Newcastle University
MSc in International Marine Environmental Consultancy
MST8023 Marine Consultancy 2017-2018

Lobsters on the ground: improving understanding of shellfish populations on the Northumberland coast

Author: Jimmy Wright
Supervisor: Clare Fitzsimmons
Client: Natural England
Partner: Northumberland Inshore Fisheries and Conservation Authority

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Acknowledgements

I would like to thank my supervisor Dr Clare Fitzsimmons, for her support and guidance throughout the project. Thank you to Natural England, specifically to Dr Catherine Scott, for giving me the opportunity to complete this study. Further thanks must go to NIFCA, particularly to Natalie Wallace and Alex Aitken, for their help and advice. Thanks also to skipper Neil Armstrong, and crew Barry Pearson, and John Knowles, for their invaluable knowledge, assistance and advice throughout whilst on the Princess Royal Research Vessel.

1.0 Abstract

Management of high value lobster and crab fisheries is reliant on stock assessment to provide estimates of the health of populations. Production of accurate estimates is therefore paramount to ensuring appropriate management and in turn sustainable fisheries. Current stock assessment methods have inherent inaccuracies caused by a variety of understudied factors including catchability and habitat utilisation of crab and lobster, which impact upon final population estimates. Previously, catchability had only been estimated through modelling. This study deployed camera mounted lobster pots to produce the first empirical evidence that there is a significant difference between crabs caught in pots at time of haul and crabs 'on the ground' ($P>0.05$). Equipment limitations prevented the same comparisons for lobster populations but has highlighted necessary method improvements required to produce such data. The utilisation of catchability values to predict population densities has emphasised that even small differences in value of catchability creates large differences in population density estimates produced. This further confirms the need to improve understanding of this aspect of shellfish stock estimation. Additionally, habitat utilisation of shellfish has been quantified, producing findings similar to existing literature, that lobster abundance is higher on rock habitat and that crab abundance is higher on mud. These findings have implications on the management of shellfish fisheries in the Northumberland Inshore Fisheries and Conservation Authority district and the UK, and have the potential, with further study, to inform governing authorities to produce the most appropriate level of fisheries management.

2.0 Introduction

The shellfish fishery in the Northumberland district, targets *Homarus gammarus* (European lobster), *Cancer pagarus* (Edible crab) (hereafter referred to as lobster and crab respectively), *Necora puber* (Velvet swimming crab), and *Nephrops norvegicus* (Norway lobster). Lobster and crab are the most economically important in terms of landings. The lobster fishery alone is valued at £3 million (Turner et al., 2009; MMO, 2015), with crab landings being a larger proportion of catch weight but of a lower value (Turner et al., 2014). The fishery also has social and cultural importance in the region, being a provider of employment and a traditional way of life (Reed et al., 2013). Due to the importance of this fishery, it requires careful and appropriate management to create a sustainable fishery which not only provides economic and social stability to the human population, but also ensures the ecological health of the area (Eddy et al., 2017). This responsibility falls to the Northumberland Inshore Fisheries and Conservation Authority (NIFCA) locally, and nationally on the Marine Management Organisation (MMO).

2.1 Stock assessments

In order to assess the health of shellfish populations, stock assessments are completed by regional and national authorities (IFCAs and CEFAS) which aim to assess the health of exploited shellfish populations (Welby, 2016; Cefas, 2017). Stock assessments are conducted using a combination of Monthly Shellfish Activity Returns (MSARs) and biosampling data collected from processing plants (Welby, 2015, Welby, 2016). Stock assessments are completed by district across the nation for shellfish, by which the health and sustainability of the stock is assessed (Cefas, 2017). The results of the stock assessment are then used to inform local authorities on whether the stock is overexploited or not and therefore whether management measures need to be reviewed. Most recent stock assessments found lobster and crab stocks to be over exploited (Cefas, 2017). This system relies on stock assessments being a true reflection of the population in the area and is therefore reliant on high quality data to ensure accuracy. However, within stock assessments, there are a number of factors which can also influence the variability of results (Skerritt, 2014). For example, catchability and rate of loss are identified as key parameters in estimating population density as they are unable to be accounted for through catch data alone (Bell et al., 2003; Spencer, 2013). This study focusses on developing catchability estimates from empirical data, as a means of improving overall stock assessments.

2.2 Catchability

Catchability can be referred to as the proportion of individuals that will be caught in a given area, and can be influenced by various biotic and abiotic factors such as season, time of day, temperature, sea state, inter and intraspecific competition (Tremblay et al., 2006). Understudied, especially within Europe, it can cause inaccuracy within a stock assessment (Skerritt, 2014). Stock assessments assume that numbers of shellfish caught in pots by fishers is proportionally representative of the population. However, this may not be the case, for example, where pots are found empty, individuals are likely present in the trapping area (Appendix 2) but were not caught, either due to never entering the pot, or entering and then escaping (Tremblay & Smith, 2001). Very few direct observations of catchability have been made (Smith et al., 1999). Catchability is usually taken into account during stock assessments and population density estimates using corrective catchability coefficients. Prior research has only been able to make estimates of catchability through modelling (Bell et al., 2003; Spencer, 2013). This study looks to investigate the ability of catch data to represent individuals observed in an area around pots. This will be achieved by monitoring commercial shellfish pots *in situ* using time lapse photography. It will increase understanding of shellfish interactions with pots, how this affects catchability and in turn shellfish populations ‘on the ground’.

2.3 Aims and objectives

This study aims to provide a detailed assessment of size structure and abundance of prosecuted shellfish to relevant partners, allowing them to improve models necessary for the management of lobster and crab. It will achieve this by:

1) Use of camera mounted lobster pots to provide an empirically derived value for catchability of lobsters and crab, for use in stock assessments and application of this value to previous estimates to highlight differences in produced population density
2) Use of historical NIFCA escape gap survey data to quantifying abundances of prosecuted shellfish by benthic habitat
3) Use of historical NIFCA escape gap survey data to quantify size classes of prosecuted shellfish by benthic habitat

These objectives will be delivered using the methods outlined below.

3.0 Methodology

3.1 Catchability

3.1.1 Study area

The NIFCA district ranges from the Tyne to Berwick (figure 1). Historical data derived from an escape gap survey completed by NIFCA was collected throughout the district (figure 1). For new data collection, sites were chosen within the Coquet to St. Marys Marine Conservation Zone (CQSM MCZ), over previously mapped rock and mud habitats (Fitzsimmons et al., 2015). Sites to the south of the district were selected to minimise transit times from the Blyth base, maximising soak/observations windows.

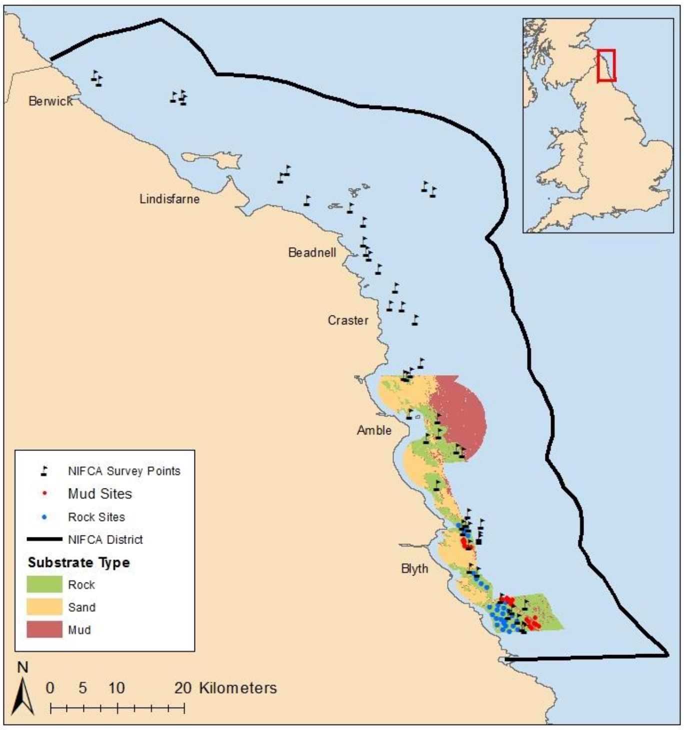

Figure 1: Total study area for both the NIFCA escape gap survey and camera mounted pot deployments (rock and mud)

3.1.2 Equipment

Available equipment and funding, permitted the production of 4 sets of camera mounted pots, enabling 4 drops per trip. The pots were standard parlour pots baited with plaice (*Pleuronectes platessa*) and fitted with a steel frame running through the centre of the pot and attached to the bottom with cable ties to prevent slipping. This frame allowed the attachment of a GoPro Hero 4, and accompanying torch (Bigblue AL1200XWP LED Diving Torch, with red filter). These were positioned 1m above the frame base (47 cm above pot). Torches were positioned over the entrances to the pot to maximise chances of observing shellfish when ambient light levels were low (figure 2).

Each of the GoPro Hero 4 cameras recorded onto 32GB SD cards and were fitted with GoPro BacPacs to enable 5 hours of continuous recording. Cameras were set to take one image every 30 seconds, deemed suitable as due to the slow-moving nature of shellfish (O'Grady et al., 2001); movement patterns and behaviour were captured, but battery life was optimised over video or more frequent frames.

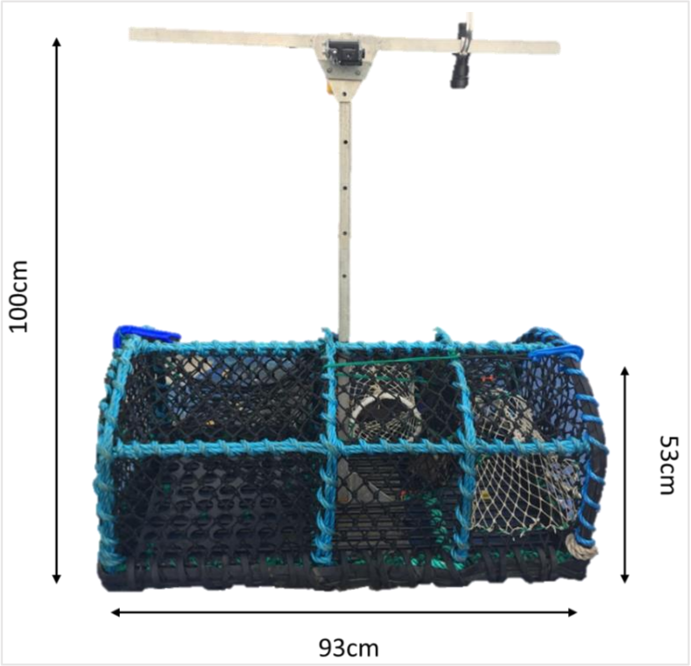

Figure 2: Camera mounted parlour pot used for deriving estimates of catchability of crab and lobster

3.1.3 Data collection

Data were collected using the Princes Royal Research Vessel (RV) based at Blyth Marine station, Northumberland. Rock and mud areas within CQSM MCZ (Fitzsimmons et al., 2015) and a maximum radius of 15km from Blyth, for logistical reasons, were chosen as areas for deployments. 'Sites' were then identified by generating 34 random points within each habitat. On arrival at a site, the substrate type was checked against OLEX seabed hardness data available on the RV. This ensured that the pot would be deployed on the targeted substrate. Four pots were deployed each morning and left to soak/record for 5 hours. Upon collection, catch was removed from pots and was counted and measured, then returned to the sea. Camera data were downloaded onto both a laptop and a hard-drive. Batteries and SD cards were replaced to allow quick re-deployments. Afternoon deployments were only performed when collection was possible the next morning. A total of 60 deployments were completed (32 on rock, 28 on mud) between the 28th June and 10th August 2018. This time of year is the most appropriate for this methodology as it has the highest likelihood of favourable conditions (clear water, calm sea state, strong sunlight, and long day lengths).

3.1.4 Data extraction

Abundance and size data were extracted from the images by scrutinising each photo for shellfish activity. When an individual was observed, the species and size was recorded. Size was recorded through Image J software, which allows measurements to be made against a known distance/scale (rope on pot = 30 cm). When ascertaining the abundance of individuals observed by cameras, size was used to distinguish between individuals. This was necessary as sometimes individuals came in and out of the frame before going into the pot. This method produces a conservative estimate, as where two individuals of the same size approach and leave, they will be recorded as one individual, unless both are seen in the same frame or become captured in the pot. This was deemed preferable to an over-estimate.

When measuring length from images, depth perception causes animals further away to appear smaller. This distortion was corrected manually using known distance to top of pot and the lens specifications of GoPro Hero4 cameras. Accuracy was determined in examples where only one crab was observed in the footage and that individual was caught. This allowed a comparison made between actual catch size and image derived catch size. Camera derived and caught size data were tested for normality (Kolmogorov–Smirnov). Data were normal ($P > 0.05$) and equally varied (Levene's, $P > 0.05$) so a t-test was conducted. There was no significant difference between mean size of individuals that were caught and measured (mean=130.7 ± 14.2mm SD) and individuals measured through image analysis (mean = 132.1 ± 15.8mm SD), ($t = 0.067$, $df = 12$, $P > 0$ 05). The lack of significant difference in means shows the accuracy of this technique was high and therefore this method was assumed to be reliable.

3.1.5 Catchability and population density calculations

A value for catchability and population density can be calculated from data collected from camera mounted pots, using the following equation (Tremblay et al., 2006):

Equation 1:
$$N = \frac{C}{Eq}$$

Where q = catchability, C = catch, E = effort, and N = density. A value for q was derived using caught crabs as C, pots fished as E and observed crabs as N. These data were standardised to represent density per km^2 and plotted in figure 5 to show the relationship between catchability and population density.

