#340 MAY 2018

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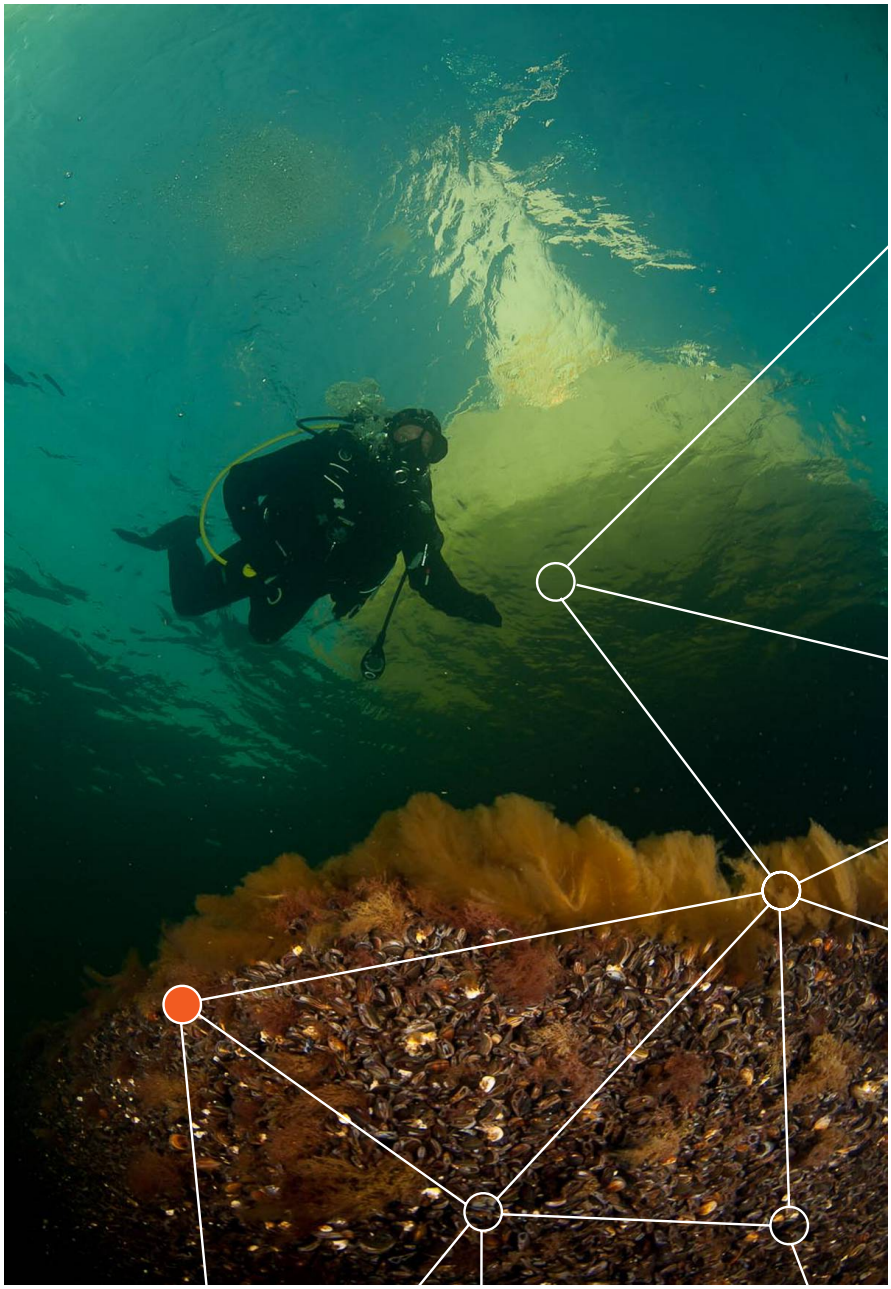

ICES INTERNATIONAL COUNCIL FOR THE EXPLORATION OF THE SEA
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NO. 340

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Using underwater television surveys to assess and advise on *Nephrops* stocks

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Recommended format for purposes of citation:

Leocádio, A., Weetman, A., and Wieland, K. (Eds). 2018. Using UWTV surveys to assess and advise on *Nephrops* stocks. ICES Cooperative Research Report No. 340. 49 pp. https://doi.org/10.17895/ices.pub.4370

Series Editor: Emory D. Anderson

http://doi.org/10.17895/ices.pub.4370

ISBN 978-87-7482-212-7

ISSN 2707-7144

Contents

Foreword

Norway lobster (*Nephrops norvegicus*) is a commercially important species in the Northeast Atlantic, and in relatively recent years, fisheries in many countries in this region have expanded rapidly to exploit this valuable market.

In the last 20 years, underwater television (UWTV) surveys have played a significant and ever increasing role in gathering data for use within ICES stock assessment process. Management advice on *Nephrops* stocks is derived from these data and, with several countries now undertaking such surveys, standardized approaches and technologies have been agreed and adopted as best as practically possible.

This report describes the use of UWTV surveys in the assessment and provision of management advice for *Nephrops* stocks. This includes (i) the history of underwater photography and the development of *Nephrops*-specific surveys; (ii) the equipment used and the utilization of various survey designs; (iii) *Nephrops* burrow identification and quality control; (iv) caveats and uncertainties associated with the methodologies; (v) the statistical analyses used and the incorporation of survey results into the assessment process; and (vi) the further utilization of the survey data beyond the primary task.

This report was compiled by various members of ICES Working Group on *Nephrops* Surveys (WGNEPS) and we thank Ian Tuck, University of Auckland, for his review.

1 Introduction

Colm Lordan

Nephrops are found on the continental shelf and slope throughout the Northeast Atlantic, from the Canary Islands in the south to Iceland in the north. The species is also found in the western Mediterranean, Adriatic, and Aegean seas. Throughout its range, *Nephrops* are a target or bycatch species in commercial fisheries which yield annual landings in the order of 60 kt. The majority of landings are made in trawl fisheries, but smaller-scale creel or pot fisheries also occur in many areas. Ensuring sustainable fisheries is a key objective of managers and fishers of *Nephrops* stocks.

Nephrops construct distinctive burrows in muddy sediments that range from fine-grained mud through sandy mud and muddy sands to muddy gravel in water depths from 4 to 800 m. Characteristics such as growth and population density vary in a manner that suggests links with sediment type, food availability, and local hydrography. Some populations are characterized by dense assemblages of small animals, while others are composed of lower density groups that have a wider size range of animals including some large sized individuals.

The life history characteristics of *Nephrops* vary across its range, e.g. in relation to the time of spawning, duration of egg incubation, timing of larval release, duration of planktonic phase, whether eggs are spawned annually or biennially, timing of moulting and mating. Following the pelagic phase (three zoea stages), post-larvae settle into the seabed, some at least connecting their burrows with those of adults. The lifestyle of juveniles appears to be burrow-oriented; they are poorly represented in catches (even those from fine-meshed gear) until after the pubertal moult. Little is known about the juvenile phase of the life cycle.

Reviews of the life history and biological parameters of *Nephrops norvegicus* are provided by Figueiredo and Thomas (1967), Farmer (1975), Chapman (1980), Sardà (1995), and Bell *et al*. (2006). These comprehensive works include information on growth (growth curves, growth rates, moulting patterns, etc.), reproduction (size at first maturity, reproductive cycle, fecundity, and larval development), burrowing and emergence behaviour (diurnal activity patterns, seasonal patterns, etc.), food and feeding, predation, mortality, fisheries, and management. Data regarding Mediterranean *Nephrops* are collected in a monographic volume of Scientia Marina (Sardà, 1998).

Nephrops fisheries exhibit strong temporal patterns in catch rates linked to the biology and behaviour of the species. This makes traditional trawl surveys problematic because catch rates are not necessarily indicative of abundance. Until recently, it was thought to be impossible to directly and accurately age *Nephrops*, making reliable age-based assessment methods impossible (Sheridan *et al*., 2015). Indirect age estimation, although possible, is difficult in many stocks due to the lack of variability in year-class strength and contrast in the observed length frequency distributions. These are the two main factors that have led to the development of this alternative approach of using underwater television (UWTV) surveys to assess stock development and provide management advice.

Currently, UWTV surveys are used to provide population estimates for *Nephrops* based on functional units (FUs) in ICES Area 27 and geographical subareas (GASs) in the Mediterranean (Figure 1.1).

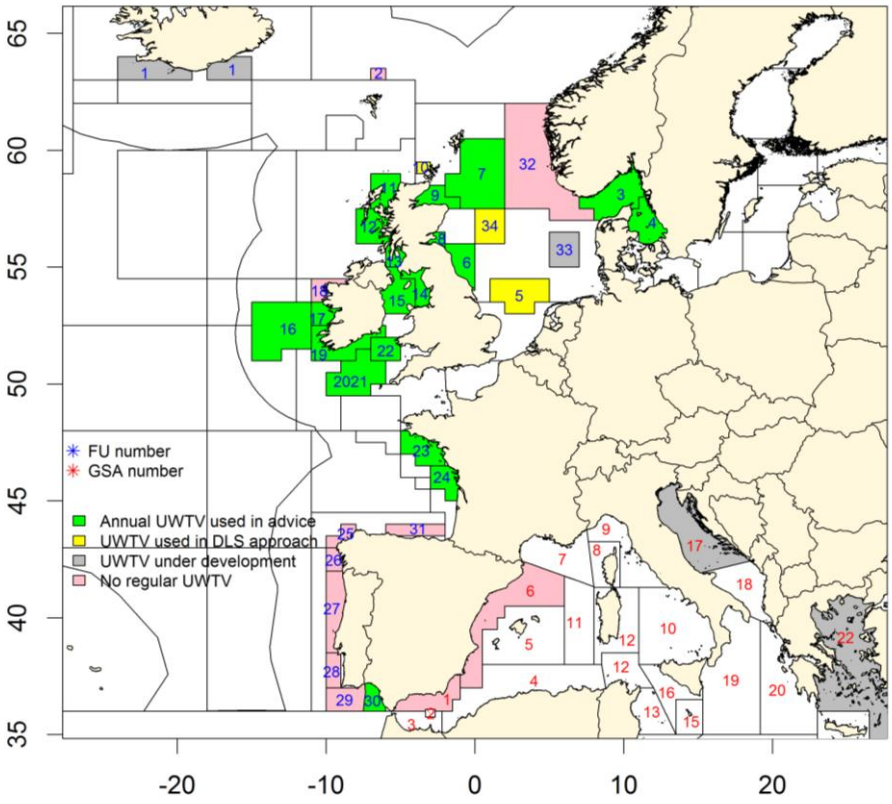

Figure 1.1. Functional units and geographical subareas used for *Nephrops* surveys (UWTV survey coverage in 2017).

2 History of *Nephrops* underwater television surveys

Adrian Weetman

2.1 Pioneering surveys

The first photograph of the seabed was taken off the coast of southern England in 1856 by William Thompson (Brown, 1985; Watson and Zielinski, 2013) with a pole-mounted camera in a glass housing. The resulting image was, unfortunately, partially water-damaged. There followed more successful attempts by the marine zoologist Louis Boutan in 1893 (Boutan, 1893) who took photographs while diving. As well as finding that these early images were poorly illuminated and grainy, he also faced many practical challenges not least with the diving equipment which was extremely cumbersome. However, over time, interest in this work prompted technological advances, developments in diving equipment, and considerable improvements in the quality of photographs taken.

Although photographs taken today by divers with high quality equipment and good lighting provide the best medium for detailed examination of benthic subjects, this approach has limitations, particularly for survey purposes. These include the depth to which divers can descend, restrictions on the size of the survey area due to diver endurance and practicalities, potentially the evasive reaction of the subject being studied, and limited possibilities for quantitative analyses and subjective descriptions/assessments of the survey based on the diver's observations. The introduction of underwater video capture in 1950 using 35 mm cine film (Chesterman, 1954) was a significant advancement for marine scientists and the military alike. Initially, divers were used to record footage, although remote systems were soon deployed, mounted on frames for recording at fixed sites with live feed to the shore (Czihak and Zei, 1960). The first trials of a cathode ray tube (CRT) video system were carried out by the Scottish Marine Biological Association, Millport, Scotland (Barnes, 1952) on *Nephrops* grounds in the Clyde, southwest Scotland. It involved video equipment mounted on a frame connected to the survey vessel by an umbilical cable that provided power and video lines which transmitted a live picture feed as the vessel drifted over the seabed. This work was undertaken as a general exploratory benthic fauna survey and was not aimed specifically at estimating *Nephrops* abundance.

