a further weight loss of 0.95 % between boiling and packing. We also estimate a total weight loss between capture and packing of 10.26 %, leading to a correction factor of 1.11. Moreover, statistical analysis shows that the weight loss differs by season, with greater weight lost during Q2 and Q3, compared to Q1 and Q4. Such findings suggest that the current correction factor should be reduced from 1.13 to around 1.11

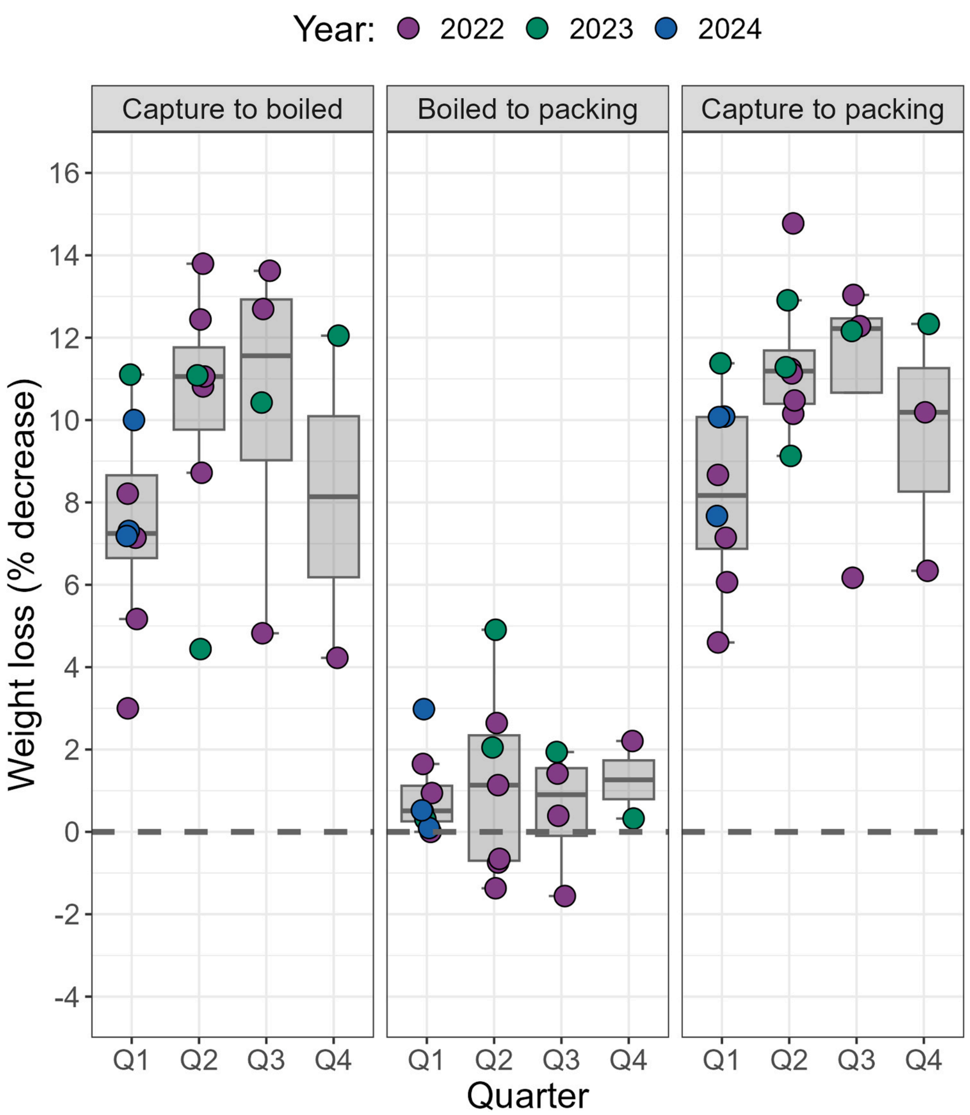

Fig. 4. Weight loss of a 1 kg sample of shrimp measured on-board following capture, boiling and packing. Weight loss is plotted by quarter, where Q1 – Jan-Mar, Q2 – Apr-Jun, Q3 – Jul-Sep and Q4 – Oct-Dec. Boxplots describe the median and interquartile range (25th and 75th). Points represent individual samples and are coloured based on which year they were taken: 2022 (purple; n = 14), 2023 (green; n = 6) and 2024 (blue; n = 3). Positive (above the dotted line) and negative (below the dotted line) signify a loss and gain in weight, respectively.

Table 2
Fixed effect coefficients and confidence intervals (lower = 2.5 % - higher = 97.5 %) for weight loss of shrimp measured on-board following capture, boiling and packing. All values are extracted from the most parsimonious models detailed in Table S2. All values have been rounded to two decimal places.