3.1.6 Statistical Analysis

Data were analysed using IBM SPSS 24 statistical software. Caught and observed abundances, and size data were tested for normality (Kolmogorov–Smirnov) and equal variance (Levene's). T-tests to compare means were completed where data were normal. Non-normal data were log transformed to base 10 then similarly tested, and where normality could not be achieved Mann-Whitney *U* tests were conducted. Regression analyses show the relationship between caught and observed data. The relationship between catchability and population density was plotted on a scatter graph with a moving average trendline.

3.2 Analysis of Lobster and Crab Size and Abundance data by Habitat

3.2.1 Data collection and analysis

Pot data collected from a NIFCA escape gap survey (08/2016 – 06/2017) were analysed by habitat. Strings of 10 pots where dropped throughout the NIFCA district, 50% of pots on each string with escape gaps and 50% without. Pots were numbered 1-10 and marked accordingly. Start and end points were recorded and uploaded into ArcGIS 10.5. Pot positions along the line between start and end co-ordinates were marked (Appendix 2), and these data overlaid on NIFCA OLEX hardness data, and a habitat type for each pot derived. This was compared with the higher resolution habitat map for the CQSM MCZ (Appendix 1) (Fitzsimmons et al., 2015), and only slight differences were observed. Being assessed as suitable, OLEX data were then used as a larger proportion of the district is covered. Substrate values of 23 or below were recorded as soft/muddy. Above 23 was determined to be hard/rocky (Skerritt, 2014). Strings north of the Farne Islands were discarded due to poor resolution OLEX data. Pots with escape gaps were discarded from the data set as full-size spectra were desired for analysis. 150 pots were found to lie on hard substrate, and 35 were found on soft substrate. The abundance and size of shellfish in each standard pot were recorded.

3.2.2 Statistical analysis

Abundance and size data at rock and mud substrates was tested for normality (Kolmogorov-Smirnov) and equal variance (Levene's). Where data were normal t-tests were conducted to compare means. Where data were not normal and could not be transformed, Mann-Whitney *U* test was performed to compare medians. Size data were plotted on a size frequency graph to show distribution of size classes within the population.

4.0 Results

4.1 Catchability

4.1.1 Pot caught versus camera observed

Due to insufficient data derived from low catch rates, statistical analyses were not viable for lobster.

Crab numbers were higher, so abundance and size values for caught (individuals caught in pots at time of haul) and camera observed (individuals observed in images but not caught in pots at time of haul) were tested for differences regardless of habitat (total deployments), over rock and over mud habitats.

Crab abundance data from all deployments were non-normal (Kolmogorov–Smirnov, $P < 0.05$) and could not be transformed, therefore Mann-Whitney U tests were performed. There was a statistically significant increase in crab abundance observed (median =1 ± 7 range) to crabs caught (median = 0 ± 5 range) for total deployments (Mann-Whitney U-test, U = 698.5, n_1n_2 = 36, $P < 0.05$). There was also a significant increase from caught to observed when tested at rock (observed (median =1 ± 3 range) caught (median = 0 ± 1 range) (Mann-Whitney U-test, U = 186.5, n_1n_2 = 20, $P < 0.05$)). On mud there was no significant difference between observed abundance (median = 3 ± 7 range) and caught abundance (median = 1 ± 5 range) (Mann-Whitney *U*-test, U = 137.0, n_1n_2 = 16, $P > 0.05$). These results are represented in figure 3.

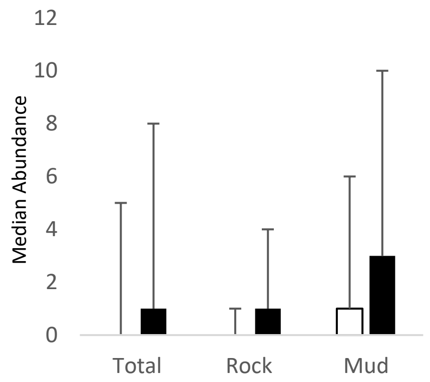

Figure 3: Median crab abundance for total, rock and mud camera mounted pot deployments ± range

Spearman's Rank Correlation was also performed and a significant correlation between observed and caught crabs was found for all deployments (Spearman's Rank Correlation Coefficient, $P < 0.05$) Regression analyses (figure 4) showed that as crabs observed increases, crabs caught increases, but at lower rate, thus creating a shallower slope (Total, R^2 =0.590, Rock, R^2 =0.311 mud, R^2 =0.492). Regression lines allow visualisation of percentage crab observed that were caught for total, rock and mud deployments (52.7, 35.0 and 59.3% respectively)

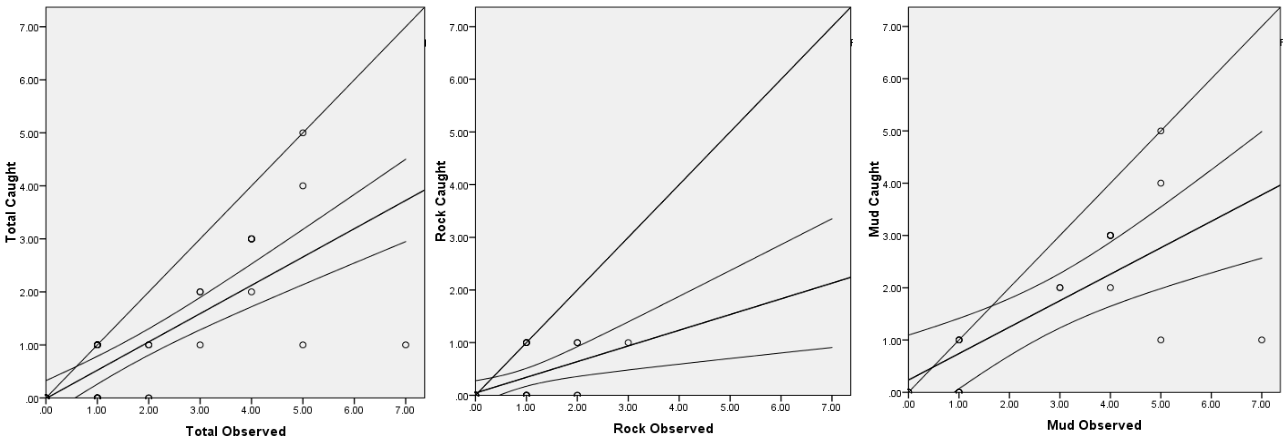

Figure 4: Linear regression of observed versus caught crabs for total deployments (left), rock (middle), and mud deployments (right). X=Y are reference lines showing slope if there was no difference between caught and observed crabs

Differences in size between caught and observed crabs were also tested for all deployments. Data were not normal, and were successfully Log10 transformed, conforming to normality (Kolmogorov–Smirnov, $P > 0.05$) and equal variance (Levene's, $P > 0.05$). There was no significant difference in mean size of crabs caught (mean = 117 ± 26.4 mm SD) and mean size of crabs observed (115.1 ± 31.4 mm SD) (t-test, $t = 0.338$, $df = 20$, $P > 0.05$).

4.1.2 Catchability and Population density

The relationship between catchability and population density is plotted in figure 5. In the NIFCA district, only two recent population estimations have been completed, one for crab (Spencer, 2013) and one for lobster (Skerritt, 2014). Estimations were produced from Capture Mark Recapture (CMR) studies, over a 6-week period, which derived catchability values through modelling.

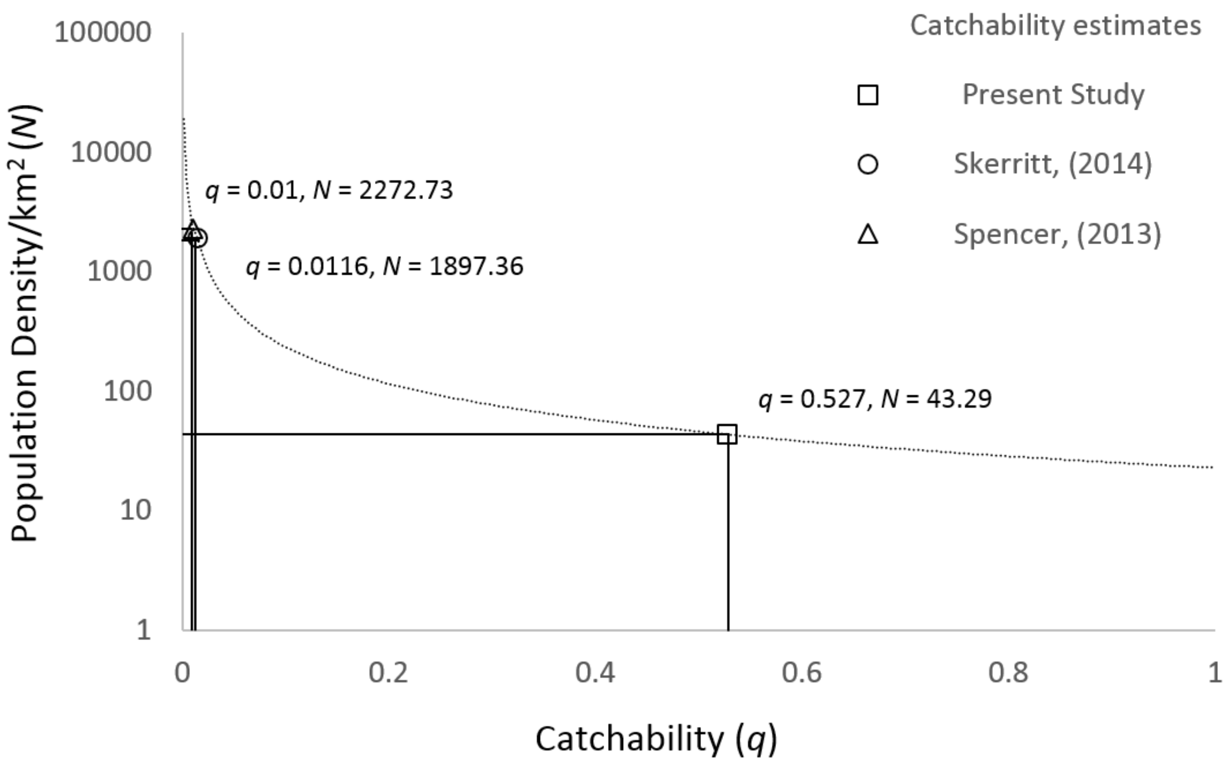

Figure 5: Catchability estimates (q) from CMR studies and the present study, and the population density estimates (N) they produce through application of equation 1.

Figure 5 was produced by taking a range of hypothetical catchability values from 0-1 and applying the values to equation 1 alongside catch data from the present study, resulting in the above curve. As catchability value increases, population density/km^2 decreases exponentially. The catchability value (q) from the present study was 0.527, which equated to a population density of 43.29 crabs/km^2. The q value from Skerritt, (2014) was 0.00116 (mean male and female q) derived from CMR study model, which equated to a population density of 1897.36 lobsters/km^2. Finally, the q value from Spencer, (2013) was 0.001, equating to a population density of 2272.72 crabs/km^2.

4.2 Analysis of lobster and crab size and abundance by habitat

Lobster abundance data were not normal (Kolmogorov-Smirnov, $P < 0.05$), and could not be transformed. Mann-Whitney U testing revealed a significant increase in median abundance of lobster on rock (median = 1 ± 5 range) than on mud habitat (median = 0 ± 5 range) (Mann-Whitney U-test, $U = 2041.5$, $n_1 = 150$, $n_2 = 35$, $P < 0.05$). The opposite was true of crab abundance which was higher on mud (median = 2 ± 26 range) than on rock habitat (median = 0 ± 17 range) (Mann-Whitney U-test, $U = 1785.0$, $n_1 = 150$, $n_2 = 35$, $P < 0.05$).

Size was also tested between habitats. Lobster size data were not normal (Kolmogorov-Smirnov, $P > 0.05$) and could not be transformed therefore a Mann-Whitney U test was performed. There was no significant difference in median lobster size between rock (median = 81 ± 75) and mud habitats (median = 79 ± 45 range) (Mann-Whitney U-test, $U = 2092.0$, $n_1 = 173$, $n_2 = 27$, $P > 0.05$). Size data for mud was not normal and was therefore Log10 transformed (Kolmogorov-Smirnov, $P > 0.05$). Data was equally varied (Levene's, $P > 0.05$) therefore a t-test was conducted. A significant increase was found in mean crab size between rock habitat (mean = 128.7 ± 22.6) and mud (mean = 123.8 ± 22.1 mm) (t-test, $t = 2.16$, $df = 385$, $P < 0.031$). These results are represented in figure 6 and 7.