In the 1960s, Craig (1963) and McAda (1965) investigated the possible use of video and still photography for fish population assessment. This coincided with a time when the cost of the equipment was falling rapidly and advances in technology were making devices smaller and more adaptable, as well as considerable improvements being made in the quality of the video footage.

In 1967, scientists and engineers at the Marine Laboratory, Aberdeen, Scotland designed video camera housings suitable to be mounted on frames to be used either by divers or to be fixed to static submersible structures. There followed a series of underwater investigations directed at *Nephrops* at a time when the fishery was beginning to gather pace and little was known about the animals' behaviour or habitat . Many publications were produced from this work and that of others working in similar fields (Cole, 1967; Foulkes and Caddy, 1973; Chapman, 1979; Chapman *et al.*, 1975; Chapman and Howard, 1979).

The use of videotape recorders (Wardle and Priestley, 1976) and latterly DVD recorders represented a significant improvement to video analysis, as the high quality foot-

age could be re-examined and discussed post-survey, as well as being made available to other interested parties or evaluated for other purposes.

In 1980, work was carried out on the west coast of Scotland specifically to look at *Nephrops* burrow distribution. This followed on from earlier static video work by Chapman (1985) and resin casting by the University Marine Biological Station Millport, Scotland (UMBSM) that described the unique structure and characteristics of *Nephrops* burrow complexes. These studies made use of a sledge on which a forward-facing video camera and other equipment were mounted, based on Holme and Barrett's design (1977). The sledge was towed across the seabed by a mother ship, which allowed for greater spatial coverage than could be obtained by diver-based surveys. Chapman (1985) significantly modified the sledge design and arrangement of the equipment. Shand and Priestly (1999) improved the design further and this became recognized as the standard template for this type of work. This method was adopted by other countries as an approach to surveying *Nephrops* burrow abundance and, due to the use of a video camera mounted on the sledge which relayed live video footage to TV monitors aboard a research vessel, it became known as the "underwater television" (UWTV) survey.

In early surveys, the sledge was towed by a vessel using a fishing warp with a separate power/coaxial line, which was manually attached and detached from the warp on each deployment and recovery of the sledge. Later, these separate cables were replaced by a single umbilical that provided towing capabilities; Kevlar and polyurethane protected the sensitive electrical cables housed within the core of the cable, a design now widely accepted as standard. In the early 1990s, scientists and engineers from the Marine Laboratory carried out UWTV surveys on the east coast of Scotland to compare the relationship between the number of *Nephrops* burrow complexes observed from video footage and population abundance estimates from analytical stock assessments. Following studies by Farmer (1974) and Rice and Chapman (1971), there was evidence to assume that one animal inhabited one burrow complex. Therefore, theoretically, the number of animals in a specific area could be calculated by counting the number of complexes over a known surface area and raising this value to the known area inhabited by *Nephrops*, with each area being assigned a unique Functional Unit label (FU) by ICES. These values could then be compared with the outputs from the models. In 1992, the first fully quantifiable and statistically designed UWTV surveys were carried out by the Marine Laboratory, Scotland at Fladen (FU 7), Moray Firth (FU 9), and Firth of Forth (FU 8) aboard MRV "Scotia" (Bailey *et al*., 1993).

Difficulties in applying traditional stock assessment approaches to *Nephrops* stocks (see Sections 1 and 7) prompted consideration of an alternative, fishery-independent approach to stock assessment and the provision of management advice. It was agreed that the UWTV method was best suited to provide the information required despite the various assumptions with this method (ICES, 2007, 2009a, 2010a, 2012). Further refinements to the survey over the following years resulted in Fladen being the first functional unit to make use of UWTV survey data in the provision of catch options (ICES, 1998). By 2006, all of the major Scottish *Nephrops* stocks were being assessed based on UWTV surveys providing *Nephrops* abundance by functional unit.

As time passed, and problems with the use of analytical stock assessment methods became more apparent, other countries with interests in *Nephrops* stocks began to develop UWTV surveys. The Aran Grounds (FU 17) were first surveyed in 2002, followed by the Irish Sea West (FU 15) the next year. Although all surveys used the same basic approach, specific aspects relevant to individual sledges (conductivity, temperature, depth units (CTD), odometers, lasers, van Veen sediment grabs, field of

view, etc.) varied among different institutes, as did the survey designs (random stratified, randomized isometric grid, fixed grid, and fixed stations). Table 2.1 gives an overview of the different survey designs used. These variations relate to budgetary constraints, the availability of equipment, and the nature of the grounds surveyed. Consequently, the methods used in working up the data also varied among institutes. In 2008, these differing methods were reviewed, documented, and procedures were agreed upon so that the outputs generated provided comparable results among different functional units (ICES, 2008).

Table 2.1. Survey design for UWTV surveys by *Nephrops* functional unit (FU) and geographical subareas (GSA).

Country/Institute	FU	GSA	Ground name	Survey design
Ireland/Marine Institute	16		Porcupine Bank	Randomized isometric grid
Ireland/Marine Institute	17		Aran Grounds	Randomized isometric grid
Ireland/Marine Institute	19		South and south-west Ireland	Random stratified
Ireland/Marine Institute	20–21		Labadie, Jones and Cockburn	Randomized isometric grid
Ireland/Marine Institute	22		The Smalls	Randomized isometric grid
UK and Ireland/ AFBI and Marine Institute	15		Irish Sea West	Randomized isometric grid
UK/Cefas	5		Botney Gut/ Silver Pit	Fixed grid
UK/Cefas	6		Farne Deeps	Fixed grid
UK/Cefas	14		Irish Sea East	Fixed grid
UK/Marine Scotland	7		Fladen Ground	Random stratified
UK/Marine Scotland	8		Firth of Forth	Random stratified
UK/Marine Scotland	9		Moray Firth	Random stratified
UK/Marine Scotland	10		Noup	Random stratified
UK/Marine Scotland	11		North Minch	Random based on VMS boundary
UK/Marine Scotland	12		South Minch	Random stratified
UK/Marine Scotland	13		Clyde	Random stratified
UK/Marine Scotland	13		Jura	Random stratified
UK/Marine Scotland	34		Devil's Hole	Fixed stations
UK/Marine Scotland	NA		Stanton banks	Random stratified
UK/Marine Scotland	NA		Arbroath	Random stratified
Denmark and Sweden/ DTU Aqua and SLU	3–4		Skagerrak and Kattegat	Random stratified
Spain/IEO	30		Gulf of Cádiz	Randomized isometric grid
France/IFREMER	23–24		Bay of Biscay	Randomized grid
Iceland/MFRI	1		Off South Iceland	Randomized grid
Italy and Croatia/ CNR and IOF		17	Adria (Pomo pit)	Random stratified

2.2 ICES developments

In 2007, the first ICES *Nephrops* UWTV workshop, ICES Workshop on the use of UWTV surveys for determining abundance in *Nephrops* stocks throughout European waters (WKNEPHTV), took place. At this meeting, the various UWTV survey methods and the use of the resultant abundance estimates for advice purposes were discussed and documented for the first time. WKNEPHTV also identified and tabulated the uncertainties associated with UWTV surveys for *Nephrops*. The following year, an ICES workshop and training course on *Nephrops* burrow identification (WKNEPHBID) developed reference sets of video footage for three different areas (ICES, 2008). At that workshop, burrow-complex identification training took place and training documentation was drafted. In 2009, ICES Study Group on *Nephrops* surveys (SGNEPS) reviewed the training procedures and updated the relevant documentation. The potential for an UWTV survey database was discussed and the use of VMS data to improve survey design was investigated (ICES, 2009a).

The first benchmark workshop on *Nephrops* assessment (WKNEPH) occurred in 2009 (ICES, 2009b). The workshop concluded that UWTV survey estimates of *Nephrops* abundance could be used, in the short term, as absolute measures of abundance provided they were used in conjunction with estimates of the various potential sources of bias (for which preliminary estimates were derived) (see Section 6). Standard protocols for the processing and work-up of UWTV survey data and the generation of ICES catch option tables were produced and incorporated into the stock annexes for each functional unit. Following the 2009 benchmark meeting, ICES began to routinely provide catch advice for *Nephrops* stocks based on UWTV survey data.

In 2010, SGNEPS (ICES, 2010a) reviewed survey protocols and considered the importance of edge effects as a bias to the absolute abundance estimate. In 2012, SGNEPS evaluated the relative merits of the various survey designs and technological advancements made by different institutes, assessed trawl surveys, and further investigated some of the uncertainties relating to UWTV survey estimates of abundance.

In 2013, the Working Group on *Nephrops* Surveys (WGNEPS) was established and is currently the coordination expert group for *Nephrops* UWTV and trawl surveys within ICES Area 27 and in some geographical subareas (GSA) in the Mediterranean.

With the basic survey design, quality control measures, core equipment, and data work-up well established and documented, institutes, in recent years, have, where possible, extended their survey programmes to investigate uncertainties associated with the UWTV approach in an attempt to improve the quality and use of the data. The additional work, which has met with varying degrees of success, has included (i) resin casting to look at burrow occupancy, (ii) methods to relate the size of animal to that of the burrow entrance, (iii) exploring the use of lasers to account for edge effects, (iv) sledge mounted sediment grabs, (v) CTD monitoring, (vi) recording ancillary data from the video footage for ecosystem applications (sea pens, fish, clarity, etc.), (vii) testing different camera angles, (viii) alternative vehicle design to survey areas where the likelihood of entanglement is high (e.g. drop frames, landers), and (ix) mapping *Nephrops* grounds previously not surveyed as part of the assessment. Recommendations for continued improvements to the quality of the data and utility of the surveys are proposed annually at WGNEPS.

3 Survey methodology

Jennifer Doyle and Ana Leocádio

3.1 Equipment

The equipment used by each institute typically has slight differences, but the basic sledge-based equipment generally includes:

- a forward-facing video camera at an oblique angle to the seabed;
- lights to fully illuminate the field of view;
- lasers to delimit the field of view, usually dot or fan lasers;
- a recovery system so that the sledge can be retrieved if lost;
- data loggers to record turbidity readings, depth, and salinity;
- a wheel to record the distance run in each TV tow (or alternatively, the track distance can be calculated using the sledge or vessel positional information).

Equipment on board the research vessel includes:

- DVD recorder or other medium for recording the footage (e.g. hard drives);
- monitors (flat screen or CRT);
- power supplies;
- personal computers;
- paperwork.

Many institutes are currently making a transition to full high-definition (HD) cameras and digital video recording systems.

3.2 Operation procedures

All survey operations follow the same general procedure. The sledge is deployed from the stern of the vessel and a cable length to water depth ratio of ca. 1.8 is used to land the sledge on the seabed. This ratio depends on surface conditions and vessel speed, with more cable required to counteract a vessel's motion in poor weather. When the sledge reaches the seabed, the vessel should then proceed at a low speed of ca. 0.7 knots to ensure that the recorded footage allows for a detailed examination of the seabed when played back. Before beginning to record the footage, it is usually necessary to wait several minutes to allow the vessel speed to stabilize and potential sediment clouds to settle. Winches should be used to assist in controlling the speed of the sledge and maintaining ground contact by paying out or taking in cable as required. The objective is to record the best quality video footage to identify and count burrows where sledge speed is neither too fast nor too slow and ground contact is maintained.

UWTV survey tows should have a duration of ten minutes. Previous investigations (Afonso-Dias, 1998) concluded that longer tows (providing that conditions remained constant) did not significantly improve the accuracy of the resulting abundance estimates. However, in certain situations, tows are shortened, such as at the edge of grounds in the Irish adaptive surveys. In Scotland, recordings of less than five minutes are usually discarded. If poor viewing conditions are encountered during the tow (e.g. sustained periods of zero visibility due to sediment disturbance or the sledge flies off the seabed), additional minutes are added to the end of the tow. Analyses presented to WKNEPTV (Annex 2 in ICES, 2007) demonstrated that the mean count was usually established after a short period and underwent little change after five minutes, the underlying data consisting of counts every 15 seconds.

The cumulative variance also remained relatively stable after five minutes. During WKNEPHTV, further analysis was undertaken using the minute-by-minute counts provided by Scotland and Ireland. Cumulative mean counts were calculated for each viewing of each tow, and these were then standardized to the mean cumulative count for that viewing of that tow. The areas chosen for analysis were those with more than 20 stations. The results showed a clear reduction in the variability of the average counts at around five to seven minutes, after which it increased again. The analyses presented suggest that the number of minutes which must be counted to provide a robust estimate of density could be less than ten and that this reduction in minutes counted may, in fact, decrease uncertainty in the density estimate from each tow. The analysis was conducted on count data from moderate- and high-density areas. In cases of particularly low density, the full ten minutes may be required to obtain sample sizes large enough to overcome integer artefacts; for this reason, the FU 16 Porcupine Bank UWTV survey (Doyle *et al*., 2014) uses a 10-minute survey track for density estimation. For other functional units, standard practice is to record ten minutes of high-quality footage, but to recount only seven minutes from each station for the density estimation. Average estimates for burrow density, its range, and standard deviations by FU or GSA are given in the annual WGNEPS reports.