	Weight loss (%)			
Comparison	Q1 (Jan-Mar)	Q2 (Apr-Jun)	Q3 (Jul-Sep)	Q4 (Oct-Dec)
Capture to boiled	7.39 (5.28 – 9.50)	10.34 (5.13 – 15.54)	10.39 (4.62 – 16.17)	8.14 (1.30 – 14.98)
Boiled to packing	0.95 (0.23 – 1.67)			
Capture to packing	8.66 (6.67 – 10.53)	11.43 (6.93 – 15.88)	10.91 (6.08 – 15.89)	9.62 (4.53 – 14.88)

for the Swedish fishery and should probably vary based on when shrimp are caught.

A primary outcome of this study is the confirmation that shrimp lose weight during boiling. Previous studies agree with this conclusion, demonstrating that boiling causes the loss of both water and proteins, and that weight loss increases with increased water temperature, increased boiling time, increased core temperature, and how long the increased core temperature is held (Benjakul et al., 2008; Martínez-Alvarez et al., 2009; Manheem et al., 2012). Some studies also show that weight loss is higher with increased salinity (e.g., Niamnuy, et al., 2008). Here, we find some evidence that a longer boiling time leads to greater weight loss, however, we find little relationship between salinity and weight loss, and between temperature and weight loss. This lack of a relationship could be due to lack of contrast in boiling temperatures and water salinities used among Swedish fishers, who tended to add extra salt to the boiler and start boiling the shrimp at a water temperature around 90℃ (Table S1). In the controlled experiment by Niamnuy et al. (2008), the impact of increased salinity is only particularly evident when comparing low salinity levels (0 and 2 %) with moderately higher concentrations (3 and 4 %) and boiling for 1 minute. At extended boiling times, 3 minutes or more, the difference in weight loss between salt concentrations were less pronounced. In this study, salinities were generally much higher, with an average of 14.5 % with only one haul being less than 10 % (Table S1). Moreover, the boiling duration often exceeded 4 minutes (Table S1). Despite this, the lack of relationship could also be linked to the relatively low sample size of our study, and the large variance in weight loss that was observed across trips and between hauls of the same trip. For instance, in one of the trips analysed (Table S1), several hauls were sampled, and indicated up to a 5 % variation in the amount of weight lost between hauls. Such differences, combined with the observed differences in weight loss across years, suggest that other biological or environmental factors not explicitly considered here (e.g., size of individual shrimps, the condition of individual shrimp, the size or age distribution of the population and/or weather conditions) might be playing some role in the observed rates, and highlight both the sensitivity of any derived correction factor and a need for routine monitoring over time with more substantial sample sizes.

Differences in the handling and processing on-board vessels might also play an important role in the weight loss of shrimp. We know that Swedish shrimp vessels typically follow the same core process following capture, namely sorting, boiling, cooling and packaging. We also ensured that our on-board samples were always treated in the same way to the rest of the catch and included a random intercept term for trip in our models of weight loss to account for any unobserved trip-level variation. Despite this, we suspect that there remains a variety of different ways in which shrimp might get handled or processed, and that this is likely to vary by vessel, season or year. Such factors can't necessarily be controlled for on-board, and as a consequence we recommend a second laboratory-based study should be done to validate our findings.

Weight loss was also found to vary on a seasonal basis. Specifically, our work indicated that boiled shrimp may lose around 9 % in Q1 and Q4 compared to 11 % in Q2 and Q3. Such quarterly variation could be linked to changes in air temperature and air flow (i.e., windiness). Once boiled, larger female shrimp are left to air dry on cooling racks on deck before being packed. In Q2 and Q3, the air temperature in the northern hemisphere is warmer, meaning that shrimp are likely to lose weight at a faster rate. That said, we did observe that shrimp are often left to air dry on deck for longer periods during the winter compared to the summer (Table S1). In the summer, cooling shrimp are often moved below deck to a refrigerated space after only a few hours. This means that shrimp are likely exposed to differing amounts of air and different temperatures based on when they are caught, and this may impact how much weight is lost or gained between the boiled weight and the packed weight. Air-cooling is the preferred method in the Swedish fishery, but differing cooling methods are used in Norway and Denmark and may result in differences in weight loss (ICES, 2022). For instance, preliminary results from Norwegian studies suggests that the weight loss of boiled shrimp cooled in cold water is minimal, removing the need for a correction factor (ICES, 2022). Moreover, smaller raw shrimps (i.e., those not boiled) that are stored on ice for several days prior to landing are thought to gain weight in the Danish fishery (ICES, 2022). Such differences indicate that cooling method and storage may also play important roles in the weight loss of shrimp, and could result in different correction factors. For instance, in Canada *Pandalus borealis* are first frozen and then boiled and a conversion factor of 1.1 is used, whereas a conversion factor for a different *Pandalus* species in Russia, also frozen and boiled, is 1.2 (FAO, 2000). Further, correction factors for brown shrimp (*Crangon crangon*) which are boiled from fresh on-board vary from 1.1 to 1.25 based on country (FAO, 2000).