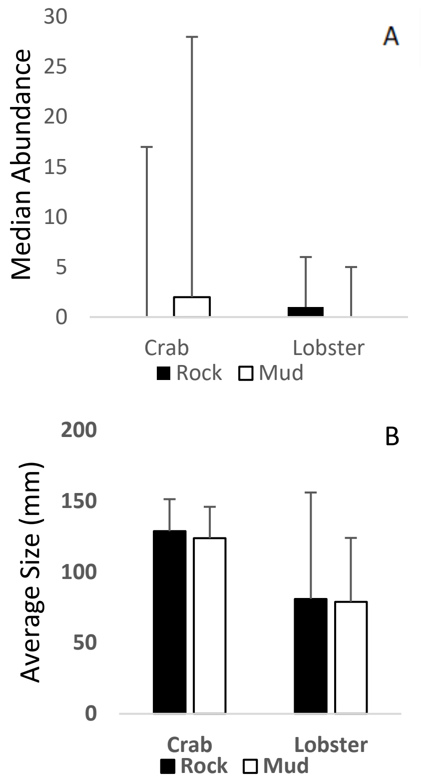

Figure 6: A) median crab abundance between rock and mud ± range. B) Mean crab size ± SD and median lobster size ± range

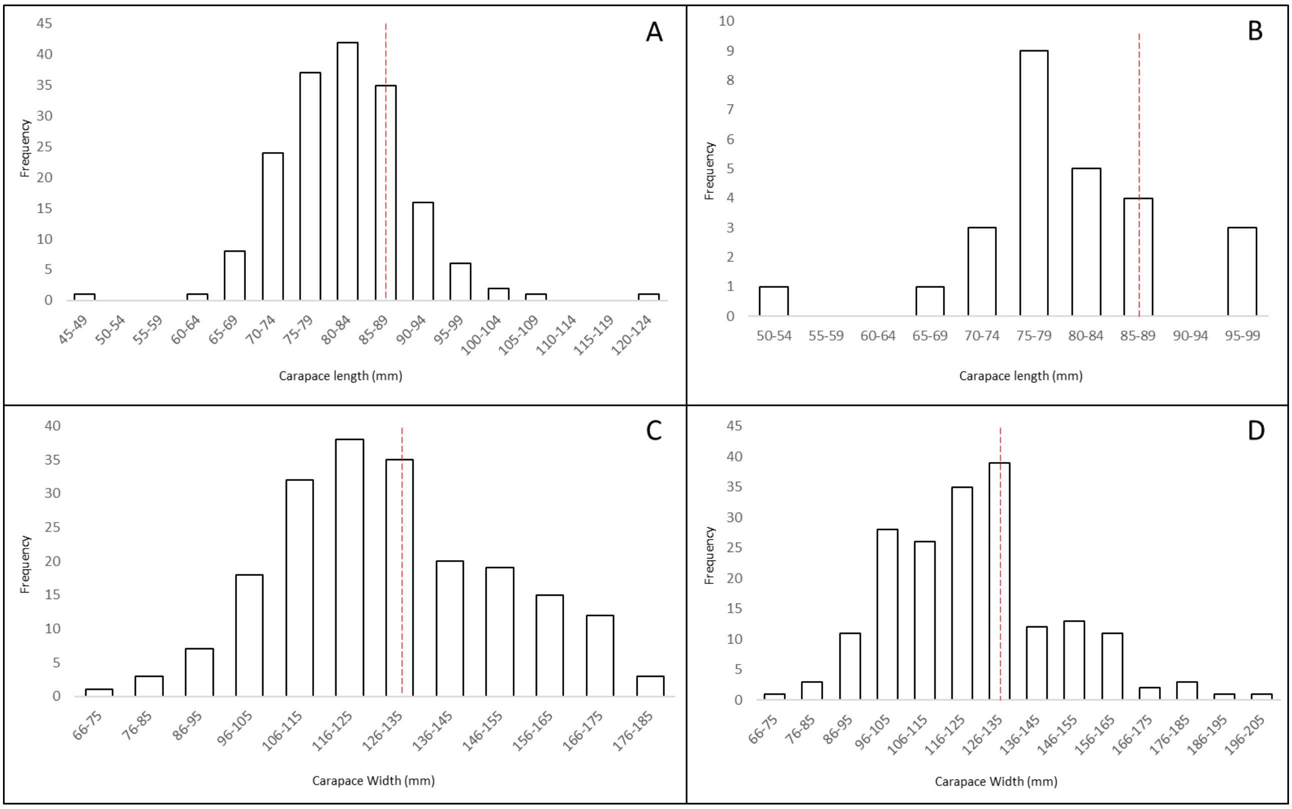

Figure 7: Lobster size distribution on rocky substrate (A), and on muddy substrate (B). Crab size distribution on rocky (C) and on muddy substrate (D). Red line denotes MLS of 87mm for lobster and 130mm for crab

5.0 Discussion

5.1 Catchability

5.1.1 Pot caught versus camera observed

The significant increase found between the numbers of crabs observed, and the number caught provides the first empirical evidence that not all individuals that interact with pots are caught. Previous model estimates had remained un-confirmed *in situ*, until now. An increase of crabs in the vicinity of the pot to crabs caught, highlights potential for inaccuracy within using fisheries dependant data such as MSARs to make estimates of stock levels. Stock assessments are reliant on high quality data in order to create accurate estimates, and the same is true of the quality of the underlying understanding of influencing factors (Öndes et al., 2017). This result confirms that a correction factor needs to be applied to catch data to create more accurate values. Catchability is an understudied and not well understood aspect of fisheries modelling (Skerritt, 2014). This study has gone some way to quantifying this.

Additionally, due to the differentiation between habitats sampled, understanding of how habitat/substrate type can affect the catchability of individuals has also improved. A higher number of crabs remain uncaught on rock than on mud (35.0% and 59.3% respectively), with no significant difference between observed and caught crabs on mud habitat. Differences in catchability between hard and soft substrate can be explained by hydrodynamic differences caused by increased rugosity creating more turbulent conditions therefore making odour plumes disperse more quickly (Tremblay & Smith, 2001).

The importance of these results lies in their application to fisheries management. Management methods are implemented in reaction or pre-emption to over exploitation reported in stock assessments. Increasing the accuracy of parameters used to produce stock assessment can have significant impacts on informing fisheries authorities of the most appropriate levels of management required. Whilst this study was unable to produce data for catchability of lobster, the results generated for crab show that there is potential, with adjusted methodology, to produce similar results for lobster.

However, these findings must be treated with caution. Whilst it is a positive step towards quantifying and understanding the relationship of catchability's role within fisheries assessment, this methodology did not control for biotic and abiotic factors. For example, this study was conducted in June-August, so is only representative of the summer months. Additionally, the survey period followed a severe winter with long periods of below average cold and high wave action. Incidents of large numbers of Crustacea washing up onshore were reported due to cold snaps and rough seas. This was followed with a well above average summer temperature (Pers. Comms.). The unusual weather extremes this year should be considered when comparing data collected in this study with other years. In addition, this study is based on an assumption that catchability rates would not change with increased soak time. A soak time of 5 hours is unrepresentative of commercial shellfish fishing, as pots are usually left between 24 and 48 hours before hauling (Stephenson, 2016). Further work is required to relate these findings to fisheries data.

5.1.2 *Catchability and population density*

The relationship between catchability and population density as displayed in figure 5 raises important questions about applying catchability to stock assessments and population density estimates. This study produced a catchability value of 0.527, using a well-established formula (Maunder & Punt, 2004) which gave a population density estimate of 43.29 crabs/km^2. The population density estimate appears to be very low, and with a catchability ratio of over half of the total population, if this was accurate, the population would be halved by every fishing occasion. The inaccuracy in this value is likely to come from the assumption that observed crabs is the total available population (N). It is almost certain that all crabs within a given trapping area, are not attracted to the pot, for the following reasons. Catchability has been found to vary according to season (Dunnington et al., 2005), moult stage (Agnalt et al., 2007), temperature (Drinkwater et al., 2006), depth (Linnane et al., 2017), and gender (Skerritt, 2014). Therefore, the population density estimate produced within this study should not be taken at face value. However, this result does allow for the comparison of the effect of having different values for catchability when estimating population size.

Several studies have made population density estimates through use of CMR studies, which use catchability as an aspect within population estimation models. Spencer, (2013) estimated catchability to be 0.01. When applying this value to figure 5, it predicts a population density of 2272.72crabs/km^2. This presents perhaps a more realistic value due to the high abundance of crabs landed reported from fisheries data. However, the result of Spencer's (2013) population density estimate was in excess of 20,000 crabs/km^2 and therefore shows that other factors within the model, other than those used in equation 1, have a significant impact on the final estimate. Further, population density estimates were also completed on the Norfolk coastline through CMR methods (Bell et al., 2003), which produced a population density output of 2100 crabs/km^2. This value is similar to the value produced when q = 0.01 is applied to figure 5. A value of q was not available from the Bell et al., (2003) study but it can be assumed to be different from (Spencer, 2013) due to the large difference in final population estimate and use of a similar model.

These estimates of catchability are derived from fundamentally different methods, with the values from Skerritt, (2014) and Spencer, (2013) being derived from modelling, and from *in situ* observations in this study. The use of modelling to derive q values may enable an estimate closer to reality due to its ability to account for a range of different variables, whereas the in-situ evidence gathered here may illuminate different behavioural factors but cannot account for other macro variables. The difference in estimates of catchability suggests high variability. Towards the lower estimates of catchability, even extremely small variations in q can cause large variation in population density. For example, an increase in q of 0.005 from 0.01 to 0.015, leads to a decrease of 757.57 crabs/km^2. This large effect caused from a small change demonstrates the importance of understanding and quantifying catchability accurately, as the values produced are used to inform management of fisheries through population estimates. A combination of both modelling and empirical methods may yield the best results.

5.1.3 Method Analysis

The methodology used in this study was a novel approach to improve understanding of shellfish fisheries. Whilst similar methods have been used to record behavioural interactions, this is the first known use for catchability. Lessons learned during this novel trial are discussed below, the methods assessed for efficacy and recommendations for improvements made.

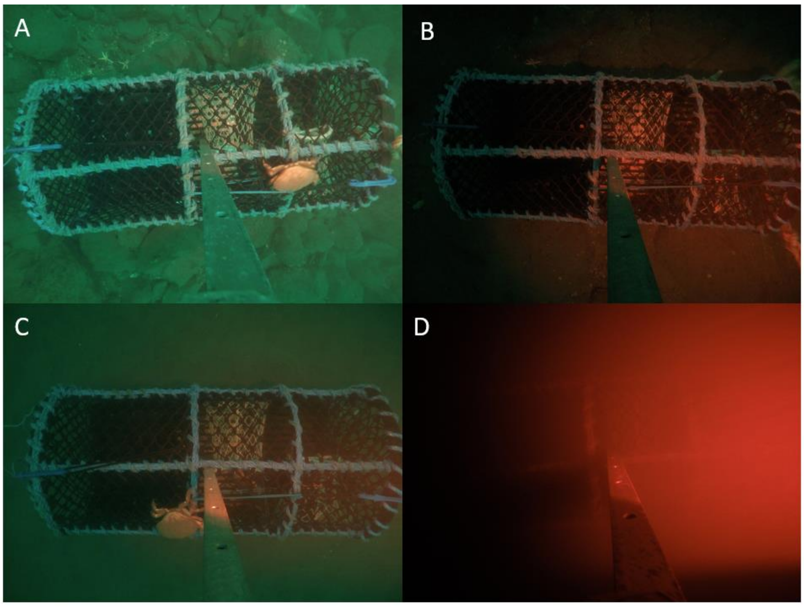

Figure 8: Quality range of images derived from camera mounted pots: A = High quality on rock, B = Low quality on rock, C = High quality on Mud, and D = Low quality on mud, Image B was derived during an evening soak

Firstly, there was some uncertainty as to whether the use of 'low budget' cameras and lighting would be effective. A range of factors such as water quality (visibility), sea state, depth, cloud cover (ambient light) all had potential to result in low quality images. However, data testify that this method can produce images of high enough quality to observe the abundance and size of shellfish interacting with pots – but with limitations. As stated above, environmental factors can cause poor image quality, this is demonstrated by the range shown in figure 8. The best quality images were obtained when there was good visibility, calm sea states, shallow depths and strong sunlight (figure 8 (A)). These images were clear with a wide field of view, as all seabed within the frame had enough light to observe individuals. This was contrasted against deployments with low light levels, either due to sunlight intensity, visibility, depth or a combination of these factors (figure 8 (D). Light was the main factor affecting image quality. Torches ensured that even in low light levels, data were collected, but as only one torch per pot was available, a proportion of the benthos in the frame could not be illuminated as shown in figure 8 (B) where ambient light is low, the torch light is able to illuminate the pot but not all substrate in the frame. This will inevitably have caused a reduction in the number of individuals observed and affected estimates. On one occasion (4 deployments), no data were recovered from the footage (Figure 8 (D)). This was due to poor visibility conditions created by large swells. This highlighted that even though there was strong sunlight on this day, the stirring up of sediment due to wave action was enough to render deployments on that day unusable.

The method used during this study looked to deploy pots twice in one day, which allowed for double the number of sites to be covered in the same time. This was feasible during the planning stage as due to the long day length in Northumberland summer, two sets of pots could be deployed with all footage captured in daylight hours, therefore avoiding any difference in behavioural aspects may differ between night and day (Smith et al., 1999) . This method was most effective for crab during the morning soaks. The ability of the cameras to have full soak time recordings allowed an accurate and complete comparison of how many individuals were observed against how many were caught. This was not the same for afternoon soaks. Within afternoon deployments, a large proportion of the soak time was not able to be observed due to the battery life of the camera. This resulted in a reverse of results shown when full observation was achieved. This was likely caused by crabs/lobsters entering the pot after the cameras had stopped recording and therefore counteracting increases in observed to caught individuals. This issue was not identified during the planning phase of the study and resulted in data sets that are fundamentally different. The afternoon deployment data were therefore not able to produce catchability estimates and was excluded from the analysis.

Further methodological issues were presented by the behavioural nature of lobster. It is described literature that lobster are nocturnal and more active (foraging/exploring) at night (Smith et al., 1998; Skerritt, 2014). This was further supported within this study by the increased abundance of lobsters caught in the evening soaks. Due to catchability data only being derived from morning deployments soaks, the number of lobsters caught or observed in this period was very low. With this methodology not being effective at estimating catchability in afternoon/overnight soaks, data for lobster catchability was too sparse for analysis. However, what was apparent was that the principle of this method was effective. This was demonstrated by multiple observations of lobster that were not then 'caught'. This provides evidence that lobster catch substantially differs from 'lobsters on the ground'. Although unable to produce a value for catchability for lobsters this time, considerable insight has been gained, upon which future studies can build.