3.3 Identifying *Nephrops* burrows and training

Nephrops burrows must be correctly identified and accurately counted from the video footage to determine the abundance calculation from the UWTV survey. There is a large body of literature describing *Nephrops* burrows from observations made in laboratory aquaria and diver-mapped information (Farmer, 1975; Marrs *et. al.,* 1996). The European-funded study by Marrs *et al.* (1996) describes *Nephrops* burrows in detail, having derived the information from burrow resin castings made in diver-accessible waters (4–30 m). *Nephrops* burrows typically have multiple entrances, and Figure 3.1 shows resin casts of *Nephrops* burrows from this study demonstrating the various tunnels, shafts, and openings they may have. A number of burrow features are specific to *Nephrops*, with the main identifier being the presence of at least one crescent-shaped opening to a shallowly descending tunnel. Excavated material can often be seen fanning out from the burrow entrance (termed "the driveway" or "delta"), and occasionally linear tracks are present which are created by the *Nephrops* as it enters and emerges from the entrance. These characteristics help identify *Nephrops* complexes, although not all openings to *Nephrops* burrows have these distinctive features. *Nephrops* burrow complexes often have multiple entrances, and the relative size of the burrow entrances and their orientation to each other can help in assigning these to a single burrow complex (also termed a "system") during the counting process. In such situations, the apex created by the crescent-shaped entrance from each burrow will converge on a central point, occasionally resulting in an apparent raised centrum. Often, however, burrow identification (and accurate counting) can be difficult, particularly when the overall burrow density is high, there is poor visibility, or when other burrow-dwelling species are present on the ground, some of which have burrows that can be confused with those of smaller *Nephrops*.

Marrs *et al.* (1996) also reported that burrows that were destroyed experimentally were rapidly re-excavated by the occupants; showing signs of re-excavation within one day, and by two days, any amelioration appeared complete. This demonstrates that if an animal is not injured by the disruption of its burrow, reconstruction or repair is accomplished relatively rapidly. Burrow complexes with two or three functional openings are the most common on the inshore grounds that have been studied using SCUBA techniques. Marrs *et al.* (1996) concluded that trained observers should

be able to identify and enumerate *Nephrops* burrows from UWTV with a reasonable degree of accuracy.

In 2008, the first workshop and training course on *Nephrops* burrow identification (WKNEPHBID) was held (ICES, 2008), as recommended by WKNEPHTV (ICES, 2007). This workshop focused on three main areas: (i) training of personnel unfamiliar with burrow counting, (ii) the development of training and reference material, and (iii) the production of reference counts for standardization of counter performance.

A significant proportion of WKNEPHBID participants were *Nephrops* burrow counting novices. Survey footage was reviewed by groups with mixed experience to identify *Nephrops* burrows and learn how to count burrow complexes from different geographical areas under different UWTV tow conditions. Novice counters (sometimes known as "operators") gained confidence and experience from these footage-review sessions. The criteria for burrow recognition and the burrow identification key (Marrs *et. al.*, 1996) was updated; this key is a very useful resource for identification training (ICES, 2008, Annex 6). The main conclusions from this guide emphasized the importance of becoming familiar with the burrows of species that can be confused with those of *Nephrops* to reduce misidentification; and also the maxim "if in doubt, do not count" so that the counts generated are conservative.

The workshop also discussed training material and recommended that each institute produce a training manual for its survey area that would provide comparisons of burrow complexes constructed by both *Nephrops* and other burrowing species, such as *Calocaris macandreae* in FU 15 Irish Sea West. It was agreed that training material should include one minute of annotated video footage covering a range of densities, different levels of water clarity, and other burrowing species encountered, and also a photographic guide of signature features of *Nephrops* burrows. Figures 3.2–3.4 show examples of annotated stills used for training from different survey areas.

Reference sets to validate counter performance (consisting of footage and agreed counts) for three survey areas (FU 6 Farn Deeps, FU 7 Fladen, and FU 15 Irish Sea West) were created at this workshop. A reference set for a specific area consisted of footage from ten runs, each run being of five minutes duration covering different ranges of visibility (poor, medium, and good), varying *Nephrops* density (low, medium, and high), and species complexes likely to be encountered in each area. To create counts for this footage (reference counts), three international counters reviewed the footage in isolation. Results were compared and where significant differences between the counters occurred, the footage for that minute was re-examined and a consensus among the three counters was reached. The reference count for each area was taken as a weighted average of the three counters, with the local expert for each area having twice the weight of the other counters. It was agreed that each institute would produce reference counts for each area they surveyed and a standard operating procedure for counting.

The workshop also discussed the use of Lin's concordance correlation coefficient (CCC) which measures the ability of counters to exactly reproduce each other's counts using the reference datasets (Lin, 1989). The CCC values were considerably higher in FU 6 and FU 7, reflecting the easier reading conditions of these areas compared to FU 15.

Reference counts created during WKNEPBID (2008) were based on results generated by the three most experienced counters: one each from Cefas (UK), Marine Scotland Science (UK), and the Marine Institute (Ireland). Since then, each institute has created

reference sets for most of the remaining FUs using experienced counters (ICES, 2010a). For new and developing UWTV surveys, it may take a few years before reference counts can be produced, but in the interim, reference footage from survey areas with similar morphologies should be used to train and validate counter performance. If there are any changes to a UWTV system such as camera set-up, camera signal, lighting, etc., it is recommended that new reference counts be generated to take account of likely changes to video footage. Future workshops could be used to generate reference counts similar to the process undertaken at WKNEPHBID.

At ICES Study Group on *Nephrops* Surveys (SGNEPS; ICES, 2009a), further work was presented on Lin's CCC to analyse the performance of reference counting. This statistical test measures correspondence between paired counts and has distinct advantages over standard correlation analysis or *t*-tests. In medical environments such as blood counts, where counting should be less subjective, the threshold for accepting an individual count should be high > 0.8. Given the nature of the UWTV footage (water clarity, variety of burrowing species present, etc.), a lower threshold might be considered acceptable and an arbitrary minimum value of 0.5 has been recommended. Although CCC requires a minimum of two points, a minimum of ten are recommended for robustness (five pairs). As each reference set contains low/medium/high density stations as well as good/ok/poor visibility stations, it is possible to pool stations into various categories, which boosts the sample size to satisfactory levels and allows the quantification of how well individual counters are performing in each scenario.

WKNEPHBID recommended, that prior to a survey, counters should re-familiarize themselves with the training material and review footage from a minimum of two reference sets, comparing their counts to the agreed reference counts (using Lin's CCC with a minimum threshold of 0.5). This allows survey leaders to identify counters who need further training. Counters who remain unable to get close to the reference count for particular scenarios could read a limited set of the survey counts (i.e. not reading the scenarios for which they underperformed). Figure 3.5 shows individual counting performance in 2015 for FU 17 against the reference footage as measured by Lin's CCC. A threshold of 0.5 was used to identify counters who needed further training.

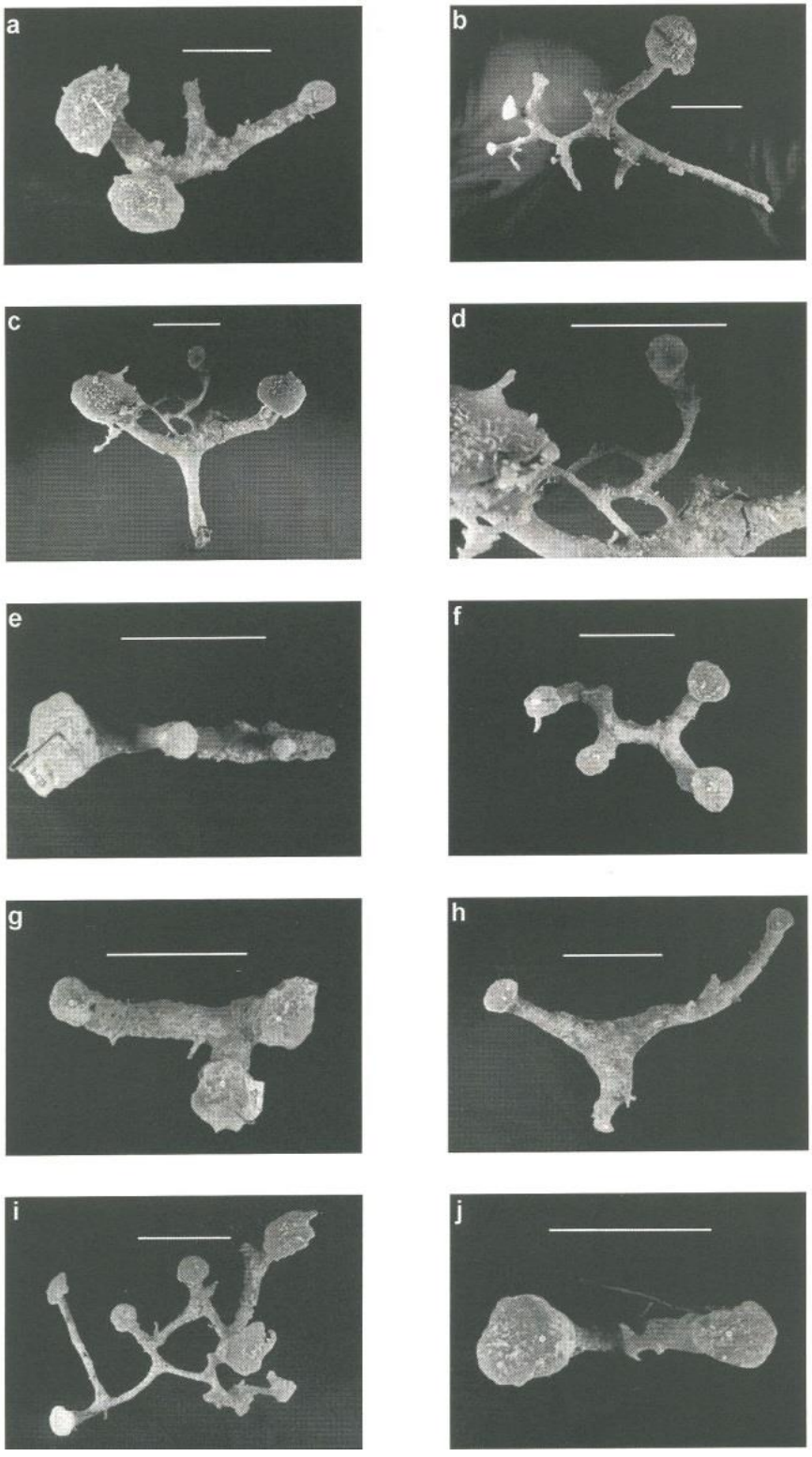

Figure 3.1. Resin casts of *Nephrops* burrows (Marrs *et al.*, 1996). Scale bar lengths 20 cm (a, c–j), 30 cm (b).

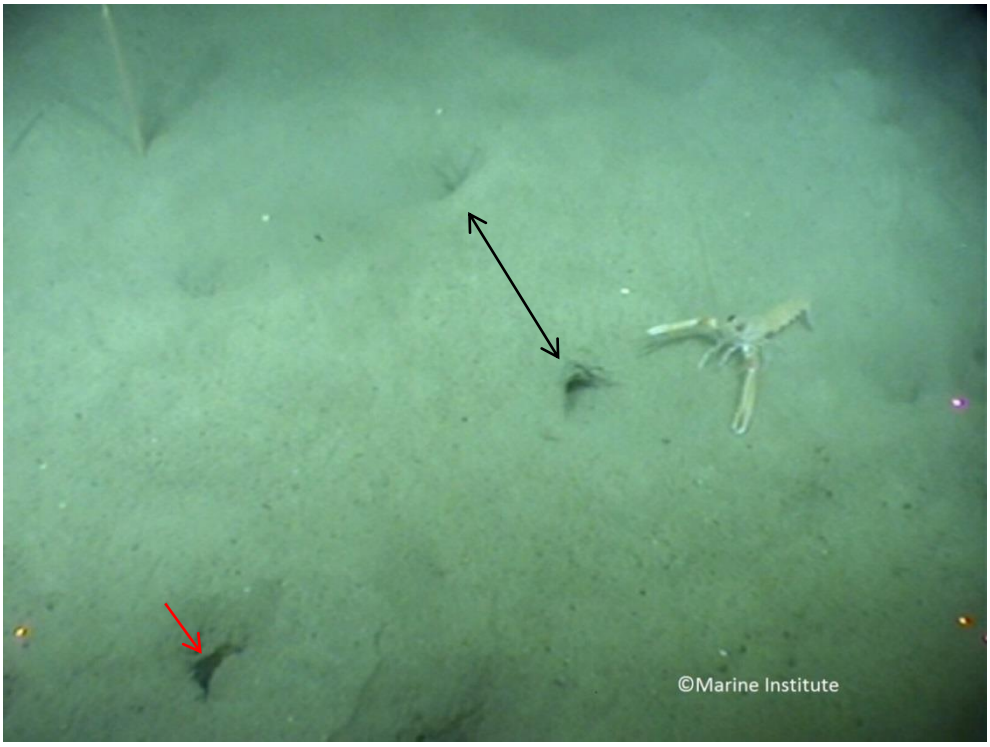

Figure 3.2. Still image taken from FU 22 The Smalls video footage ~120 m depth. Illustrating a linear burrow system (black double arrow) and a second burrow complex with one entrance visible (red arrow). Also visible are a seapen, species *Virgularia mirabilis* (top left), and a *Nephrops norvegicus* active outside of burrow. Point lasers (orange dots) visible at edge of image denote field of view 75 cm. (Photo © Marine Institute).