Changes in weight loss may also be linked to the biology of the species. The sex and maturity stage of individual shrimp were not noted in our experiments. However, female shrimp are known to release their eggs for hatching in March-April and carry their eggs on their abdomen for up to 6 months preceding that (Shumway et al., 1985; Knutsen et al., 2015). This means that the majority of the shrimp included in our samples during Q4 and Q1 were likely to be carrying eggs. This could impact weight loss in several ways. For instance, during reproduction, individuals will invest a large amount of their energetic resources into producing eggs and carrying them prior to release. This means that an individual may be lacking protein, which is prone to being lost when submerged in boiling water (Benjakul et al., 2008; Martínez-Alvarez et al., 2009; Manheem et al., 2012). The opposite may be true during the summer months, as individuals store their resources and build their reserves prior to the next bout of reproduction. Hence, large females may have more weight to lose in Q2 and Q3. Alternatively, differences in weight loss could be driven by the presence of eggs themselves. We are not aware of any specific studies on the subject, but future work on that compares the weight loss of individual shrimp with and without eggs might be informative.

Moving from a correction factor of 1.13 to one of 1.11 for the Swedish fishery might seem like a small change but it will likely affect the assessment of the stock. Assuming all other inputs remain equal, a small reduction in the landings of shrimp will reduce the estimated stock size and the estimated fishing mortality. This is because stock assessment models use landings data as a proxy for stock biomass and assume that a fishery will catch more shrimp if there are more shrimp there to be caught, and vice versa. Moreover, if the total landings decline so will the estimated fishing mortality. One further impact relates to the proximity of the estimated total catch to the annual TAC. During the last 10 years, the shrimp fishery has frequently exceeded the annual TAC by an average of 6 %, with high values of 30 % and 11 % in 2019 and 2022, respectively (ICES 2024a; 2024b). Our study indicates at least a part of this TAC overshoot may be due to a too high correction factor being used. A smaller correction factor would bring the annual estimates of total catch closer to the annual TAC, even if the catch in most cases would still exceed the TAC due to estimated rates of discarding (ICES, 2024a; 2024b). A change in correction factor would, however, have no impact on the stock's biological reference points. This is because the management strategy evaluations used to estimate them already include an implementation bias of 8 % (a value that seems sensible based on our findings) to account for the fact that the TAC is not adjusted for weight loss (ICES, 2022; ICES 2023d).

In conclusion, our study confirms that shrimp lose weight as part of the boiling process on-board Swedish fishing vessels and that a correction factor is needed to ensure that landed weights represent the original live weight. This study also shows that the current correction factor of 1.13 might be too high for the Swedish shrimp fishery, and that a factor of 1.11 should be used instead. Weight loss was, however, found to vary across years, seasons and boiling times. It also found to vary across vessels and hauls. This variability suggests some degree of routine monitoring may be warranted if resources are available. It is also notable that our sample size is relatively small and further work on the role that differing handling and processing methods, as well as other environmental or biological variables such as weather conditions or shrimp size are critical to establishment of a robust and unifying correction factor for the Swedish fleet. Sampling is also needed for the second, albeit smaller, part of the Swedish shrimp fishery, namely those vessels that operate more inshore with trawls equipped with a shrimp grid but without a fish retention tunnel.

Our findings are directly informative to the stock assessment and provision of scientific advice, and are relevant to ongoing management efforts. This is particularly true for the northern shrimp stock in the Skagerrak and Kattegat and northern North Sea in the Norwegian Deep, which is currently overexploited and has landings that need to be corrected to ensure sustainable levels of exploitation. The experimental methodology used here could also be used to estimate weight loss in other shrimp fisheries.

CRediT authorship contribution statement

Risberg Ronja: Writing – review & editing, Methodology, Investigation. **Cardinale Massimiliano:** Writing – review & editing, Formal analysis. **Norén Katja:** Writing – review & editing, Investigation. **Sörman Lisa:** Writing – review & editing, Methodology, Investigation.

Griffiths Christopher A.: Writing – original draft, Visualization, Methodology, Formal analysis. **Bergenius Nord Mikaela:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Hjelm Axel:** Writing – review & editing, Visualization, Investigation. **Björklund Emilia:** Writing – review & editing, Visualization, Methodology. **Prista Nuno:** Writing – review & editing, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Competing Interest

All authors declare no conflicts of interest in relation to the manuscript "Shrinking shrimp - investigating the weight loss of northern shrimp Pandalus borealis following boiling".

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107356.

Data Availability

Data and R code to reproduce the analysis and figures is freely available via GitHub at https://github.com/cagriffiths/shrinking_shrimps.

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