Data collected show that the method was effective at understanding the catchability of crab in good conditions, during day time soaks where the full soak time was recorded. One of the main positive aspects of this methodology is the cost of the set up. At just below £500 per camera mounted pot, this methods is cost-effective in comparison to other custom built camera equipment for in-situ studies (Jury et al., 2001; Steen, 2015), it is also simple to set-up and deploy. This allowed provision of multiple set ups and increased boat efficiency, which is often the most costly aspects of fisheries studies. However, the limitations of this methodology must be addressed and improved to produce stronger evidence for catchability, specifically for lobster populations.

5.1.4 Scientific Recommendations

Developing understanding of catchability is an important aspect of improving shellfish fisheries assessments. Within the NIFCA district, further work needs to be completed to ensure stock assessments are as accurate as possible, to inform the most suitable management regimes. This study recommends the following work:

1) Improve equipment to allow continuous, well illuminated recording for 24 hours

This will allow a catchability value for lobsters to be produced, as the current methodology has been able to for crabs. This can be achieved through customised cameras and torches that have external battery packs. This would also improve validity as it would match more closely soak times used in commercial shellfish fisheries.

2) Repeat study in wide range of variable conditions

Catchability has been shown to be highly variable and affected by multiple environmental factors. To try and quantify this variability and how each factor affects catchability, this method should be repeated in a range of conditions and locations and analysis of how each aspect causes changes in catchability value. This may be achieved ex situ through lab-based experiments and then applied to models as certain factors can be difficult to control *in situ.*

3) Production of shellfish recognition software to create automated data extraction

At present the data extraction of abundance and size data is time consuming and adds a considerable cost of labour to the method. This would only increase with further development of the method and equipment to allow longer burn times and recordings. In response to this, there is scope to develop software which could analyse image data in order to reduce time and labour required in the data extraction process.

5.2 Analysis of Lobster and Crab Size and Abundance by Habitat

5.2.1 Habitat and Abundance

Significant differences in abundance and size between habitats further confirm certain aspects of shellfish lifecycle/behaviour. It is understood that rock/hard habitat is preferred by lobster (Bannister et al., 1994; Van Der Meeren, 2005), and mud is favoured by crabs (Hall et al., 1991). However, the literature that supports this is not current and changes in population structures that may have occurred since publishing may have gone unnoticed due to the lack of current literature. Further, the majority of studies assessing habitat preference are derived from ex situ studies and hatchery experiments (Linnane et al., 2000; Mehrtens et al., 2005). Habitat analysis found that crab abundance was significantly higher on mud than on rock, which agrees with existing literature, stating crabs prefer mud habitat, likely due to their tendency to burrow into sediment (Skajaa et al., 1998). The opposite was found for lobsters with higher abundances found on rocky habitat, which again, is in agreement with literature and anecdotal information (Van Der Meeren, 2005). These results must again be treated with caution due to the relatively low sample size, especially for mud (rock, n=150, mud, n=35). However, confidence can be taken in their support of existing literature.

5.2.2 Habitat and Size

Habitat analyses provided more information about size classes of shellfish populations on the ground. Crab sizes were smaller on muddy substrate as perhaps to be expected, as often in population structures, high abundances often correspond with smaller size (Jennings & Dulvy, 2005). The lack of significant difference in lobster size between habitat, does not fit the same pattern. These data allowed the production of size frequency plots (figure 7), which shows that the majority of populations of both lobster and crab sit below the minimum landing size (MLS). It is often reported that the average size sits either on or just above MLS (Welby, 2016). This study contradicts such findings. This may be explained by the inclusion of all sizes of catch, which the escape gap survey methodology allows, rather than MSAR data and landing spot checks due to discard of undersized individuals.

A significant increase in crab abundance on mud habitats has implications for confidence in stock assessments as it is proposed that habitat composition is a factor affecting population carrying capacity (Seitz et al., 2014). If stock assessments are completed assuming homogenous habitats throughout the district, the difference in abundance due to habitat may cause inaccuracy in estimates in population size. Differences in habitat utilisation could suggest corrections need to be applied due to the proportions of different habitats present within a fisheries region (Welby, 2015). However, this result is reliant on assumptions that the differences in catch are representative of the abundance of the population and not just that crabs are more catchable on muddy habitats. The results from the previous section may suggest that this may be the case, which further exhibits the importance of fully understanding catchability and the factors that cause it to vary.

5.2.3 Method analysis

The method used to identify substrates for shellfish pots has strengths and weaknesses. Firstly, the data collection for NIFCA, was the escape gap survey delivered by fishers. Cost effective and an efficient use of NIFCA resource, this method was not designed to study habitat utilisation, OLEX hardness data being retrospectively extracted to achieve this, so improvements can be made moving forward. Trying to identify habitat on a pot by pot basis in patchy areas is limited by the resolution of the habitat data. The OLEX data used in the study varies in resolution, as the system interpolates data between lines travelled by the vessel (Parnum et al., 2009). This leads to lower resolution data in areas less travelled. Even where resolution is high, this method is still assuming that pot spacing is equal between marked start and end points of pot strings. Within these assumptions is a strong potential for error due to the fine scale needed within patchy habitats.

5.2.4 Scientific Recommendations

Due to time and resource limitations within this study, new fieldwork could not be completed. This method would be improved if rock and mud habitats were targeted by surveys using individual pots to avoid setting on incorrect habitat, a source of error which is associated with long string lengths.

6.0 Conclusion

Whilst estimated through modelling, until now, catchability of crab and lobster had not been empirically investigated. The result of a significant increase in abundance of crabs on the ground compared to crabs caught in pots has provided the first empirical evidence that not all individuals that interact with pots are caught. The current methodology could not produce the same comparison for lobster, however, what little data were collected showed promising signs that the same methodology can be applied with improvement /modification. This study can conclude, that whilst in its infancy, the use of camera mounted lobster pots is a useful tool in furthering the understanding of shellfish catchability. The application of catchability values to population density estimates highlights the implications of even minor inaccuracies, and therefore the importance of further research into this understudied aspect of fisheries estimation. Additionally, the use of historical NIFCA data has provided support to outdated literature regarding habitat utilisation in relation to abundance and size of lobster and crab. Due to low sample numbers, caution is required when interpreting the results of the habitat utilisation study, however, confidence can be drawn from similarities with existing literature. The conclusions drawn from this study can be utilised within the NIFCA district and across the UK, to produce increasingly accurate stock assessments and therefore ensure the most effective and appropriate management is in place.

7.0 References

Agnalt, A.L., Kristiansen, T.S. & Jørstad, K.E. (2007) Growth, reproductive cycle, and movement of berried European lobsters (*Homarus gammarus*) in a local stock off southwestern Norway. *ICES Journal of Marine Science*. 64 (2), 288–297.

Bannister, R.C.A., Addison, J.T. & Lovewell, S.R.J. (1994) Growth, movement, recapture rate and survival of hatchery-reared lobsters (*Homarus gammarus* Linnaeus, 1758) released into the wild on the English east coast. *Crustaceana*. 67 (2), 156–172.

Bell, M.C., Eaton, D., Bannister, R.C.A. & Addison, J.T. (2003) A mark-recapture approach to estimating population density from continuous trapping data: application to edible crabs, *Cancer pagurus*, on the east coast of England. *Fisheries Research*. 65, 361–378.

Cefas (2017) Lobster (*Homarus gammarus*). *Cefas Stock Status Report*.

Drinkwater, K.F., Tremblay, M.J. & Comeau, M. (2006) The influence of wind and temperature on the catch rate of the American lobster (*Homarus americanus*) during spring fisheries off eastern Canada. *Fisheries Oceanography*. 15 (2), 150–165.

Dunnington, M.J., Wahle, R.A., Bell, M.C. & Geraldi, N.R. (2005) Evaluating local population dynamics of the American lobster, *Homarus americanus*, with trap-based mark-recapture methods and seabed mapping. *New Zealand Journal of Marine and Freshwater Research*. 39 (6), 1253–1276.

Eddy, T.D., Lotze, H.K., Fulton, E.A., Coll, M., Ainsworth, C.H., de Araújo, J.N., Bulman, C.M., Bundy, A., Christensen, V., Field, J.C., Gribble, N.A., Hasan, M., Mackinson, S. & Townsend, H. (2017) Ecosystem effects of invertebrate fisheries. *Fish and Fisheries*. 18 (1), 40–53.

Fitzsimmons, C., Stephenson, F. & Lightfoot, P. (2015) Coquet to St Mary ’s rMCZ post-survey site report.

Hall, S.J., Basford, D.J., Robertson, M.R., Raffaelli, D.G. & Tuck, I. (1991) Patterns of recolonisation and the importance of pit digging by the crab *Cancer pagarus* in a subtidal sand habitat. *Marine Ecology Progress Series*. 72, 93–102.

Jennings, S. & Dulvy, N.K. (2005) Reference points and reference directions for size-based indicators of community structure. *ICES Journal of Marine Science*. 62 (3), 397–404.

Jury, S.H., Howell, H., O’Grady, D.F. & Watson, W.H. (2001) Lobster trap video: in situ video surveillance of the behaviour of *Homarus americanus* in and around traps. *Marine and Freshwater Research.* 52 (8), 1125–1132.

Linnane, A., Mazzoni, D. & Mercer, J.P. (2000) A long-term mesocosm study on the settlement and survival of juvenile European lobster *Homarus gammarus* L. in four natural substrata. *Journal of Experimental Biology and Ecology*. 24, 951–964.

Linnane, A., McGarvey, R., Feenstra, J. & Graske, D. (2017) Northern zone rock lobster (*Jasus edwardsii*) fishery stock assessment 2015/16. *SARDI Research Report Series No. 912*.

Maunder, M.N. & Punt, A.E. (2004) Standardizing catch and effort data: a review of recent approaches. *Fisheries Research*. 70, 141–159.

Van Der Meeren, G.I. (2005) Review: potential of ecological studies to improve survival of cultivated and released European lobsters, *Homarus gammarus*. *New Zealand Journal of Marine and Freshwater Research*. 39 (2), 399–424.

MMO (2015) Marine Management Organisation. 2011 to 2015 UK fleet landings and foreign fleet landings into the UK by Port Data. *Available online at: https://www.gov.uk/government/statistical-data- sets/uk-sea-fisheries-annual-statistics-report-2015.*

O’Grady, D.F., Jury, S.H. & Watson, W.H. (2001) Use of a treadmill to study the relationship between walking, ventilation and heart rate in the lobster *Homarus americanus*. *Marine and Freshwater Research.* 52 (8), 1387–1394.

Öndes, F., Emmerson, J.A., Kaiser, M.J., Murray, L.G. & Kennington, K. (2017) The catch characteristics and population structure of the brown crab (*Cancer pagurus*) fishery in the Isle of Man, Irish Sea. *Journal of the Marine Biological Association of the United Kingdom*. 1–15.

Parnum, I., Justy, S., Gavrilov, A. & Parsons, M. (2009) A comparison of single beam and multibeam sonar systems in seafloor habitat mapping. *3rd International Conference & Exhibition on 'Underwater Acoustic Measurements: Technologies & Results'*.

Reed, M., Courtney, P., Urquhart, J. & Ross, N. (2013) Beyond fish as commodities: understanding the socio-cultural role of inshore fisheries in England. *Marine Policy*. 37 (1), 62–68.

Seitz, R.D., Wennhage, H., Bergstro, U., Lipcius, R.N. & Ysebaert, T. (2014) Ecological value of coastal habitats for commercially and ecologically important species. *ICES Journal of Marine Science*. 71 (3), 648–665.

Skajaa, K., Ferno, A., Lokkeborg, S. & Haugland, E.K. (1998) Basic movement pattern and chemo-oriented search towards baited pots in edible crab (*Cancer pagurus* L.). *Hydrobiologia*. 371/372, 143–153.

Skerritt, D.J. (2014) Abundance, interaction and movement in a European lobster stock.

Smith, I.P., Collins, K.J. & Jensen, A.C. (1998) Movement and activity patterns of the European lobster, *Homaras gammarus*, revealed by electromagnetic telemetry. *Marine Biology*. 132 (4), 611–623.

Smith, I.P., Collins, K.J. & Jensen, A.C. (1999) Seasonal changes in the level and diel pattern of activity in the European lobster *Homarus gammarus*. *Marine Ecology Progress Series*. 186, 255–264.

Spencer, A. (2013) An assessment of the Northumberland edible crab *Cancer pagarus* and velvet crab *Necora puber* fisheries.

Steen, R. (2015) Video-surveillance system for remote long- term in situ observations: recording diel cavity use and behaviour of wild European lobsters (*Homarus gammarus)*. *Marine and Freshwater Research.* 65, 1094-1101

Stephenson, F. (2016) Shellfisheries, seabed habitats and interactions in Northumberland.

Tremblay, J.M. & Smith, S.J. (2001) Lobster (*Homarus americanus*) catchability in different habitats in late spring and early fall. *Marine and Freshwater Research*. 52, 1321–1331.

Tremblay, M.J., Smith, S.J., Robichaud, D.A. & Lawton, P. (2006) The catchability of large American lobsters (*Homarus americanus*) from diving and trapping studies off Grand Manan Island, Canadian Maritimes. *Canadian Journal of Fisheries and Aquatic Sciences*. 63 (9), 1925–1933.

Turner, R.A., Fitzsimmons, C., Forster, J., Mahon, R., Peterson, A. & Stead, S.M. (2014) Measuring good governance for complex ecosystems: perceptions of coral reef-dependent communities in the Caribbean. *Global Environmental Change*. 29, 105–117.

Turner, R.A., Hardy, Michael, H., Green, J. & Polunin, N.V.C. (2009) Defining the Northumberland lobster fishery. *Report to the Marine Fisheries Agency, London.*

Welby, P.R. (2015) Crab and Lobster Stock Assessment. *Research Report. Inshore Fisheries and Conservation Authority.*

Welby, P.R. (2016) Crab and Lobster Stock Assessment. *Research Report. Inshore Fisheries and Conservation Authority*.