Figure 3.3. Still image taken from FU 6 Farn Deeps video footage 120 m depth. Illustrating signature features of a T-shaped *Nephrops* burrow complex. Crescent-shaped entrance, sediment ejecta, and radial scrapings around entrance and appearance of a "driveway". Single to multiple entrances focusing on an apparent raised centrum. *Nephrops* visible in burrow entrance. (Photo © Cefas)

Figure 3.4. Still image taken from FU 16 Porcupine Bank video footage 500 m depth. Illustrating signature features of a T-shaped *Nephrops* burrow complex in centre of image and a second system with two visible entrances in the background. (Photo © Marine Institute).

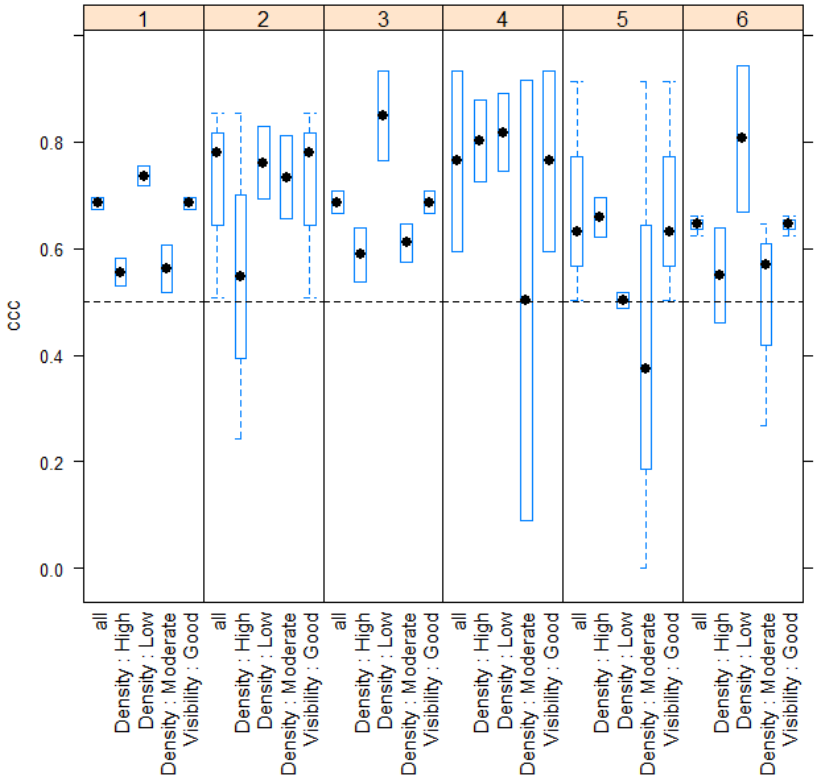

Figure 3.5. Counting performance against the reference counts as measured by Lin's CCC for 2015 FU 17 Aran grounds. Each panel represents a counter. The *x*-axis (from left to right), all stations pooled, high density, low density, moderate density, and visibility good.

3.4 Quality control

Quality control of what to count and how to count is now established for UWTV surveys, as discussed in Section 3.3, and these standard procedures should be followed by new and developing UWTV surveys. Quality assurance is also required for the provision of final burrow counts, and a standard protocol for reviewing footage has been agreed and will be documented in the UWTV Series of ICES Survey Protocols (SISP). This can be summarized as: (i) each UWTV station is to be reviewed by a minimum of two counters in isolation and independently of each other, and (ii) counts are recorded in one-minute blocks where counts include *Nephrops* burrow complexes, *Nephrops* in burrows, and *Nephrops* outside of burrows. In addition, the number of seconds within each minute of when counting could not be undertaken, for example, in cases when visibility is reduced or when the sledge glides should also be recorded. Results of comparisons among counters working in isolation and concurrently (Working Document 9, Annex 2 in ICES, 2007) demonstrated a significant decrease in individual abundance values, yet a harmonization of variance when working together, creating a bias. It was expected that there would be a reduction in overall variance; however, the counters actually became more conservative in their criterion for what constituted an individual burrow complex. These results suggested that counting is best performed in isolation. Subsequent discussions proposed that, if returning to review footage after a lengthy break (more than three hours), a warm-up count is recommended requiring one station from the same area in which the footage to be reviewed is from, allowing the reviewer to re-familiarize themselves with the features associated with those grounds.

When all counts are completed, additional independent or consensus counting must be carried out to account for discrepancies between counts. Lin's CCC can be used to check which stations will need to be revisited and if a third counter, or more counters, need to be added. Marine Scotland and Cefas UWTV surveys have followed this process for several years and it is being extended to other institutes involved in WGNEPS. Consensus counting needs counters to agree on a threshold of difference in burrows, and this needs to be adequate and proportional to the average density in the ground. When differences in counts are higher than the identified limit, counters will revisit the stations and agree on a final count for those stations.

As the vast majority of recounting now takes place during the cruise (i.e. at sea), SGNEPS recommended that the best place for interannual consistency checking is on the same cruise (ICES, 2009a). There is limited time available for recounting, and the counting of additional, historical data is impractical given the existing schedule. It is proposed that time can be saved on recounting by reducing the time recounted to seven "good" quality minutes as opposed to the existing ten. Some counters would welcome the first minute as a "warm-up" minute to adjust to the conditions at that particular station, in which case, eight minutes would be counted, but only the last seven minutes used (a two-minute saving per station). Reducing the counting time to seven minutes provides a compromise between having enough data to ensure counter consistency (CCC analysis) to stabilize the mean and variance of the counting and saving enough time on the recounts to reinvest in the historical comparisons.

Analysis of historical survey counts for FU 15 was presented at SGNEPS (ICES, 2009a). At that time, a time-series of six years of TV survey data was available, and the mean density estimates calculated by the survey appeared to be quite high in the first years (2003 and 2004). A 30% random subsample of the 2003 and 2004 FU 15 UWTV survey stations were recounted in the laboratory to check if there had been any change in burrow identification criteria since the start of the survey series. The

results demonstrated that there had been a change in what reviewers agreed were burrows and in both surveys this mainly happened at the high density stations. It is thought that this was due to the relative inexperience of the counters in early surveys, especially in areas difficult to review where there were both high densities of other burrowing macrofauna (most notably *Calocaris macandreae*) and small *Nephrops* burrow systems. This generated a considerable amount of additional work for the scientists, having to recount 150 stations from each survey.

Various bespoke quality control (QC) scripts in R have been developed by some institutes which produce a series of plots for each UWTV station. These plots allow for QC of the survey data for the station as a whole, including burrow count data, navigation data, and tow quality information (qualitative statements describing, for example, speed, visibility, and ground type). Figures 3.6–3.8 show an example of QC plots (at both station level and for the whole survey from the 2015 UWTV survey on the FU 20–21 Labadie, Jones, and Cockburn) and how these plots would be interpreted. These QC plots show the:

- tow quality information by minute in relation to station speed, visibility, and ground type;
- number of counters and counter identification;
- ship and USBL speed scatterplot which depicts the quality of the navigation signal;
- count data by operator by minute;
- track of the ship position data to account for any noise in the logged positions the track is first smoothed using the spline function in R;
- track of the USBL (sledge sensor) position data to account for any noise in the logged positions the track is first smoothed using the spline function in R;
- scatterplot analysis of counts by paired counters;
- bubbleplot of variability of density between minutes;
- bubbleplot of variability of density between operators.

These plots are especially useful as they can be produced "on the fly" during the survey so that the data quality can be quality checked efficiently so that problems with sledge sensors can be picked up and resolved and counting problems visually inspected and checked. UWTV surveys on some grounds such as FU 15 (Irish Sea West) aim to complete about 100 stations annually (Ligas *et al.*, 2014). Quality-control plots such as these provide the scientist in charge with a concise summary of a large dataset and enable easy identification of any problems or errors in the data.

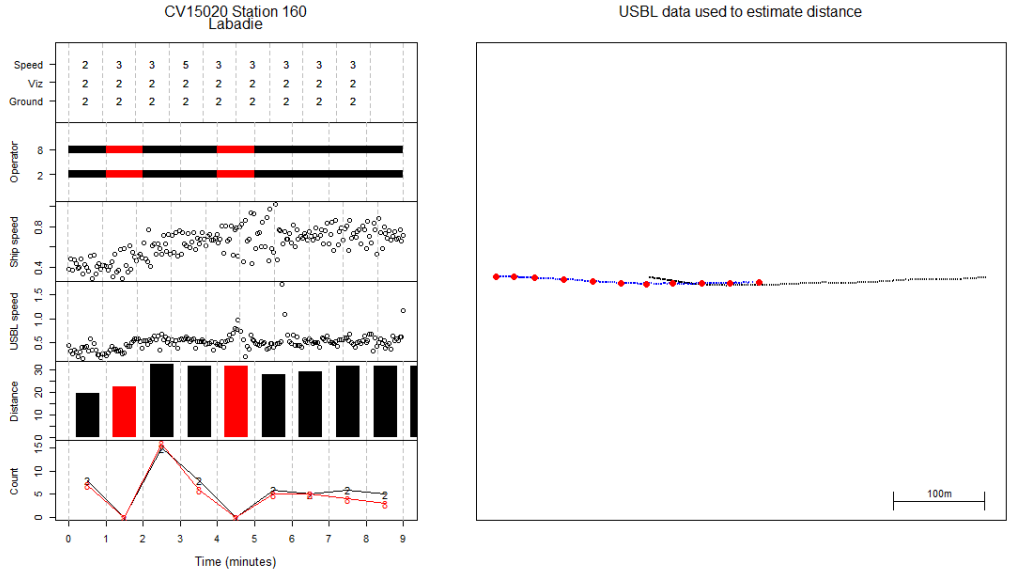

Figure 3.6. Station 160 quality control plot (Marine Institute). Minutes highlighted in red will be removed from the final analysis as 30 seconds or more were flagged as unusable in these minutes because of unfavourable tow conditions, such as poor visibility or variable speed.

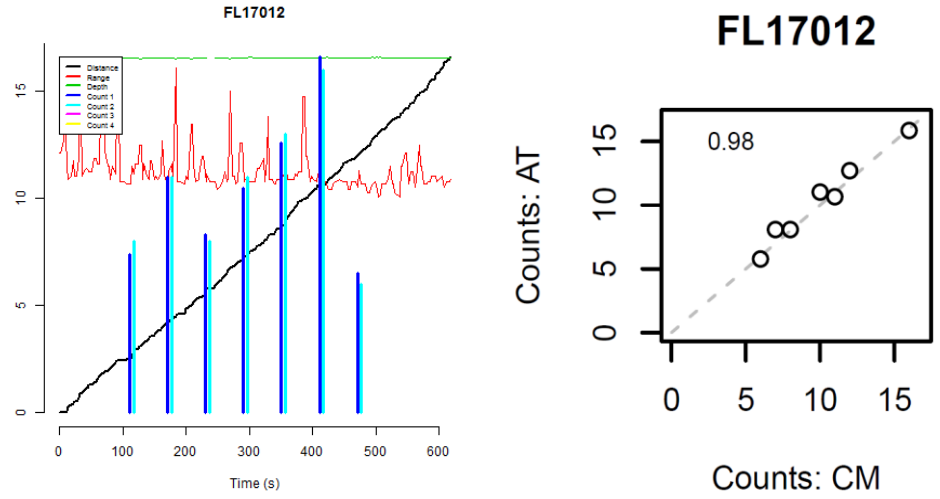

Figure 3.7. Fladen, Station 12 quality control plots 2017 (Marine Scotland Science). The chart on the left provides an illustration for each minute from one 10-minute run showing a good correlation between the two counters, steady transition over the ground and slight fluctuations in the camera proximity to the seabed which is accounted for in the field of view calculations. The plot on the right shows the output from Lin's CCC using data from the same station. AT and CM are the initials of the readers.