Appendix 1.0 – Camera mounted pot deployment sites

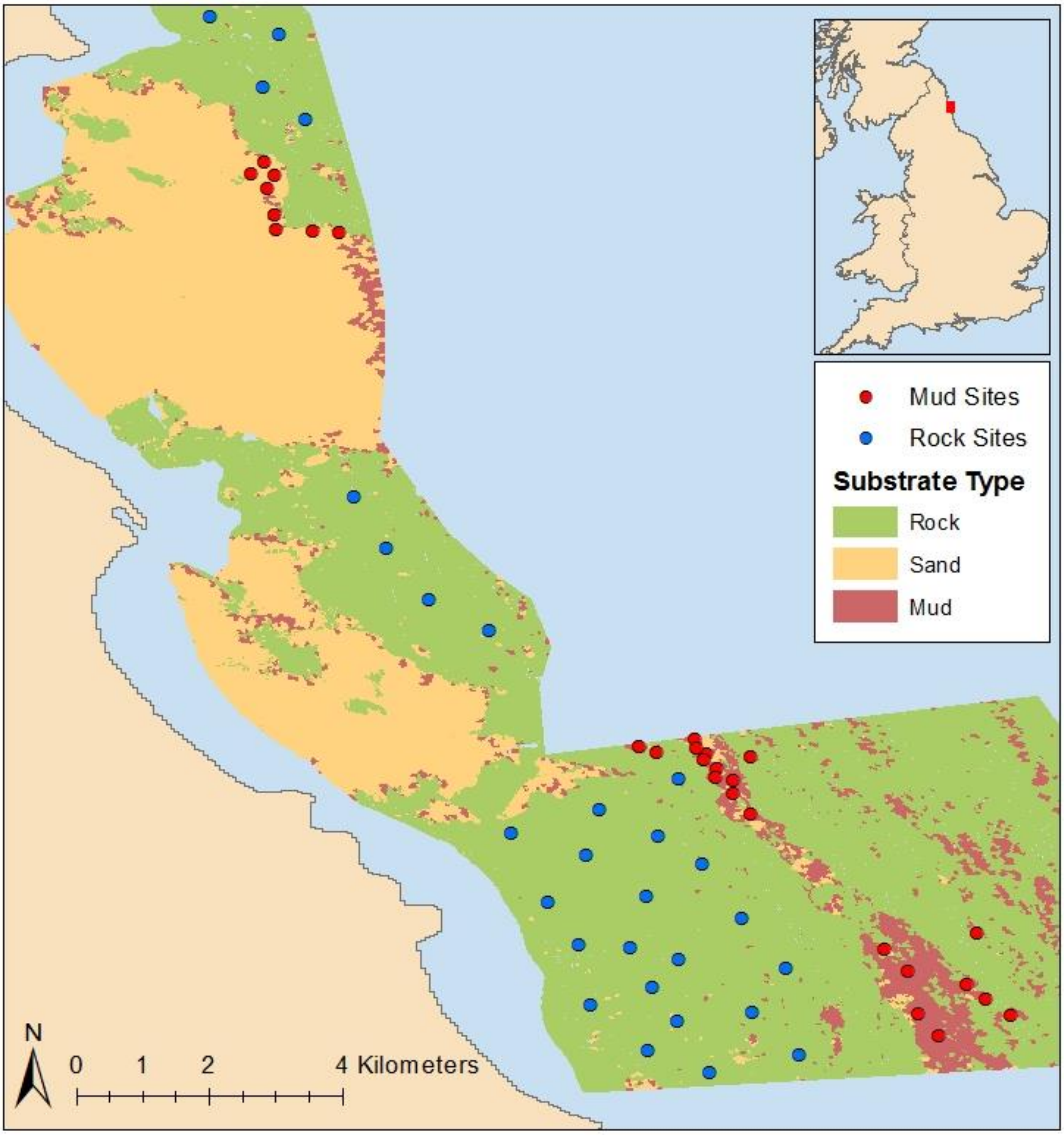

Figure S1: Location for camera mounted pot deployments in relation to substrate type, derived from CQSM MCZ habitat map (Fitzsimmons et al., 2015)

Appendix 2.0 – NIFCA escape gap pot position identification method

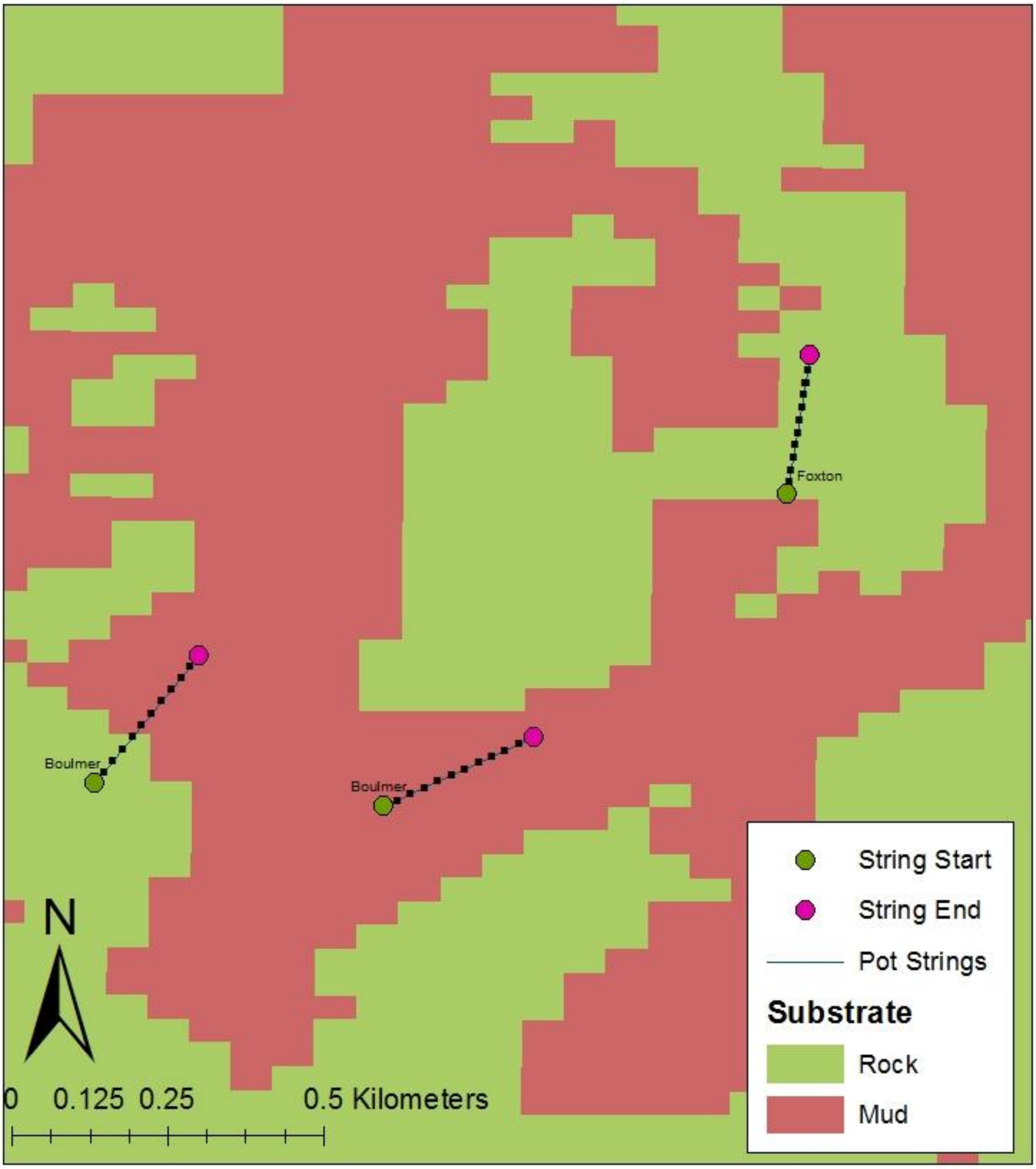

Figure S2: NIFCA escape gap survey pot strings with individual pot position marked over substrate type (OLEX data)

Appendix 3.0 – Pot trapping area

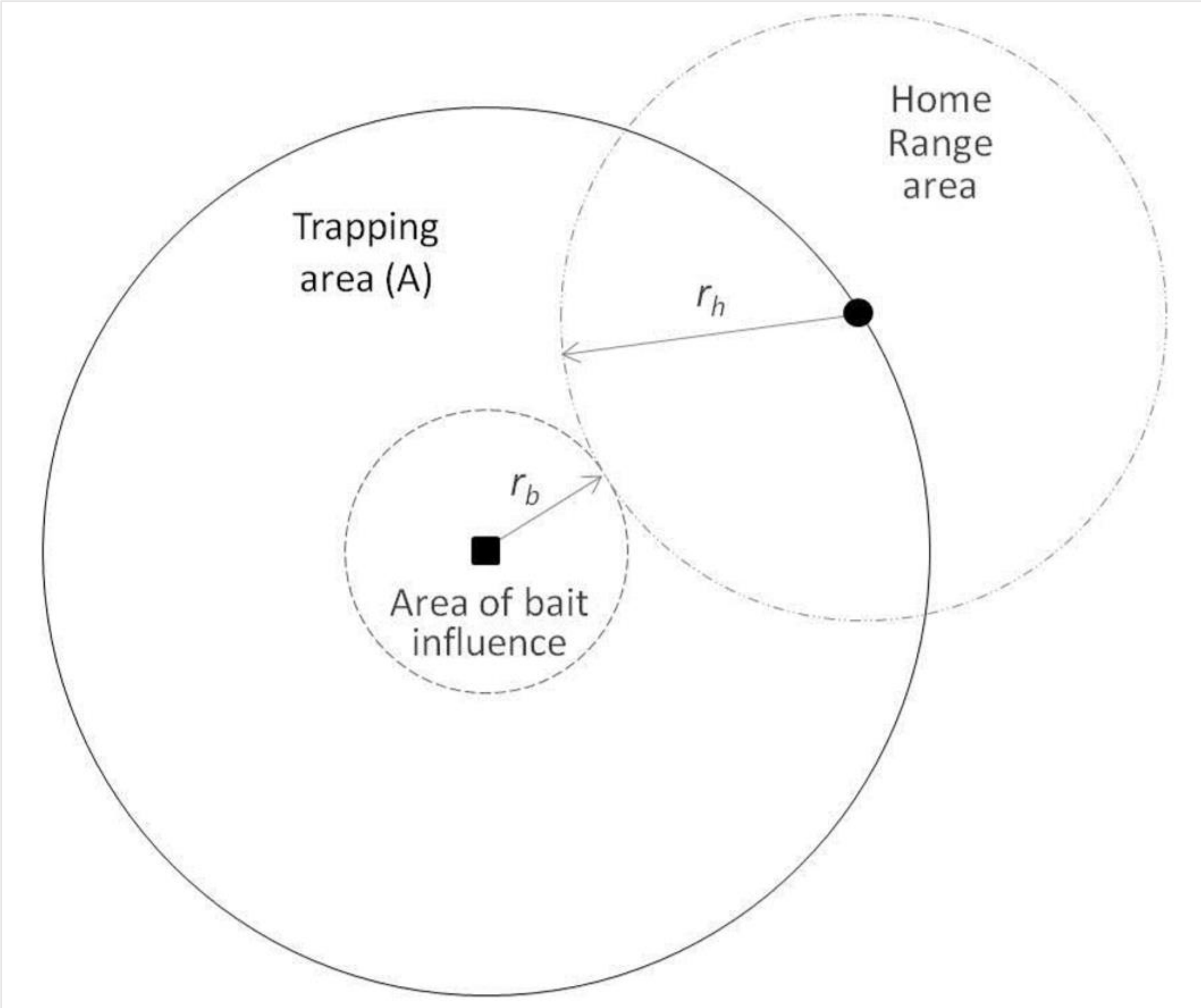

Figure S3: Method of determining trapping area of lobster pot (Bell, 2013; Skerrit, 2014) where r_b = 11m, and r_h = 100m. Total trapping area = 0.039km^2

Appendix 3.0 – Literature review: Assessment of European lobster (*Homarus gammarus*) **stock assessment and management methods used within the Northumberland Inshore Fisheries and Conservation Authority district.**

1.0 Abstract

The lobster fishery in the Northumberland Inshore Fisheries and Conservation Authority (NIFCA) district has high socio-economic value and as such requires careful monitoring and management to ensure a sustainable and healthy fishery. Stock assessments are utilised in many fisheries worldwide, providing a benchmark from which to assess the changing state of a stock. This review assesses various lobster stock assessment and management methods used within the NIFCA district and draws upon methods utilised in other regions for comparison. Comprehensive stock assessments can be conducted regularly to further improve knowledge of the lobster stock in the NIFCA district, alongside Capture Mark Recapture studies to provide an estimate of population density. However, further research into uncertainties including rate of loss and catchability will allow increased confidence in results. Due to the reported declining lobster stock, use of successful management methods from other regions may be useful in producing the most appropriate management regime for the NIFCA district.

2.0 Introduction

European lobster (*Homarus gammarus*) and edible crab (*Cancer pagurus*) (hereafter referred to as lobster and crab respectively) make up the largest fishery on the Northumberland Coast. Significant economic, social and cultural benefits result from the provision of income, employment, and a traditional way of life (Reed et al., 2013). Lobster are high value within the food industry with annual landings of around £32.1 million in the UK and £3 million in Northumberland Inshore Fisheries and Conservation Authority (NIFCA) district (MMO, 2015). Whilst crab are not as expensive per kilo, they represents a significant proportion of the fishery value due to higher catch (Turner et al., 2015). The high economic value of the shellfish fishery has been well exploited for many years (Hold et al., 2015), with increasing demand and vessel capability making shellfish vulnerable to overexploitation (Stephenson et al., 2018). This could lead to stocks collapsing, as demonstrated in both Norway and North America, causing serious impacts on both local ecology, and fishing livelihoods (Henry & Johnson, 2015; Sundelöf et al., 2015).