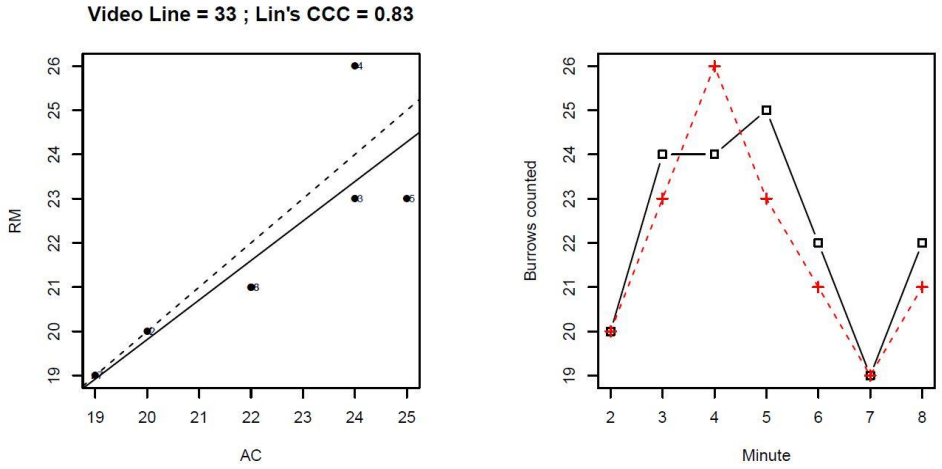

Figure 3.8. Quality control plots from a Farne Deeps station (Cefas). The left plot shows an example of Lin's CCC output. The right plot is a line chart comparing observations in relation to each minute. RM and AC are the initials of readers.

4 Survey design

Jordan Feekings, Kai Wieland, and Colm Lordan

4.1 Defining the spatial extent of the habitat

The spatial extent of the suitable habitat for *Nephrops* is essential in the process of raising the observed density estimates to total stock abundance. Therefore, the assumed spatial extent of the habitats can cause large differences in stock abundance estimates depending on what data are used to calculate it.

Owing to its burrowing behaviour, the distribution of *Nephrops* is restricted to areas of mud, sandy mud, and muddy sand. Therefore, the spatial extent of *Nephrops* grounds has traditionally been based on the spatial extent of suitable sediment types along with logbook and vessel monitoring system (VMS) information. The introduction of VMS provides a more accurate representation of the extent of the fishery in some areas. However, the accuracy of current boundaries of suitable *Nephrops* habitat is considered to be a source of uncertainty by WKNEP (ICES, 2006, 2009b), particularly in highly heterogeneous grounds where differences between fished area, surveyed area, and population area are likely to exist.

VMS data linked to logbook information, acoustic remote sensing of the seabed, and sediment data provide a definition of *Nephrops* habitat distribution, as described in recent benchmark workshops (ICES, 2017). VMS data make it possible to link geographical information on the positioning of vessels to landings data resulting in more detailed information on the spatial distribution of fishing effort in the *Nephrops* trawl fishery. Although VMS coverage has expanded to include all vessels > 12 m in length (since 2012), such fine-scale fishery data are still unavailable for smaller vessels. Therefore, the spatial extent of the *Nephrops* fishery is not as well defined in inshore areas that are mainly exploited by these smaller vessels, e.g. the sea lochs in FU 11 (ICES, 2010a).

Given that VMS data do not cover the entire fishery, logbook and at-sea-sampling data can be used as an additional source of information to determine the spatial extent of suitable *Nephrops* habitats. For example, logbook data can be used to determine whether the spatial extent of the VMS-covered vessels is different to the spatial extent of vessels without VMS recordings.

The methods used to define the spatial extent differ across functional units and are dependent on the data available and the heterogeneity in sediment type. Areas consisting of heterogeneous sediment types (such as FU 3, FU 4, and FU 11) are characterized by numerous islands and sediment types, resulting in patchiness in the spatial extent of the habitable sediment type and distribution of the fishery. Validation and modification of survey areas from incorporation of additional and/or improved data needs to occur on a regular basis when data become available. All available data should be used to redefine the spatial extent of suitable habitats for *Nephrops* which is part of the benchmark process.

4.2 Sampling design

There are two main UWTV survey design approaches currently in use: grid (fixed or randomized) and stratified random design, where in some surveys there is a buffering between stations to ensure a more even spatial coverage than unrestricted random selection of sampling positions (Cochran, 1977). Both approaches allow the application of geostatistical models or classical statistics to estimate abundance and

precision levels. The grid is normally extended in an adaptive way until boundaries are established. The stratified random approach uses *a priori* data on sediment and or integrated VMS data to define strata with similar densities. The definition of the survey boundaries and its stratification is essential to meet the required level of precision.

Survey sampling effort should be at a level that ensures a reasonably precise measure of *Nephrops* burrow density. A coefficient of variation (*CV*) of < 20% is considered adequate (ICES, 2012).

5 Survey-based assessments

Ewen Bell, Colm Lordan, and Jennifer Doyle

5.1 Comparison with other methods

Abundance indices (whether relative or absolute) from surveys rely strongly on the ability to estimate the catchability characteristics of that survey for the stock concerned. Catchability can be defined as the product of availability (whether a species enters the survey gear) and selectivity (whether a species is retained in the survey gear). Estimates of selectivity can be achieved through experiment but availability is more difficult to determine, and emergence that enables capture may be impacted by numerous biotic and abiotic factors (see Section 1). The main advantage of the UWTV-based approach is that burrows, which are static and relatively constant if well maintained, are counted rather than individuals, which have varying emergence patterns. The approach does require some assumptions to be made, most notably on the size of individuals for which identifiable burrows can be counted and that, on average, one animal occupies one burrow complex. One of the main advantages is that *Nephrops* density tends to be highly spatially autocorrelated. As a consequence, *Nephrops* UWTV surveys tend to have relatively high precision compared to trawl surveys. A disadvantage of the UWTV surveys is that although they give abundance estimates, these alone do not provide information on the size structure of the population.

5.2 Relative abundance indices and absolute abundance estimates

Emergence is known to vary with environmental and biological factors, which means that trawl catch rates may not represent population abundance and estimation of the age distribution of stocks is not achievable due to ageing problems.

Recent research has indicated that direct ageing of decapod crustaceans may be possible through sectioning the gastric mill ossicles, which are thought to retain growth increments of potentially annual periodicity (Kilada *et al*., 2012; Leland *et al*., 2015). In *Nephrops*, however, these gastric mill ossicles have been shown to be lost and replaced at moulting (Sheridan *et al*., 2016). Therefore, it does not seem feasible that they could be used for direct ageing of this species.

Due to these issues, it has long been recognized that the standard assessment-prediction procedure used for finfish is not readily applicable to *Nephrops.* Therefore, the methods for providing advice on *Nephrops* have evolved over the years.

In 2009, WKNEPH debated the use of UWTV surveys as either an absolute measure of abundance or a relative index (ICES, 2009b). WKNEPH considered that using the surveys as relative indices to calibrate an assessment of the stock dynamics at that time was not possible due to unreliable catch data. Prior to 2006, reported landings were known to be lower than actual values, and this could lead to bias in the estimation of historical harvest rates.

The approach that emerged from WKNEPH uses UWTV surveys to provide an absolute estimate of abundance from which recommended catch and landings are derived according to an accepted harvest rate (HR = catch in numbers/abundance). However, WKNEPH considered that the use of UWTV surveys as absolute estimates of biomass, without explicit consideration of the bias associated with the surveys, would not be a sufficient approach. The workshop analysed key bias contributions for each FU. Overall, these suggest that in order to be used as absolute estimates of biomass

within an assessment, the survey data should be adjusted on an individual FU basis, as illustrated below (Table 5.1).

5.3 Length at first UWTV selection

Previously, UWTV surveys were assumed to have the same selectivity as the fishery. In 2009, WKNEPH carried out a comparison of fishery-dependent and fishery-independent scientific trawl survey data in the Irish Sea and demonstrated that there was a portion of the population that was physically on the ground and available to fishing gear, but that does not appear in the sampled catches. These smaller *Nephrops* are capable of constructing their own independent burrows, which suggests that the UWTV survey likely observed burrows of individuals that are considerably smaller than the fishery selects. Using a combination of expert knowledge and on-screen measurements, the group suggested a knife-edge detection selectivity of 17 mm for all areas. This revision of TV survey selectivity required a revision of the sustainable harvest rate for each functional unit (ICES, 2009b).

5.4 Bias correction factors

A number of factors are believed to contribute bias to UWTV survey estimates of *Nephrops* abundance. In order to use the survey abundance estimate as absolute, it is necessary to correct for these potential biases. The bias estimates are based on simulation models, preliminary experimentation, and expert opinion (Table 5.1). These factors, however, may change over time and updates occur when a stock is benchmarked.

5.4.1 Edge effect

The current methodology is to count all burrow systems that cross a defined point on the reviewing screen. However, including all burrow systems which lie beyond the edge of the field of view will result in an overestimate of the population, which is described as the "edge effect".

Campbell *et al*. (2009) identified the edge-effect issue as a likely source of bias in the *Nephrops* abundance estimates derived from UWTV survey data. This work showed that edge effects are responsible for an overestimation of population size of between 4 and 55%, depending on the width of the field of view and the mean size of the burrow complex. This overestimation is countered to some extent by variability in burrow entrance structure, which leads to *Nephrops* burrows going unrecognized. Nowadays, all UWTV survey abundance estimates are corrected for edge effects.

Table 5.1. Bias correction factors as currently used by functional unit.

Area	FU	Edge effect	Burrow detection	Burrow identification	Burrow occupancy	Cumulative bias
Off South Iceland	1	1.27	0.95	1	1	1.22
Skagerrak and Kattegat (3a)	3-4	1.3	0.75	1.05	1	1.1
Farne Deeps	6	1.3	0.85	1.05	1	1.2
Fladen Ground	7	1.45	0.9	1	1	1.35
Firth of Forth	8	1.23	0.9	1.05	1	1.18
Moray Firth	9	1.31	0.9	1	1	1.21
Noup	10	1.31	0.9	1	1	1.35
North Minch	11	1.38	0.85	1.1	1	1.33
South Minch	12	1.37	0.85	1.1	1	1.32
Clyde	13	1.19	0.75	1.25	1	1.19
Irish Sea East	14	1.3	0.85	1.05	1	1.2
Irish Sea West	15	1.24	0.75	1.15	1	1.14
Porcupine Bank	16	1.26	0.95	1.05	1	1.26
Aran Grounds	17	1.35	0.9	1.05	1	1.3
South and southwest Ireland	19	1.25	0.9	1.15	1	1.3
Labadie, Jones and Cockburn	20–21	1.25	0.9	1.15	1	1.3
The Smalls	22	1.35	0.9	1.05	1	1.3
Bay of Biscay	23–24	1.15	0.94	1.15	1	1.24
Gulf of Cádiz	30	1.24	0.9	1.15	1	1.28
Devil's Hole	34	1.45	0.95	1	1	1.4

5.4.2 Burrow detection and identification

Burrow detection rate and burrow identification are two issues that need to be considered to correctly enumerate *Nephrops* burrows. The burrow detection rate relates the number of *Nephrops* burrows counted to the number of *Nephrops* burrows present on the seabed. Burrow density (both *Nephrops* and other burrowing megafauna), water clarity, illumination, and camera angle all affect burrow detection rates. Poor viewing conditions, which occur in some FUs, are likely to result in reduced burrow detection. To mitigate this problem, optimum illumination and camera arrangements (angle and height) for UWTV surveys have been identified to create evenly distributed light across the field of view. In situations of reduced visibility, such as strong tides or nearby commercial fishing vessel activity, the scale is variable. However, planning the timing of a survey or station can reduce these effects of poor visibility.

The main challenges affecting burrow identification are the presence of other burrowing megafauna and the accurate detection of systems. Confusion caused by the presence of other species is likely to result in an overestimation of *Nephrops* burrow

counts. Although the level of overestimating *Nephrops* burrow densities is likely to be low, regular training, performance checking, and knowledge of burrowing species spatial overlap will further reduce burrow identification bias (ICES, 2007).

Marrs *et al.* (1996) compared *Nephrops* burrow system counts from video survey tows and divers and found that estimates were not significantly different in relatively "simple" burrow communities, but that detection rates from video (video count/diver count) were 1.5 (counts overestimated by 50%), where other burrowing species made detection more complex. However, the authors also stated that the trained observers would be able to identify *Nephrops* burrows with reasonable accuracy, which is the case for the current procedure. It is unlikely that properly trained counters would overestimate densities as much as was observed by Marrs *et al.* (1996). Detection of burrow systems in high-density grounds is considered to probably be an underestimate. The scale of this is deemed to be moderate where this can be improved through knowledge of burrow system structures from resin casts and footage observations.

5.4.3 Burrow occupancy

Burrow occupancy rate relates the number of burrows to the number of *Nephrops* in the survey area. Currently, the assumption is that one *Nephrops* occupies each burrow system counted, although it has been discussed that some burrows could be empty and other burrow systems could have more than one animal present.

It is agreed that an empty burrow would collapse where local oceanographic effects can cause the burrow apex to fall in and sediment to build up at the entrance. The current counting methodology is to ignore such burrows with collapsed or filled-in surface features.

Juvenile burrows tend to be found in close proximity to adult systems (Marrs *et al*., 1996). Some burrow systems are conjunctions of the tunnels of adults and one or more juveniles. The current counting methodology recognises such instances and such burrows are counted as a single burrow system.

However, to date, burrow occupancy investigations have been based on shallow water populations. This assumption would require dedicated observational and experimental effort given the potential contribution to the overall survey uncertainty.

6 Survey-based advice

Helen Dobby, Ewen Bell, Colm Lordan, and Ana Leocádio

6.1 Introduction

As far back as 1993, ICES considered estimates of abundance from UWTV surveys in its provision of management advice (ICES, 1994). At the time, the Fladen *Nephrops* fishery was a relatively new and expanding fishery and the commercial data available for assessment purposes was somewhat limited. ICES considered that UWTV surveys indicated a relatively stable abundance at a biomass level (based on mean weights from trawl surveys) which could potentially sustain higher catches in this functional unit.

Over subsequent years, a method for providing quantitative landings advice based on the UWTV survey data and the application of a "harvest ratio" (defined as the ratio of total removals to total abundance in number) was developed for the Fladen *Nephrops* stock at WGNEPH (ICES, 1998, 1999). The UWTV abundance in number was multiplied by a suitable "harvest ratio" to obtain an estimate of potential removals in number. Dividing this by the actual removals in number (derived from commercial sampling data) gave a raising factor, which was used to adjust the current landings to give potential landings for advice purposes:

$$Potential\ landings = Current\ landings \times \frac{Harvest\ ratio \times UWTV\ abundance\ (number)}{Current\ removals\ (number)} \quad (1)$$

An arbitrary conservative harvest ratio of 7.5% was initially chosen for the provision of advice, resulting in landings advice of ca. 9000 t for the Fladen FU (ICES, 1999). This value allowed some increase in the fishery, but was considered a precautionary option and at the lower end of harvest ratios experienced by the stocks assessed by ICES at that time (ICES, 1998).

During 2003–2005, concern arose over the quality of the UK landings figures (Section 6 in ICES, 2003); it was believed that there could be considerable underreporting occurring. Although not accurately known, the extent of underreporting was thought to be relatively large compared to a number of other stocks due to (i) the practice of selling *Nephrops* by contract (rather than at a fish market) and (ii) rapid quota uptake, leading to some controls being placed on quota allocation.

This concern had implications for the continued use of the catch-based virtual population analysis (VPA)-type assessments conducted for many stocks as well as the provision of management advice based on recent reported landings. ICES concluded that UWTV survey results provided the best indications of stock status, both in terms of abundance and trend, and advised that catches should be set at a level that did not allow for an increase in effort (ICES, 2006). However, the provision of catch options in accord with this advice proved problematic.

ICES working groups advocated a modification of the approach used previously to provide advice for Fladen *Nephrops* (with no specific reference to total current landings, deemed unreliable):

$$Potential\ landings = Harvest\ ratio \times UWTV\ abundance\ (number) \times average\ individual\ weight\ of\ dead\ removals \times retained\ proportion\ (by\ weight) \quad (2)$$

However, in attempting to apply this method to other stocks, it was recognized that actual harvest rates of long-established *Nephrops* fisheries were likely to be well above the 7.5% precautionary level used for the Fladen. In 2005 and 2006, ICES advice used a harvest ratio derived from historical landings and survey data. However, given the known misreporting problems for landings in the historical period, this approach was seen as a stopgap until an alternative method could be agreed (ICES, 2006).

Around the same time, methods for deriving harvest ratios consistent with fishing at a sustainable level were being explored. STECF (STECF, 2005) used a yield-per-recruit (YPR) curve to derive a reference fishing mortality, which was then translated into a harvest ratio for use in the approach described above (used by ICES in the Fladen *Nephrops* fishery 2005 and 2006) . Due to sex-specific behaviour and growth, single-sex YPR outputs were derived using a length cohort analysis, then summed to obtain a combined sex curve. The overall fishing mortality (F on the x-axis of the YPR curve) was calculated as the mean F_{bar} weighted by the catch of each sex (in numbers) at the current level of exploitation, as calculated by length cohort analysis (LCA). For most *Nephrops* stocks to which this method was applied, the harvest ratio associated with $F_{0.1}$ (a relatively conservative reference point) equated to around 20%.

Although this method was used as the basis for providing *Nephrops* TAC advice in some areas, a number of potential problems were identified. The LCA approach to deriving a combined sex YPR curve had not appropriately accounted for the likely different exploitation rates of male and female (WKNEPH, ICES, 2006), potentially leading to an inappropriately defined fishing mortality reference point. In addition, the method had assumed that the UWTV survey abundance represented an unbiased absolute measure of harvestable abundance (see sections 5 and 6 in this report).

6.2 Description of models and assumptions

6.2.1 Yield-per-recruit analysis

To address the particular characteristics of *Nephrops* population dynamics, more sophisticated population models (than previously used in STECF, 2005) underpinning the yield-per-recruit analysis were explored. Two approaches were developed, both dependent on length, but with slightly different model structure. The first utilizes an underlying age-structured population model, i.e. equal intervals in time with length derived from a growth curve, but with narrow age intervals such that the model is near continuous in length. The second uses a length-structured model, implying equal intervals of length with age derived from the inverse of a growth curve. The first approach has the same model formulation as that used in the NOAA Fisheries Toolbox length-based yield-per-recruit (YPRLEN) analysis, although the model described here is more flexible in that it models discards and the specific characteristics of *Nephrops* population dynamics. Although structured differently, the assumptions regarding biological and fishery processes and parameters are largely similar in the two approaches. The biological assumptions are described here using the age-structured (length-dependent) model, with additional comments on the length-structured approach where required. ICES previously described both appraoches (ICES, 2009b).

Male and female *Nephrops* grow and behave differently and, therefore, the size/age composition and relative proportions of each sex in the stock and fishery will be different. As a consequence, the model has to be structured by sex (s = male or female). The equations below define the population dynamics in the age-structured model (a represents the age class rather than actual age in years):

$$N_{s,1} = 0.5 \times R$$

$$N_{s,a} = N_{s,a-1} e^{-Z_{s,a-1}\Delta a} \quad \text{with a = 2,..MaxA x } \left(\frac{1}{\Delta a}\right) \tag{3}$$

where R is total recruitment to the population (and is split equally between males and females in the first age class), MaxA is the maximum age in years, and Δa is the time spent in each age class (fraction of a year).

$Z_{s,a}$ is the annual total mortality rate and is defined as

$$Z_{s,a} = M_{s,a} + F_{s,a} \tag{4}$$

In the length-structured modelling approach, the total annual mortality [in the exponent of the exponential decay, equivalent to Equation (3)] is multiplied by a term Δa_l which is a variable that is defined as the length of time individuals take to grow through length class l into $l+1$ (and can be derived from a rearranged form of the von Bertalanffy growth function).

6.2.2 Biological processes

6.2.2.1 Maturity

In the age-based model, maturity is considered knife-edged such that:

$$pmat_{s,a} = \begin{cases} 0 & l(s,a) > l_{\text{s,mat}} \\ 1 & otherwise \end{cases} \tag{5}$$

where $l(s,a)$ is the length of sex s at age a and $l_{\text{s,mat}}$ is the sex dependent length-at-maturity.

In contrast, in the length-structured model, maturity is modelled using a logistic ogive with a length at 50% mature at $l_{\text{s,mat}}$ and slope parameter (k_{mat}) of 1.

6.2.2.2 Growth

Each sex/age class has a length, $l(s,a)$, associated with it which is derived from a von Bertalanffy growth function with sex/maturity dependent parameters applied to the mid-age of each class. Female growth slows considerably at maturity and is modelled as an amalgamation of two growth curves (one for immature individuals and one for mature individuals). This follows the approach first advocated by ICES (1989) and traditionally taken by ICES *Nephrops* working groups. Figure 6.1 gives an example of a typical growth curve.

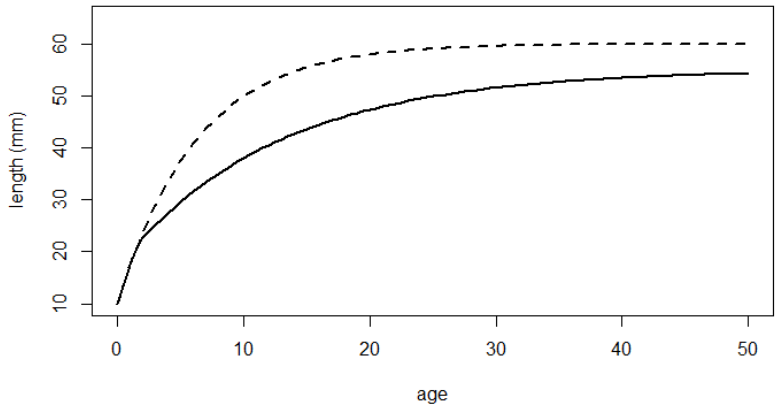

Figure 6.1. Typical growth curve for female (solid line) and male (dashed line) *Nephrops* (length represents carapace length and age is in years). Note the discontinuity in the female curve which occurs due to the change in growth parameters at the age/length of maturity.

Sex-dependent length-weight relationships are used to determine the mean weight $(w_{s,a})$ of an individual in age class *a*:

$$w_{s,a} = A_s l(s,a)^{B_s} \tag{6}$$

where A_s and B_s are sex-dependent parameters.

6.2.2.3 Natural mortality

Mature female *Nephrops* have lower burrow emergence when carrying eggs (Thomas and de Figueiredo, 1965; Redant, 1987) and, therefore, are typically subject to lower mortality rates than male and immature female *Nephrops*. Natural mortality is poorly known for *Nephrops*. For most FUs, natural mortality is defined as:

$$M_{s,a} = \begin{cases} 0.2\ year^{-1} & if\ s = female\ and\ l(s,a) > l_{\text{s,mat}} \\ 0.3\ year^{-1} & otherwise\ (Morizur, 1982) \end{cases} \tag{7}$$

where $l_{s,mat}$ is the size at maturity of sex *s*.

In contrast to the usual assumption of a maturity-dependent change in the values of the female biological parameters (von Bertalanffy and natural mortality), the length-structured model assumes a smooth transition between parameter values by using a weighted average between immature and mature values (weighted using the proportion mature at length). This implies, for example, that the von Bertalanffy L_∞ for females at length $l_{\text{s,mat}}$ lies halfway between the L_∞ for immature and mature females (likewise for the von Bertalanffy *k* and natural mortality).

In both modelling approaches, immature female *Nephrops* are assumed to have the same biological parameters as male *Nephrops*.

6.2.2.4 Fishing mortality

Fishing mortality is assumed to take the form of a length-dependent logistic ogive:

$$S_{l(s,a)} = \frac{1}{1+\exp[-k_S(l-L_{50\%})]} \tag{8}$$

where $L_{50\%}$ is the length at 50% selection and k_s is a measure of the slope of the curve. The function is subscripted by *l(s,a)* to denote length dependence with the length being a function of sex and age class.