The European lobster has not received as much attention in published literature as its American counterpart, the American lobster (*Homarus americanus)* (figure 1). Within the NIFCA district, lobster populations remain relatively understudied but given the importance of this fishery, careful monitoring and management based on strong scientific evidence is required (Skerritt, 2014). Increased research will work towards the

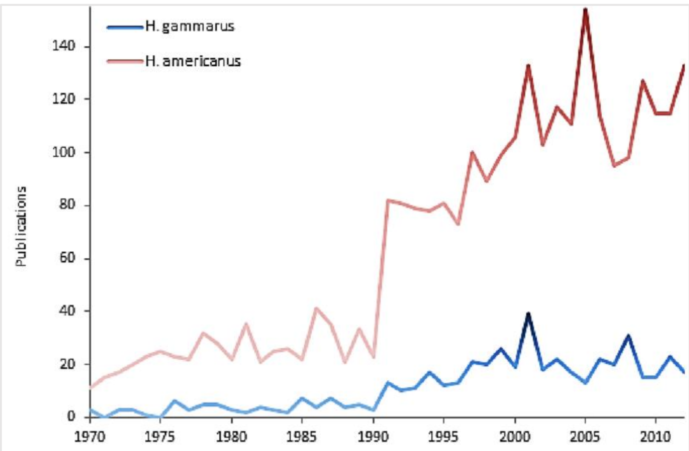

Figure 1: Number of publications released on European lobster (*Homarus gammarus*) versus American lobster (*Homarus americanus*) (Skerritt, 2014)

NIFCA's aim of creating a sustainable fishery that can continue to provide existing socio-economic benefits for current and future generations (NIFCA, 2018). Within the UK, there are various levels of management; European Union regulations, national regulations stipulated by the Marine Management Organisation (MMO), and also on a local/regional level through Inshore Fisheries Conservation Authorities (IFCAs), who have devolved power to create regional byelaws. Fisheries operating out of Northumberland are managed by the Northumberland IFCA (NIFCA). This review focuses on two aspects of the shellfish fishery in the NIFCA district. Firstly, the stock assessment methods used to monitor shellfish population dynamics and stock status, and secondly the management methods in place. Each relies on scientific evidence to underpin management and monitoring in order to produce appropriate and effective results (Smith & Addison, 2003). This review will assess the various strengths and weaknesses of methods currently utilised in the NIFCA district, in comparison with those studied in other fisheries.

2.1 Aims and objectives

This review aims to provide a comprehensive assessment of both the stock assessment methodologies used to monitor and quantify shellfish populations within the NIFCA district, and the management models used to control exploitation and create sustainable fisheries. This will be achieved through the following objectives:

1) Review stock assessment methods used by NIFCA and in lobster fisheries in other regions to compare most effective techniques.
2) Review lobster management methods used within the NIFCA district, assessing the relative efficacy of these and others in use elsewhere.

Given the lack of peer-reviewed literature in the district, grey literature and technical reports from the NIFCA district and other regions will be utilised to collate information, assess the efficacy of NIFCA methods and make suggestions for improvements.

3.0 Methods

Literature was found using various academic search engines, including Web of Knowledge, Scopus, Newcastle University library search, and google scholar. Further information was gained from technical reports available on the NIFCA website, and other IFCA online resources which provided up to date information on current sampling and management measures. Examples of search terms include: "European lobster stock assessments" AND "NIFCA", "Lobster management methods" and "Capture Mark Recapture" AND "Lobster".

4.0 Stock assessment methods

Understanding population dynamics of shellfish requires abundance, size, and sex data from targeted species such as lobster and crab. Various sampling methods are employed, with differing strengths and weaknesses. Most sampling effort is used for stock assessments, which estimate whether stocks are over exploited or fished at sustainable levels, enabling local authorities to make decisions about management. Table 1 provides a brief assessment of the strengths and weaknesses of the various methodologies used in the NIFCA district, which are then discussed and assessed throughout this section.

4.1 MSARs and biosampling

All fishers are required to document catches and report them to the local IFCA through Monthly Shellfish Activity Return (MSAR) forms (CEFAS, 2017). This includes total catch of lobsters and crab (weight), total pots worked, days fished, average catch per day (weight) and location fished by ICES rectangle (MMO, 2014). This provides consistent, thorough data on the biomass of shellfish landed in the district monthly. Data from MSARs are then standardised by fishing effort which produces Catch Per Unit Effort (CPUE) data (Welby, 2015). This can produce a basic estimate of abundance and therefore a reference point to which future CPUE data can be compared against, to show either a stable, increasing or decreasing stock level (Addison, 1995). Whilst useful, it lacks information on population structure, such as size distribution and sex ratios within a population (Laloë, 1995). CPUE data have been extensively used within fisheries for surplus production models, which in turn is used to calculate maximum sustainable yield (MSY). This method requires relatively little data and is therefore useful where fisheries data is sparse (Smith & Addison, 2003). However, due to lack of resolution, surplus production models lack the ability to assess newly implemented management measures such as change in Minimum Landing Size (MLS), and as such were recommended to be dropped as the primary model for stock assessment (Welby, 2015).

To combat this lack of resolution, biosampling is combined with MSAR data to provide higher resolution data. This is conducted at holding tanks where live catch is stored before being sold (Welby, 2016). A subsample of catch is selected, recording the size and sex. This is then utilised within Length Converted Catch Curves (LCCC) and Yield per Recruit (YPR) analysis, producing fishing mortality estimates (Díaz et al., 2016). LCCC and YPR analysis is more sensitive to changes in management regimes (Pauly, 1984), but this method of stock assessment is more data intensive requiring increased sampling effort (Welby, 2016). LCCC and YPR analysis has been used within EIFCA stock assessments since 2014 (Welby, 2014), and recently an un-official stock assessment was completed in the NIFCA district (Woodruff, 2017). However, there are still areas of uncertainty within this method. The use of weight as an indicator of the quantity of individuals removed from the fishery is insensitive to difference in size of lobsters (McGarvey et al., 1997). It is also reliant on assumptions that catch data is representative of population structure (Skerritt, 2014). Further, where sampling effort is low, confidence levels in mortality estimates is also low, restricting this method to areas and species where data is sufficient (Bridges, 2017). Assuming methods stay constant, these results still allow changes to be seen in stock abundance and structure, but do not provide an assessment of the health of the population, or an estimate for population density.

Table 1: Stock assessment methods used within the NIFCA district.

Method	Strengths	Weaknesses	Citation
MSAR	Provides large amounts of data with little need for resources, used nationwide and therefore standard approach	Lacks resolution, excludes non-landed individuals (undersized, v-notched or berried)	(Smith & Addison, 2003; Welby, 2015)
Biosampling	Combines with MSAR sampling to provide higher resolution and more informative about population structure, size/gender ratios	Only samples landed individuals, high sampling effort required, and reliant on modelled assumptions	(Welby, 2016; Bridges, 2017)
CMR	Able to produce estimates of population density and structure	Time consuming and expensive, reliant on assumptions and modelling	(Bell , 2003; Spencer, 2013; Skerritt, 2014)

4.2 Capture-Mark-Recapture studies.

In contrast to the methods above, Capture-Mark-Recapture (CMR) studies, while not completely independent due to use of commercial fishing equipment, are more independent of the fisheries and can produce data tailored to fill specific gaps in knowledge. CMR studies are used to estimate population densities through marking caught individuals, releasing them in a specified area and then recapturing them which allows inferences to be made about the size of the population. This has been completed for both lobster (Skerritt, 2014) and crab populations in the Northumberland district (Spencer, 2013). These studies produce an estimate of population density in a given area, which can then be extrapolated to the size of the district allowing approximate population size. CMRs rely on various assumptions and on modelling to produce values for the unknown parameters of population density, catchability and rate of loss being two major uncertainties (Bell et al., 2003). These studies are highly sensitive to estimates of trapping area. Small changes in this estimate can lead to large variations in the produced population density. It is stated that lobster have variable home ranges and therefore estimates of trapping area should be treated with caution (Skerritt, 2014). Additional variability is caused as short-term studies only provide a snapshot in time in which sampling was conducted; environmental factors, which vary temporally, are known to produce behavioural differences in shellfish which affects interactions with traps, and therefore the population estimates (Tremblay & Smith, 2001).

Vast differences in population estimates (table 2) highlights the uncertainty within this methodology. Bell et al., (2003) completed a CMR study on the Norfolk coastline, which produced a population density of 2101 crab/km^2. This estimate was regarded as very low, relative to the amount of crabs being caught in the fishery at the time. Using similar methodology, Spencer (2013) reported an estimate of over 20,000 crabs/km^2 in the Northumberland district. While these studies are not directly comparable due to the difference in location, it is unlikely that the causal factor for difference between both estimates is location. Variability in results is also found when using CMR methods with different crustacea species such as American lobster (table 2). Different methods were used to derive these estimates, so they cannot be directly compared, however, such large differences suggests sampling technique may not be the only factor producing the difference. A proportion of this variability is likely to be attributable to estimates for parameters affecting the calculation, such as rate of loss and catchability. These values are often derived through modelling (Skerritt, 2014, Bell et al., 2003, Spencer, 2013) and have the potential to create significant variability within population density estimates, which suggests further empirical data may be required to increase reliability of outputs.

Table 2: Population density estimates produced using CMR methodologies.

Location	Species	Population estimate/km^2	Citation
Northumberland, UK	*H. gammarus*	6,662 ± 1,475	(Skerritt, 2014)
Northumberland, UK	*C. pagurus*	20,893	(Spencer, 2013)
Norfolk, UK	*C. pagurus*	2,101	(Bell et al., 2003)
Maine, USA	*H. americanus*	65,000	(Dunnington et al., 2005)
Northumberland Strait, Canada	*H. americanus*	450 ± 50	(Bowlby et al., 2008)

5.0 Lobster fishery management models

Estimates of abundance for lobster and crab have been used as an indication of the health of the population and the exploitation level from fishing pressure for many years (Hilborne and Walters, 1992). Management has either focussed on preventing decline of fisheries or allowing recovery of over exploited fisheries (Smith et al., 2007). Management ranges from catch restrictions such as MLS, to stock enhancement through hatcheries (table 3). Significant social impacts often occur when new management is implemented, and resistance from fishers whose livelihoods are compromised is expected (Hattam et al., 2014). Table 3 provides a brief assessment of the efficacy of management methods used within IFCAs, which will be assessed in further detail throughout this section.

Table 3: Lobster management methods used by Inshore Fisheries and Conservation Authorities

Management Method	Used by NIFCA?	Strengths	Weaknesses	Citations
MLS	Yes – EU regulation 87mm	Established scientific evidence for benefit of use (Size at maturity)	Size at maturity variable and may allow non-mature lobsters to be removed	(MMO, 2017b; Laurans et al., 2009)
V-notching	Yes – National legislation	Provides protection for females of reproductive age for up to 2 years	Requires sampling effort to make v-notches, conflicts with berried hen ban	(Rae, 2017; Duffill-Telsnig, 2013)
Berried Hens Ban	Yes – National legislation	All ovigerous females protected with no sampling effort	Can be subjected to non-compliance from scrubbing of eggs	(MMO, 2017a; Agnalt et al., 2007)
Pot limitation	Yes -800 pots per licence	Creates a maximum number of pots that can be fished within the district	Has the potential to increase fishing pressure as some fishers may increase effort to match 800 limit	(Turner et al., 2009; Wallace, 2015)
Hatchery stock enhancement	Yes – Amble Hatchery	Potential to bolster recruitment rates and therefore population size	Potential for outbreak of disease. May change natural ecology	(Davies & Wootton, 2018; Bannister et al., 1994; Telsnig, 2014)
Escape gaps	No	Allows small lobsters to escape damage caused from handling	Unpopular due to loss of velvet swimming crab (*Necora puber)*	(Wallace & Rae, 2017)

5.1 Minimum Landing Size

Lobster, like many other crustacea, periodically shed their exoskeletons (ecdysis) in order to grow (Samuelsen et al., 2014; Wood, 2018). This leaves no permanent hard structures within their morphology, which creates difficulties when trying to determine age, and therefore size is used as a proxy for age (Tully, 2001, Wahle et al., 2001) The current MLS for European lobster in the UK is 87mm carapace length (CL) which is measured from the bottom of the eye stalk to the end of the carapace (MMO, 2017b), however, some IFCAs have increased the MLS to 90mm CL within their districts (CIFCA, 2018). The 87 mm MLS has been put in place across the European Union with the intention of allowing individuals to reach sexual maturity and avoid being removed when functionally immature (Le Bris et al., 2017). The MLS management method is based on size at onset of maturity (SOM) where analysis of the condition of berried lobsters has shown a significant proportion (50%) of lobsters are sexually mature at a specific size (L_{50}) (Laurans et al., 2009).

SOM is variable and is affected by various environmental factors including temperature, season and food availability (Le Bris et al., 2017). Wood, (2018) investigated the size at functional maturity for lobsters off the east Yorkshire coast, results found only ~0.25% of the population sampled to be mature at 87mm (figure 2).

This represented a deviation away from previous estimates of SOM which was attributed to a sampling artefact associated with exploitation. However, this study only represents one area, and SOM is known to vary spatially and temporally, with, L_{50} being highly variable at different locations around the British Isles (table 4). This variability causes uncertainty in the size at which lobster should be exploited. Initial SOM was thought to be lower, which was reflected in the original MLS of 85mm, which was then increased to 87mm in 2002 (Lizárraga-Cubedo et al., 2003) Removing immature lobsters from the fishery before they reproduce leads to lack of recruitment. Efficacy of this management method can be assessed through use of population density estimates/stock assessments. UK stock assessments for lobster fisheries have indicated that populations are over exploited (Cefas, 2017) and therefore the suitability of an 87mm MLS should be reassessed. However, stock assessments are produced through modelling and are reliant on certain assumptions and the quality of data used. Before changing MLS, the accuracy of stock assessments should be reviewed to ensure the stocks are in fact over exploited. Additionally, due to the initial financial loss to fishers caused by restrictive management measures (Sigurdardóttir et al., 2015), other methods of maintaining high recruitment should be explored, such as protection of ovigerous females, to understand how best to keep recruitment and egg production high, whilst maintaining economic benefits.

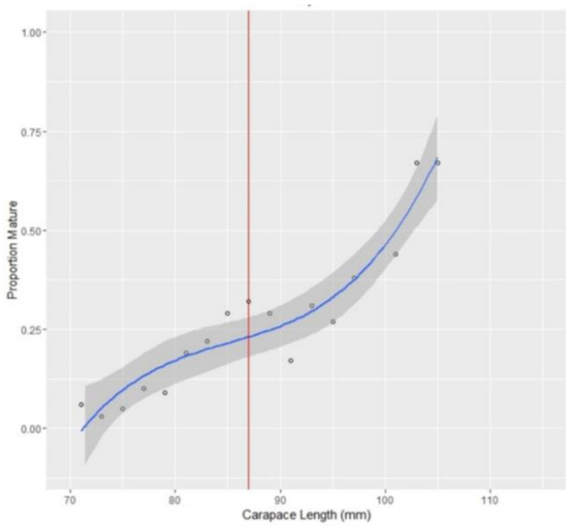

Figure 2: Size at onset of maturity for *Homarus gammarus.* Proportion mature at MLS indicated at intercept of blue and red lines (Wood, 2018)

Table 4: Range of estimates of L_{50} for functionally mature lobster from different locations (adapted from Laurans et al., 2009)

Location	Functional maturity, size (mm)	Citation
Bridlington Dale Selsey	90 105 85	(Free et al., 1992)
Northwest Ireland West Ireland Southwest Ireland Southeast Ireland	107 116 122 140	(Tully et al., 2001)
Firth of Fourth Hebrides	95 98	(Lizárraga-Cubedo et al., 2003)

5.2 V-notching and berried hens landing ban

V-Notching is the process of removing a v-shaped section of the tail of female lobster of reproductive age/capability. This national measure (Statuatory Instrument No. 874, 2000) is enacted regionally through Byelaw 3 - Crustacea conservation (NIFCA, 2017). Since the V-notching program began in 2000, NIFCA have v-notched and released over 20,000 lobsters (Rae, 2017). The landing of v-notched lobsters is illegal. As adult lobsters shed their exoskeleton (ecdysis) every 1-2 years (Agnalt et al., 2007), the v-notch only provides protection until their next ecdysis, however this should allow time to complete at least one breeding cycle (Tully, 2001). Most catch restrictions are met with resistance from fisheries due to associated financial loss, however, v-notching has proven popular, with some fishers v-notching lobsters themselves (Duffill-Telsnig, 2013). This may be caused by IFCAs providing financial compensation for v-notched lobsters. Each year

NIFCA sets aside £10,500 for compensating fishers at £14/kg (variable between years) for v-notched lobsters (Rae, 2017).

The efficacy of v-notching for improving lobster stocks has not been conclusively proven. Recent stock assessments have indicated that the lobster population remains overexploited in the NIFCA district (Cefas, 2017), despite v-notching taking place since 2000. However, other factors such as increased fishing pressure may be the cause for overexploitation (Stephenson et al., 2017). V-notching occurs in other regions of the world and has been an established management regime in Maine, USA, since 1947 (Getchell, 1987), which is believed to be very effective (Acheson & Gardner, 2011). However, in Maine, v-notching programs are completed on a much larger scale (over 60 million v-notched to date), on a different species (American lobster), and have been implemented for a significantly longer period, all of which may contribute to the success of the scheme, making direct comparisons difficult.

In 2018, a ban on the landing of berried hens (female lobsters carrying eggs) was implemented across all IFCA districts (previously berried hen ban was present in 6/10 local IFCA byelaws) (MMO, 2017a). This has a similar aim to v-notching, in that it protects reproductively active females in order to keep recruitment levels high. However, there are fundamental differences between the two methods. For example, the ban on berried hens gives protection to all females carrying eggs and does not require any of the effort and resources required for v-notching. However, lobsters that have recently dispersed their eggs are not protected. Non-compliance is also frequent, with fishers removing eggs from the hen (scrubbing), making enforcement problematic. Current research aims to develop techniques to detect where berried hens have been scrubbed (Defra, 2016). Hens are berried for approximately 9 months, so after spawning, the lobster loses protection until its next brood, unlike the v-notching scheme, which could provide over a year of additional protection. The national berried hen ban is still in its infancy, and time is needed to understand the effect it has on stocks.

In Norway and Sweden, models showed that the combination of an MLS of 85 mm and a moratorium on females produced high yields and allowed the high recruitment required to rebuild the depleted stock. Further decreasing MLS still allowed a sustainable fishery, but no recovery, while increasing to 90 mm, whilst providing a high yield, decreased reproductive value (Sundelöf et al., 2015). This is an example of where increasing management level does not have continuingly increasing benefits and demonstrates why management measures must be carefully researched before implementation. Major differences in ecology and stock status between the UK and Scandinavian fishing grounds, due to severe stock collapse experienced in the Scandinavian lobster fishery (Agnalt, 1999), does not allow for direct comparison although a similar model could be produced for the UK in order to assess the best management combinations.

5.3 Pot limitation

Pot limitations restrict the number of pots fishers are able to fish at one time. A limitation to 800 pots per licenced individual was implemented in the NIFCA district in 2009 (Turner et al., 2009). Outside the 6 nautical miles limit, fishers are not subject to this ceiling. The effects of pot limitation are poorly documented in the NIFCA district. Wallace, (2015) investigated how pot limitation influences fishing effort and found the limit had negligible effect. This was supported by Stephenson, (2016), who found no significant decrease in fishing effort within the district. This is likely to be caused by the current limit of 800 pots being too high. However, the current limit, creates a controllable total number of pots fished within the district. This prevents the fishery expanding beyond sustainable levels as decided by NIFCA. Due to current stock level being reported as over exploited (Cefas, 2017), a reduction in limit or number of licenses should be considered as a mitigation strategy to reduce fishing effort. As pot limitation in the NIFCA region is understudied, pot restrictions from other regions can be assessed in order to draw conclusions on the most suitable limit moving forward.

North American lobster fisheries are also managed through pot/trap limitations, however, experience similar issues in determining a suitable limit. Fishers using large numbers of pots were adversely affected by introduction of pot limitation whereas it allowed smaller scale or 'part time' fishers to increase their proportion of the total catch (Acheson & Gardner, 2011). Within the Greater Atlantic Region (Gulf of Maine, Georges Bank, and Southern New England), there are seven lobster management regions with varying management regimes, similar to IFCA regions in the UK. All regions have pot limitations, ranging from 800 - 1945 pots in different regions, but are also permit specific and therefore changeable dependant on individual licences. The lobster fishery in the Gulf of Maine (GOM) is thought to be well managed, due to the continuing rise in catch over a 20 year period (ASMFC, 2015). Whilst species and geographical range differ, lessons can be learned from the pot limitation regime in the North American fishery and could suggest specific limits on a permit by permit basis as an improved management strategy in the UK.

5.4 Hatchery released stock enhancement

Lobster hatchery-based stock enhancement through release of juveniles is in the early stages of development in Northumberland. Lobster larvae populate the water column when newly spawned and at this stage are highly vulnerable to predation (Van Der Meeren, 2005). Once through larval stage, juvenile lobsters are able to take shelter on the benthos and therefore become less vulnerable with higher survival rates (Linnane et al., 2000). Lobster hatchery stock enhancement methods land berried hens, hatch the eggs and rear larvae in the safety of the hatchery away from predators. Once at a size where survival rate is significantly increased, juveniles are released, causing a much higher recruitment level than if eggs were released naturally in the wild (Perez Benavente et al., 2010). This management method has been utilised in Europe and North America at different levels since the 1800s (Nicosia & Lavalli, 1999). Hatcheries currently in the UK include the Padstow hatchery in Cornwall, The Orkney Hatchery, Scotland, and recently a hatchery in Amble, Northumberland. The Padstow and Orkney hatcheries release 30,000 and 60,000 juveniles respectively each year (Duffil-Telsnig, 2014). The efficacy of this technique has been hard to quantify due to the extreme difficulty locating juvenile lobsters in the wild (Mehrtens et al., 2005). The benefits of rearing and releasing juvenile lobsters with significantly increased survival rates are obvious and could provide a strong management measure for maintaining high stock levels of lobster.

However, hatcheries share negative aspects of other aquaculture industries, such as high occurrence of disease (Daniels et al., 2013; Holt et al., 2018) and poor growth e.g. dual scissor claw development (Van Der Meeren

& Uksnøy, 2000). The potential to negatively impact natural ecosystems if disease from hatcheries is released with juvenile lobsters is an associated risk (Jørstad et al., 2001). However, studies have been completed to assess health and survival rate in hatchery-reared juveniles. Poor claw development (dual scissor claws), associated with lobster larviculture was used to identify hatchery-reared individuals within a fishery (Tveite & Grimsen, 1995), However, Schmalenbach et al., (2011) found all re-captured individuals showed no signs of disease and well developed crusher claws. Lobster husbandry techniques have improved with increasing research and may explain the improvement in quality shown in the Schmalenbach et al., (2011) study. To date there have been no documented outbreaks of widespread disease in wild lobster populations, but with increasing utilisation of hatcheries and therefore increased risk of disease, careful monitoring of water quality and pre-release specimen health must be implemented to minimise risk of outbreaks (Davies & Wootton, 2018).

5.6 Management in the Gulf of Maine – a case study

Table 5: Comparison of management methods between the NIFCA district, the UK (Cefas, 2017) and Gulf of Maine fisheries (NOAA, 2018)

Management method	UK	NIFCA	Gulf of Maine
Trap/pot limits	Some regions	Yes	Yes
Escape gaps	Some regions	No	Yes
Minimum size	Yes	Yes	Yes
Maximum size	No	No	Yes
V-notch	Yes	Yes	Yes
Closed season	No	No	Yes

The Gulf of Maine (GOM) has an extensive American lobster fishery. The scale of the fishery requires high levels of management, which has resulted in sustainable stock levels, despite high fishing pressure. This success has been measured through the continual rise in catch rates, shown from regular stock assessments. The GOM area is reported to currently be at its highest ever stock density (ASMFC, 2015). Due to the apparent success of management regimes in the GOM, there is potential to make comparisons to UK management and draw conclusions on efficacy of methods. The GOM fishery is more heavily managed than the NIFCA district and the UK (table 5), and management has been in place for longer, with MLS and prohibition from landing berried hens in place since 1870s (Acheson & Gardner, 2014). Many of the methods are the same/similar, as shown in table 5, but there are also methods that are not utilised at all in the UK such as maximum landing size and closed seasons. The NIFCA districts stock is reportedly overexploited (Cefas, 2017), and could therefore benefit from use of increased management such as these measures used in the GOM.

In the GOM, decomposable panels are required, which break down over time to prevent ghost fishing from pots that are lost at sea (Acheson & Gardner, 2014; NOAA, 2018). This management regime could be implemented in the NIFCA region and the UK at low-cost to fishers, reducing needless lobster mortality. Differences between species and geographic scale make direct comparisons difficult and may account for some variation in success of measures such as v-notching, which is well established and has strong fisher support (Acheson & Gardner, 2011). American lobster are known to have higher fecundity increase with size than European lobster (Ellis et al., 2015), therefore, protecting reproductively active females may be more effective for American lobster management. Research directly comparing biology and management regimes of

American lobster to European lobster is sparse, and more research is required before conclusions can be drawn on the suitability of seemingly effective management regimes from the GOM, for European lobster in the UK.

6.0 Conclusions

This review assessed lobster stock assessment methodologies and management methods within the NIFCA district through systematic review of available literature. Due to limited literature within the district, use of technical documents, and lobster fisheries literature in other regions have been used to draw conclusions on the efficacy of current methods. The NIFCA district is in initial stages of providing comprehensive stock assessments, with one unofficial stock assessment completed in 2017. Lessons learned through analysis of the EIFCA stock assessment process, suggest regular and thorough stock assessment through use of LCCC and YPR analysis should be completed by NIFCA. This will produce robust data estimating fishing mortality and a reference point for which to assess stock fluctuations. The high variability of CMR studies suggests further research is required into parameters such as rate of loss and catchability, in order to provide more accurate estimations of population density. The recent introduction of a nationwide berried hen landing ban may have significant impact, but impacts will not be seen immediately. To further improve management methods, examples of successful management such as in the Gulf of Maine, should be further examined and assessed for potential application in the NIFCA district. Recommendations outlined in this review could inform future management within the NIFCA district to alleviate current overexploitation.

7.0 References

Acheson, J. & Gardner, R. (2014) Fishing failure and success in the Gulf of Maine: lobster and groundfish management. *Maritime Studies*. 13 (1), 1–21.