The total fishing mortality is written as:

$$F_{s,a} = E_m Q_{s,l(s,a)} S_{l(s,a)} \tag{9}$$

where E_m is a fishing mortality multiplier used in the yield-per-recruit analysis and $Q_{s,l(s,a)}$ is an additional catchability term which allows for sex/maturity-dependent variation in catchability. So far, this has been used to allow for reduced catchability of mature females relative to the other components of the population (Figure 6.2).

$$Q_{s,l(s,a)} = \begin{cases} Q & if\ s = female\ and\ l(s,a) > l_{\text{s,mat}} \\ 1 & otherwise \end{cases} \tag{10}$$

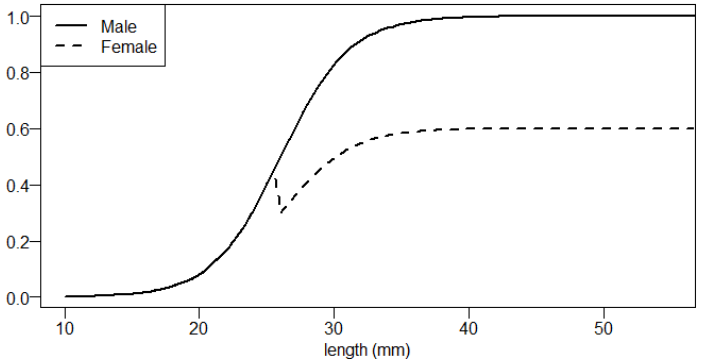

Figure 6.2. Typical selectivity curves for male (solid line) and female (dashed line) *Nephrops*. Note the discontinuity in the female curve which occurs due to reduced availability to the fishery at maturity.

In a similar manner to the biological parameters approach, the length-based approach to modelling female catchability is to use a weighted average between immature and mature values (weighted using the proportion mature at length) to produce a smoother selection ogive.

The discard ogive is assumed to be a reverse logistic ogive:

$$D_{l(s,a)} = \frac{D}{1+\exp[k_D(l-D_{50\%})]} \tag{11}$$

where $D_{50\%}$ is the length at 50% discard selection and k_D is a measure of the slope of the curve. The length-based approach uses a retention ogive (rather than a discard ogive) which is equivalent to $1 - D_{l(s,a)}$. Note that in previous descriptions of the

length-structured model (ICES, 2009b), the ogives (selection and retention) are parameterized in terms of an L_{50} and L_{25} rather than an L_{50} and K, as in the description above (Equation 8). Confusingly, the L_{25} in the earlier description is not actually the length at 25% selection/retention, but the length at $(1+e)^{-1}$%.

There is a generally held view that a proportion of *Nephrops* survive the discarding process (see Section 7.7). The discard ogive, therefore, represents dead discards as a proportion of dead catch (landings and dead discards). Similarly, the retention ogive provides the proportion of the landed dead catch (landings and dead discards).

6.2.2.5 Yield and spawning-stock biomass

Yield and spawning-stock biomass are derived on a sex-specific basis. Per-recruit curves can then either be given as totals or sex specific.

$$Y_s(E_m) = \sum_a \frac{F_{s,a}[1-D_{l(s,a)}]}{Z_{s,a}}(1 - e^{-Z_{s,a-1}\Delta a})N_{s,a}w_{s,a} \quad (12)$$

$$SSB_s(E_m) = \sum_a N_{s,a}w_{s,a}\, pmat_{s,a}\Delta a \quad (13)$$

The harvest rate (HR) can also be calculated as a sex specific or combined rate:

$$HR_s(E_m) = \frac{\sum_a C_{s,a}}{\sum_a N_{s,a}} \quad \text{or}$$

$$HR(E_m) = \frac{\sum_{s,a} C_{s,a}}{\sum_{s,a} N_{s,a}} \quad (14)$$

Given that the estimate of abundance from an UWTV survey is considered to include individuals > 17 mm in length for males and females combined, the harvest rate is calculated in relation to the total number of individuals in the population > 17 mm in length. In the age-based model, this implies summing over age classes for which the mid-length is > 17 mm.

6.3 YPR input parameters

The baseline input parameters to the model (fishery selection, female relative catchability, and discard ogive) are typically derived from a length cohort analysis (LCA) in which males and females are modelled separately and the fishing mortality is assumed to be separable (into a logistic ogive and annual multiplier). The separable LCA uses fishery length frequency data, which have been averaged over a number of years to reduce the effect of varying year-class strength in the application of this model. So far, the model has been used with "dead removals" length frequency data, i.e. ignoring the component of the discards assumed to survive in the calculation of fishing selectivity and discard ogive.

Two different parameter estimation routines have been implemented: (i) separable cohort analysis (SCA) and (ii) separable length cohort analysis (SLCA). Both use a two-stage approach to the parameter estimation, with the discard/retention ogive parameters being estimated in a separate step to the total fishing mortality (selection and relative female catchability). The main difference in the fitting procedure lies with the assumptions about the discard ogive. While the SCA model assumes a maximum discard rate of 100% (i.e. ogive plateau at 1), the SLCA does not and makes an estimate of this maximum value (must be < 1). This latter modelling approach typically gives a better fit to the observed landings and discards-at-length data (due to the

additional parameter). However, in cases where the discard input data are actually derived data (through the application of a previously estimated discard ogive to total catch data), it is probably more sensible to fix this ogive within the model, and then fit to the total catch or landings at length only. There are other minor differences related to the biological models used in the fitting process, with the SCA using smooth transitions between immature and mature female parameters (as in the description of the length-structured model above), while the SLCA uses a step function.

SCA also has the option to include an estimate of abundance (UWTV survey) in the likelihood function (in addition to the catch-at-length data) with a manual weighting term. The equilibrium assumptions in SCA mean that the estimated population numbers are not directly comparable to the UWTV abundance, which is a point estimate and, therefore, this term is typically given only very low weighting in the likelihood. Even with higher weighting, the impact on the estimated selection and relative catchability parameters (the inputs required for the per-recruit analysis) is small.

Model fitting is carried out in R using the optim function with the "L-BFGS – B" fitting method (a quasi-Newton method which allows parameters to be constrained by lower and/or upper bounds).

The biological parameters (related to maturity, natural mortality, growth, and weight) required for the analysis are typically functional-unit-dependent and known with varying degrees of confidence. Parameter values for each functional unit are provided in the stock annex of benchmark workshop or assessment working group reports.

6.4 Deriving reference points

Both yield-per-recruit (YPR) and spawning-stock-biomass-per-recruit (SPR) reference points can be calculated for either males, females, or the combined stock in terms of a fishing mortality multiplier (resulting in mean F values) and an overall harvest rate. $F_{0.1}$, F_{max}, and $F_{35\%SPR}$ are considered as potential F_{MSY} proxy reference points. Figure 6.3 shows the per-recruit curves and potential F_{MSY} proxy reference points for *Nephrops* in FU 8 (Firth of Forth). Table 6.1 gives values for these reference points, the implied harvest rates, and resulting SPR. Note that for a given fishing mortality multiplier, the implied mean F values for males and females can be quite different (typically higher for males) due to the difference in the relative catchability of male and female *Nephrops.* Fishing a stock at F_{max} or $F_{35\%SPR}$ for females would, therefore, result in the male component of the population being fished well above the male F_{max} or $F_{35\%SPR}$.

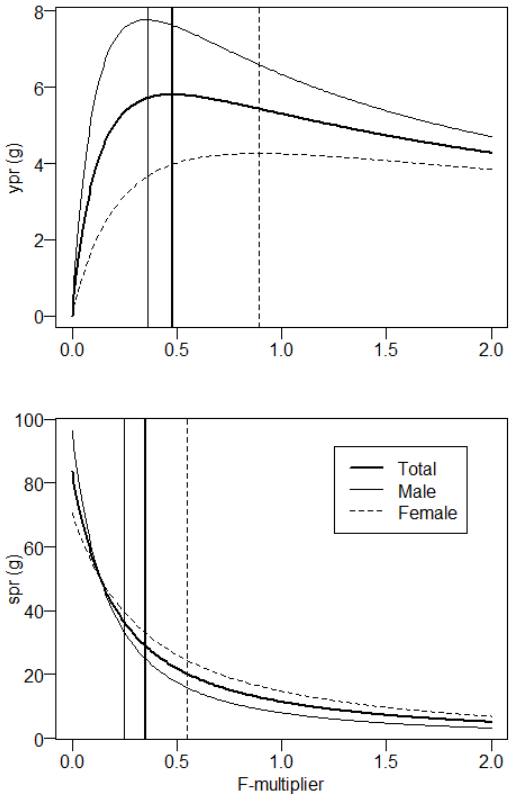

Figure 6.3. YPR and SPR curves for FU 8 *Nephrops* using fishery input parameters derived from an SLCA fitted to landings and discards length frequency data averaged over 2008–2010. Curves are shown for males, females, and the combined stock together with *F*-multipliers for the respective F_{max} (upper plot) and $F_{35\%SPR}$ (lower plot) reference points.

Table 6.1. Firth of Forth *Nephrops* (FU 8). F_{MSY} proxy harvest rates and associated fishing mortality and spawning-stock biomass per recruit as % of virgin (SPR). The *F*-multiplier value corresponds to the parameter E_m described earlier. Shaded values are those used as the F_{MSY} proxy for this FU.

F-value		*F*bar (20–40 mm)			HR (%)	SPR (%)		
		F-multiplier	*M*	*F*		M	F	T
$F_{0.1}$	M	0.2	0.14	0.06	7.7	40.8	62.3	49.9
	F	0.45	0.31	0.13	15.2	20.5	40.7	29.0
	T	0.25	0.17	0.07	9.4	34.6	56.6	43.9
F_{max}	M	0.36	0.25	0.11	12.7	25.3	46.8	34.4
	F	0.94	0.64	0.28	26.7	9.1	22.9	14.9
	T	0.49	0.34	0.14	16.3	18.8	38.5	27.1
$F_{35\%SpR}$	M	0.25	0.17	0.07	9.4	34.6	56.6	43.9
	F	0.57	0.39	0.17	18.3	16.0	34.5	23.9
	T	0.36	0.25	0.11	12.7	25.3	46.8	34.4

The appropriate F_{MSY} proxy has been selected for each functional unit independently, according to the perception of stock resilience, factors affecting recruitment, population density, knowledge of biological parameters, and the nature of the fishery (sporadic/new/stable). More conservative F_{MSY} proxies have been chosen for stocks with perceived low resilience or limited fishery/biological information. A decision-making

framework for the choice of F_{MSY} proxy reference point has been developed (ICES, 2013).

6.5 Sensitivity analysis

The Workshop on Implementing the ICES F_{MSY} framework (WKFRAME; ICES, 2010b), in their guidance on deriving F_{MSY} proxies for stocks without a full analytical assessment, suggested that "there should be a sensitivity analysis to the input parameters for the per-recruit analysis (natural mortality, growth parameters, length–weight relationships, selection pattern)."

There are a number of different approaches to the sensitivity analysis. The first uses fixed biological parameters, but derives the fishery parameters required for the per-recruit analysis by repeated fits of the SLCA to landings and discards-at-length data averaged over a moving three-year window. This approach provides an indication of the stability of the estimated reference points over time. Figure 6.4 compares the estimates of harvest rates equivalent to F_{max}, $F_{35\%SPR}$, and $F_{0.1}$ (combined sexes) over time for two FUs in the Celtic Seas ecoregion. The estimates for FU 12 are relatively stable over time (particularly for $F_{35\%SPR}$, which is used as the F_{MSY} proxy for this functional unit), although there is some suggestion of a reduction in recent years. The time-series of estimates for FU 16 shows much greater variability in all three of the reference points. In FU 16, there are known to have been significant changes in stock size (recruitment) and the fishery over time resulting in quite variable fishery parameter estimates from the SLCA over time (although with parameter estimates still within reasonable bounds) and hence highly variable per-recruit reference points. Note that $F_{0.1}$ for FU 16 is very low due to the high estimate of length at 50% selection in the fishery. For both functional units, the time-series become smoother if a five-year window is used to average the landings and discard length frequency data as a single year's data becomes less influential, and conversely, noisier if only a two-year window is used.