Acheson, J. & Gardner, R. (2011) The evolution of the Maine lobster V-notch practice: cooperation in a prisoner's dilemma game. *Ecology and Society*. 16 (1), 41-50

Addison, J.T. (1995) Influence of behavioural interactions on lobster distribution and abundance as inferred from pot-caught samples. *ICES Marine Science Symposium* 199, 294–300.

Agnalt, A-L. (1999) Stock Enhancement of European Lobster (*Homarus gammarus*): a large-scale experiment off south-western Norway (Kvitsoy). *Stock Enhancement and Sea Ranching.* (Book)

Agnalt, A.L., Kristiansen, T.S. & Jørstad, K.E. (2007) Growth, reproductive cycle, and movement of berried European lobsters (*Homarus gammarus*) in a local stock off southwestern Norway. *ICES Journal of Marine Science*. 64 (2), 288–297.

ASMFC (2015) Atlantic States Marine Fisheries Commission stock assessment overview: American lobster.

Bannister, R.C.A., Addison, J.T. & Lovewell, S.R.J. (1994) Growth, movement, recapture rate and survival of hatchery-reared lobsters (*Homarus gammarus* Linnaeus, 1758) released into the wild on the English east coast. *Crustaceana*. 67 (2), 156–172.

Bell, M.C., Eaton, D, Bannister, R.C.A. & Addison, J.T. (2003) A mark-recapture approach to estimating population density from continuous trapping data: application to edible crabs, *Cancer pagurus*, on the east coast of England. *Fisheries Research*. 65, 361–378.

Bowlby, H.D., Hanson, J.M. & Hutchings, J.A. (2008) Stock structure and seasonal distribution patterns of American lobster. *Fisheries Research.* 90, 279–288.

Bridges, T. (2017) Crab and Lobster Stock Assessment. *Research Report. Inshore Fisheries and Conservation Authority.*

Cefas (2017) Lobster (*Homarus gammarus*). Cefas Stock Status Report.

CIFCA (2018) https://www.cornwall-ifca.gov.uk/pots-and-traps [Online].

Daniels, C.L., Merrifield, D.L., Ringø, E. & Davies, S.J. (2013) Probiotic, prebiotic and synbiotic applications for the improvement of larval European lobster (*Homarus gammarus*) culture. *Aquaculture*. 416–417, 396–406.

Davies, C.E. & Wootton, E.C. (2018) Current and emerging diseases of the European lobster (*Homarus gammarus*): a review. 94 (3), 959–978.

Defra (2016) Prohibition on landing egg-bearing lobsters and crawfish; impact assessment.

Díaz, D., Mallol, S., Parma, A.M. & Goñi, R. (2016) A 25-year marine reserve as proxy for the unfished condition of an exploited species. *Biological Conservation.* 203, 97–107.

Duffil-Telsnig, J. (2014) The feasibility of aquaculture, aquaponics and a lobster hatchery.

Duffill-Telsnig, J. (2013) An assessment of the impact of v-notching European lobsters in the Northumberland district.

Dunnington, M.J., Wahle, R.A., Bell, M.C. & Geraldi, N.R. (2005) Evaluating local population dynamics of the American lobster, *Homarus americanus*, with trap-based mark-recapture methods and seabed mapping. *New Zealand Journal of Marine and Freshwater Research*. 39 (6), 1253–1276.

Ellis, C.D., Knott, H., Daniels, C.L., Witt, M.J. & Hodgson, D.J. (2015) Geographic and environmental drivers of fecundity in the European lobster (*Homarus gammarus*). *ICES Journal of Marine Science*. 72, 91–100.

Getchell, R.G. (1987) Effects of V-notching on the lobster, *Homarus americanus*. *Canadian Journal of Fisheries and Aquatic Sciences*. 44 (11), 2033-2037.

Hattam, C.E., Mangi, S.C., Gall, S.C. & Rodwell, L.D. (2014) Social impacts of a temperate fisheries closure: understanding stakeholders' views. *Marine Policy*. 45, 269–278.

Henry, A.M. & Johnson, T.R. (2015) Understanding social resilience in the Maine lobster industry. *Marine and Coastal Fisheries*. 7 (1), 33–43.

Hold, N., Murray, L.G., Pantin, J.R., Haig, J.A., Hinz, H. & Kaiser, M.J. (2015) Video capture of crustacean fisheries data as an alternative to on-board observers. *ICES Journal of Marine Science*. 72 (6), 1811–1821.

Holt, C., Foster, R., Daniels, C.L., van der Giezen, M., Feist, S.W., Stentiford, G.D. & Bass, D. (2018) *Halioticida noduliformans* infection in eggs of lobster (*Homarus gammarus*) reveals its generalist parasitic strategy in marine invertebrates. *Journal of Invertebrate Pathology*. 154, 109–116.

Jørstad, K.E., Berg, Ø. & Andersen, K. (2001) Health aspects in Norwegian lobster stock enhancement. *Proceedings of Symposium on Lobster Health Management*.

Laloë, F. (1995) Should surplus production models be fishery description tools rather than biological models? *Aquatic Living Resources*. 8 (1), 1–16.

Laurans, M., Fifas, S., Demaneche, S., Brérette, S. & Debec, O. (2009) Modelling seasonal and annual variation in size at functional maturity in the European lobster (*Homarus gammarus*) from self-sampling data. *ICES Journal of Marine Science*. 66, 1892–1898.

Le Bris, A., Pershing, A.J., Gaudette, J., Pugh, T.L. & Reardon, K.M. (2017) Multi-scale quantification of the effects of temperature on size at maturity in the American lobster (*Homarus americanus*). *Fisheries Research*. 186, 397–406.

Linnane, A., Mazzoni, D. & Mercer, J.P. (2000) A long-term mesocosm study on the settlement and survival of juvenile European lobster *Homarus gammarus* L. in four natural substrata. *Journal of Experimental Biology and Ecology*. 24, 951–964.

Lizárraga-Cubedo, H.A., Tuck, I., Bailey, N., Pierce, G.J. & Kinnear, J.A.M. (2003) Comparisons of size at maturity and fecundity of two Scottish populations of the European lobster, *Homarus gammarus*. *Fisheries Research*. 65 (1–3), 137–152.

McGarvey, R., Matthews, J.M. & Prescott, J.H. (1997) Estimating lobster recruitment and exploitation rate from landings by weight and numbers and age-specific weights. *Marine and Freshwater Research*. 48 (8), 1001–1008.

Mehrtens, F., Stolpmann, M., Buchholz, F., Hagen, W. & Saborowski, R. (2005) Locomotory activity and exploration behaviour of juvenile European lobsters (*Homarus gammarus*) in the laboratory. *Marine and Freshwater Behaviour and Physiology*. 38 (2), 105–116.

MMO (2014) Fishing data collection, coverage, processing and revisions.

MMO (2015) Marine Management Organisation. 2011 to 2015 UK fleet landings and foreign fleet landings into the UK by Port Data. https://www.gov.uk/government/statistical-data- sets/uk-sea-fisheries-annual-statistics-report-2015 [Online].

MMO (2017a) Catching or landing of berried lobsters and crawfish in England. https://www.gov.uk/government/publications/catching-or-landing-of-berried-lobsters-and-crawfish-in-england/catching-or-landing-of-berried-lobsters-and-crawfish-in-england. [Online]

MMO (2017b) Minimum Conservation Reference Sizes (MCRS) in UK waters.

Nicosia, F. & Lavalli, K. (1999) Homarid lobster hatcheries: their history and role in research, management, and aquaculture. *Marine Fisheries Review*. 61 (2), 1–57.

NIFCA (2018) http://www.nifca.gov.uk/about/ [Online].

NIFCA (2017) Northumberland inshore fisheries & conservation authority byelaws booklet.

NOAA (2018) American lobster information Sheet. https://www.greateratlantic.fisheries.noaa.gov/regs/infodocs/lobsterinfosheet [Online].

Pauly, D. (1984) Length-converted catch curves: a powerful tool for fisheries research in the tropics. Part 2. *Fishbyte*. 2 (1), 17–19.

Perez Benavente, G., Uglem, I., Browne, R. & Balsa, C.M. (2010) Culture of juvenile European lobster (*Homarus gammarus* L.) in submerged cages. *Aquaculture International*. 18 (6), 1177–1189.

Rae, V. (2017) NIFCA V-notching 2017 Report.

Reed, M., Courtney, P., Urquhart, J. & Ross, N. (2013) Beyond fish as commodities: understanding the socio-cultural role of inshore fisheries in England. *Marine Policy*. 37 (1), 62–68.

Samuelsen, O.B., Lunestad, B.T., Farestveit, E., Grefsrud, E.S., Hannisdal, R., Holmelid, B., Tjensvoll, T. & Agnalt, A.-L. (2014) Mortality and deformities in European lobster (*Homarus gammarus*) juveniles exposed to the anti-parasitic drug teflubenzuron. *Aquatic Toxicology*. 149, 8–15.

Satuatory Instrument No. 874 (2000) The lobsters and crawfish (prohibition of fishing and landing) order 2000.

Schmalenbach, I., Mehrtens, F., Janke, M. & Buchholz, F. (2011) A mark-recapture study of hatchery-reared juvenile European lobsters, *Homarus gammarus*, released at the rocky island of Helgoland (German Bight, North Sea) from 2000 to 2009. *Fisheries Research*. 108 (1), 22–30.

Sigurdardóttir, S., Stefánsdóttir, E.K., Condie, H., Margeirsson, S., Catchpole, T.L., Bellido, J.M., Eliasen, S.Q., Goñi, R., Madsen, N., Palialexis, A., Uhlmann, S.S., Vassilopoulou, V., Feekings, J. & Rochet, M.J. (2015) How can discards in European fisheries be mitigated? Strengths, weaknesses, opportunities and threats of potential mitigation methods. *Marine Policy*. 51, 366–374.

Skerritt, D.J. (2014) Abundance, interaction and movement in a European Lobster Stock.

Smith, A.D.M., Fulton, E.J., Hobday, A.J., Smith, D.C. & Shoulder, P. (2007) Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science*. 64 (4), 633–639.

Smith, M.T. & Addison, J.T. (2003) Methods for stock assessment of crustacean fisheries. *Fisheries Research*. 65 (1–3), 231–256.

Spencer, A. (2013) An assessment of the Northumberland edible crab *Cancer pagurus* and velvet crab *Necora puber* fisheries.

Stephenson, F. (2016) Shellfisheries, seabed habitats and interactions in Northumberland.

Stephenson, F., Mill, A.C., Scott, C.L., Stewart, G.B., Grainger, M.J., Polunin, N.V.C. & Fitzsimmons, C. (2018) Socio-economic, technological and environmental drivers of spatio-temporal changes in fishing pressure. *Marine Policy*. 88, 189–203.

Stephenson, F., Polunin, N.V.C., Mill, A.C., Scott, C., Lightfoot, P. & Fitzsimmons, C. (2017) Spatial and temporal changes in pot-fishing effort and habitat use. *ICES Journal of Marine Science*. 74 (4), 2201–2212.

Sundelöf, A., Grimm, V., Ulmestrand, M. & Fiksen, Ø. (2015) Modelling harvesting strategies for the lobster fishery in northern Europe: the importance of protecting egg-bearing females. *Population Ecology*. 57 (1), 237–251.

Tremblay, J.M. & Smith, S.J. (2001) Lobster (*Homarus americanus*) catchability in different habitats in late spring and early fall. *Marine and Freshwater Research*. 52, 1321–1331.

Tully, O. (2001) Impact of the v-notch technical conservation measure on reproductive potential in a lobster (*Homarus gammarus* L.) fishery in Ireland. *Marine and Freshwater Research*. 52 (8), 1551–1557.

Turner, R.A., Hardy, Michael, H., Green, J. & Polunin, N.V.C. (2009) Defining the Northumberland Lobster Fishery. *Report to the Marine Fisheries Agency, London.*

Turner, R.A., Polunin, N.V.C. & Stead, S.M. (2015) Mapping inshore fisheries: comparing observed and perceived distributions of pot fishing activity in Northumberland. *Marine Policy*. 51, 173–181.

Tveite, S. & Grimsen, S. (1995) Survival of one-year-old artificially raised lobsters (*Homarus gammarus*) released in southern Norway. *ICES Marine Science Symposium*. 199, 73–77.

Wahle, R.A., Tully, O. & O ’Donovan, V. (2001) Environmentally mediated crowding effects on growth, survival and metabolic rate of juvenile American lobsters (*Homarus americanus*). *Marine and Freshwater Research*. 52 (8), 1157–1166.

Van Der Meeren, G.I. (2005) Review: potential of ecological studies to improve survival of cultivated and released European lobsters, *Homarus gammarus*. *New Zealand Journal of Marine and Freshwater Research*. 39 (2), 399–424.

Van Der Meeren, G.I. & Uksnøy, L.E. (2000) A comparison of claw morphology and dominance between wild and cultivated male European lobster. *Aquaculture International*. 8 (1), 77–94.

Wallace, N. (2015) Lobster, fishing effort and habitat interactions in the Northumberland lobster

Wallace, N. & Rae, V. (2017) Escape Gap Project 2016-17.

Welby, P.R. (2015) Crab and Lobster Stock Assessment. *Research Report. Inshore Fisheries and Conservation Authority.*

Welby, P.R. (2016) Crab and Lobster Stock Assessment. *Research Report. Inshore Fisheries and Conservation Authority.*

Welby, P.R. (2014) Crab and Lobster Stock Assessment. *Research Report. Inshore Fisheries and Conservation Authority.*

Wood, J.M. (2018) New estimates and complications in the assessment of female functional maturity for the European lobster (*Homarus gammarus*) on the Yorkshire Coast (UK). *Journal of Fisheries*. 6 (2), 635-638.

Woodruff, J. (2017) Stock assessment - an evaluation of the minimum landing size and the pot limitation byelaw in the Northumberland lobster fishery.