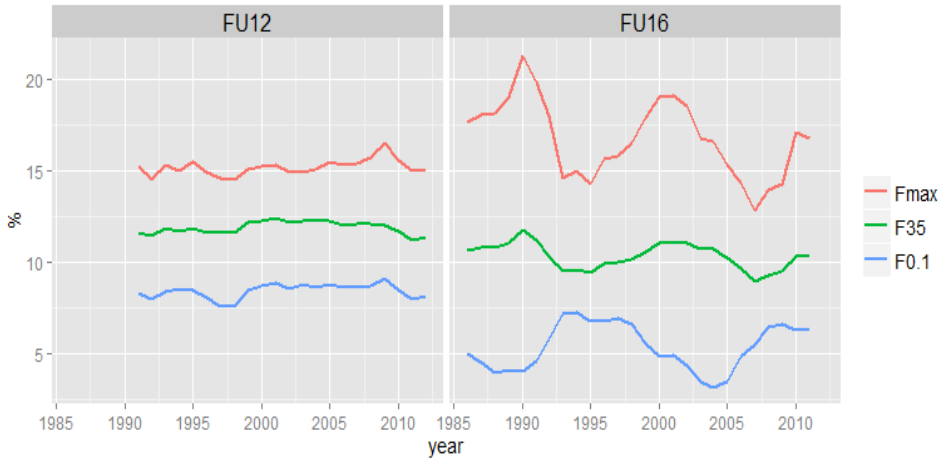

Figure 6.4. Variability of estimated per-recruit (combined sex) harvest rates over time for FU 12 (South Minch) and FU 16 (Porcupine Bank) for three F_{MSY} proxies. The SLCA uses a three-year moving average of landings and discard length frequency data, and the results are plotted against the first year of the three-year period.

Given that many of the input biological parameters are derived from a limited number of scientific studies, it is also considered appropriate to investigate the sensitivity of the MSY harvest rates to these parameters. This is carried out by systematically

varying the biological parameters in turn, then recalculating the per-recruit reference points assuming fixed fishery input parameters to the per-recruit analysis. The analysis presented is for FU 11 (North Minch) and the baseline input biological parameters for this functional unit are in Table 6.2. Note that the parameters are varied individually in this analysis (although for males and females at the same time), while in reality some (particularly estimates of von Bertalanffy parameters) are often highly correlated. The von Bertalanffy parameters (L_∞ and K), natural mortality (M), and length at maturity (L_{mat}) are varied from 75 to 125% of their baseline values (in equal steps), while discard survival is varied from 0 to 125% of its baseline value. Male and female parameters are varied by the same proportion in each model run.

Table 6.2. Baseline biological input parameters for FU 11.

Parameter	Male/immature female	Mature female
L_∞ (von Bertalanffy)	70	60
K (von Bertalanffy)	0.16	0.06
M (natural mortality)	0.3	0.2
L_{mat} (length at maturity)	27	22

Changing the natural mortality parameter (M) has the biggest impact on all three of the potential F_{MSY} harvest rates (Figure 6.5). At higher levels of M, the virgin SPR is lower and declines more gradually with increasing F (Figure 6.6). The $F_{35\%SPR}$, therefore, occurs at a higher F-multiplier, resulting in a higher harvest rate. Similarly, for YPR, the maximum is achieved by fishing at a higher rate when M is higher. For higher values of M, the maximum YPR consists of higher numbers of smaller individuals than for lower values of M; hence, a higher harvest rate at F_{max} in stocks with higher natural mortality. The impact on the harvest rate at $F_{0.1}$ is smaller with an increase from ~ 6.5 to 8.5% over the range of natural mortalities investigated.

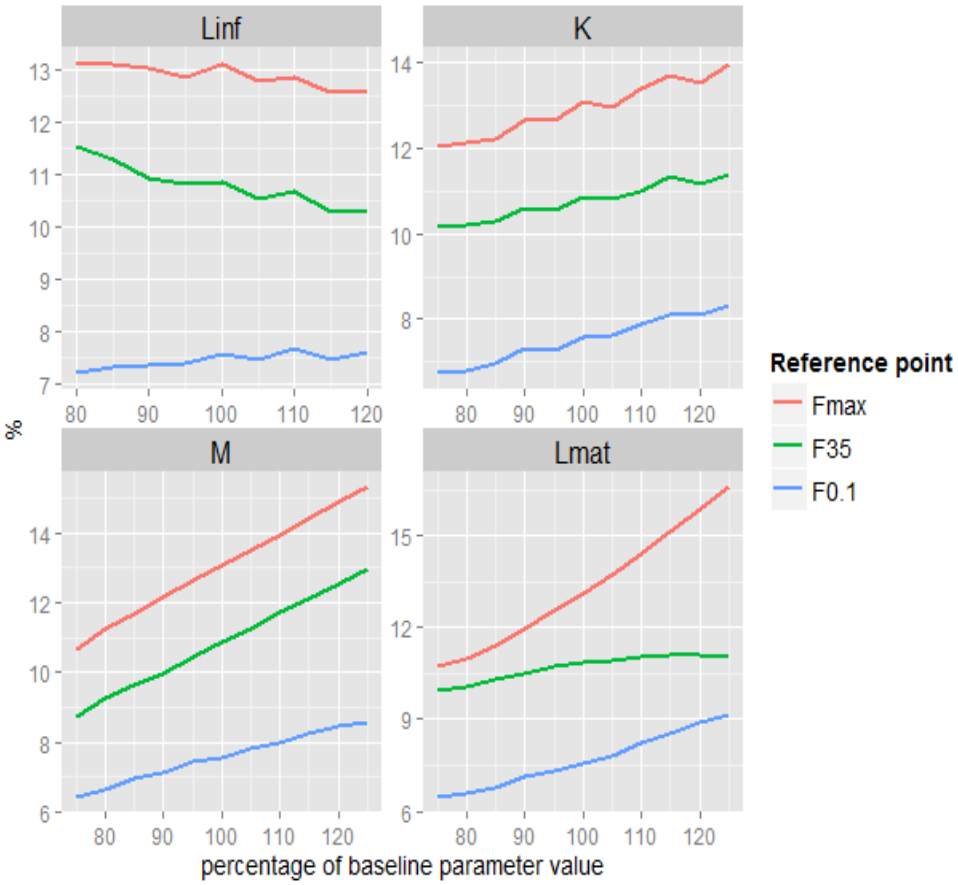

Figure 6.5. Variability of estimated per-recruit (combined sex) harvest rates resulting from repeated per-recruit analysis for FU 11 (North Minch) with varying biological input parameters for three F_{MSY} proxies. The fishery input parameters are fixed in all scenarios at the values estimated with baseline biological parameters from SLCA using fishery input data averaged over 2009–2011.

At higher values of L_∞, the mean size at age is greater for all ages; therefore, younger individuals are more available to the fishery (have a higher F). In addition, fishing at a lower rate contributes more to yield as it allows more individuals to survive and grow to larger sizes (and with higher L_∞, this is much higher). The maximum YPR is achieved at a lower F-multiplier with fewer but larger individuals contributing to the yield. Higher K results in a larger size at younger ages (i.e. faster growth), but no difference in maximum size, which implies a higher fishing mortality for the same F-multiplier.

Note that, the relationships between the estimated per-recruit harvest rates and input biological parameters are in general not smooth. This is due the use of both discrete F-multipliers in the calculation of the F reference point (increments of 0.005) and discrete age/length classes when calculating the population numbers > 17 mm in length, and the catch, for use in Equation (14) (harvest rate).

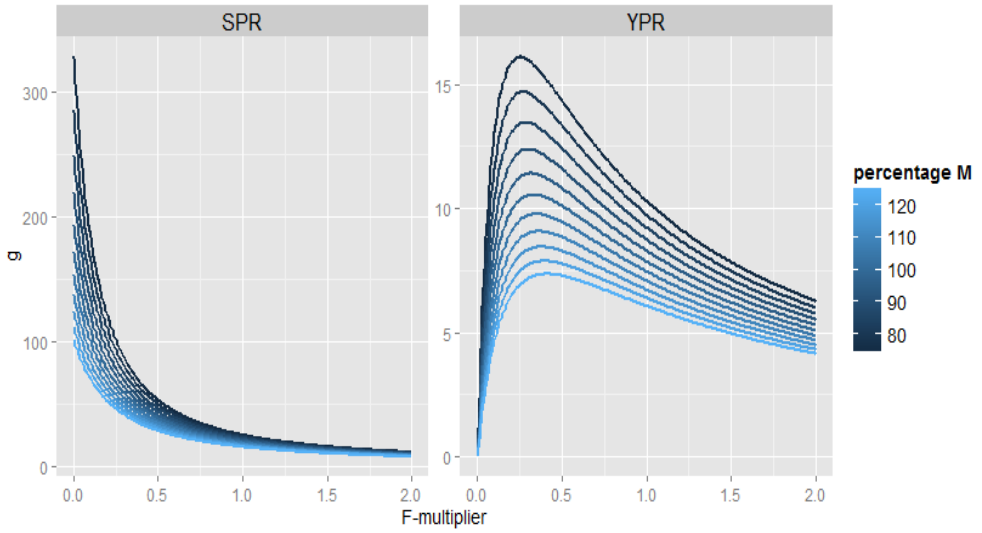

Figure 6.6. Variability in per-recruit curves (combined sex) resulting from varying the natural mortality parameter for FU 11 (North Minch) with all other input parameters fixed.

A similar analysis has been conducted in which the fishery parameters which are used as input to the per-recruit analysis are systematically varied in turn over a range of values. The analysis is again carried out for FU 11 and the baseline input parameters as estimated in the SLCA are shown in Table 6.3.

Table 6.3. Baseline fishery input parameters for FU 11.

Parameter	Estimated value (SLCA 2009–2011)
L_{50}	28.8 mm
K_{Sel}	0.33
Fem$Q$	0.41
Disc.K	0.62
Disc.L_{50}	26.6 mm
Disc.mult	0.56

A higher length at 50% selection results in a lower estimate of harvest rate as the yield is made up of fewer but larger individuals. There is a marked decline in the estimated MSY harvest rates over the range of L_{50} values explored. However, in reality, this parameter appears to be, in general, well estimated by the SLCA and, for most functional unitss, shows little variability over time. In contrast, the estimated harvest rates are relatively stable with varying K_{Sel} except when the selection curve is very shallow which results in a higher harvest rate (Figure 6.7).

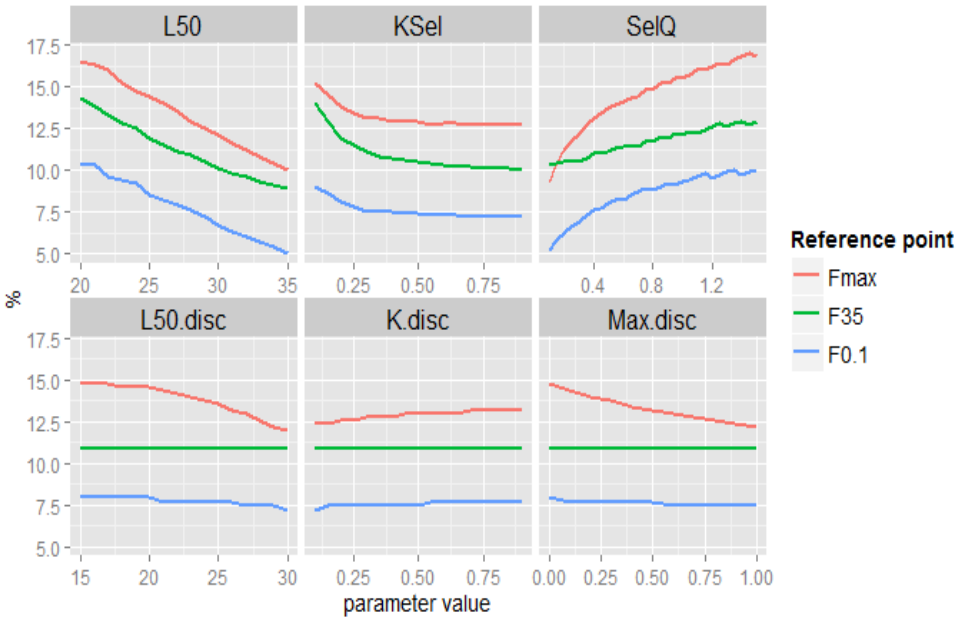

Figure 6.7. Sensitivity of estimated per-recruit (combined sex) harvest rates for FU 11 (North Minch) when individual fishery input parameters are systematically varied (with other parameters held constant).

6.6 Provision of advice

The current approach to providing catch advice follows the general method outlined in Section 6.1. The product of the agreed MSY harvest rate (as described above) and the estimated absolute abundance from the UWTV survey gives the total number of removals (R) under the MSY approach. Total removals are then partitioned into landings and discards based on recent discard rates and translated into landed and discarded weights by applying mean weights derived from recent data.

The following equations are used to provide advice on catch options (each quantity in terms of weight) when discarding occurs:

$$Landings = R \times (1 - ddr) \times \overline{w_{land}} \quad (15)$$

$$Dead\ discards = R \times ddr \times \overline{w_{disc}} \quad (16)$$

$$Surviving\ discards = \frac{Dead\ discards}{(1-sd)/sd} \quad (17)$$

where R is the total number of removals, ddr is the dead discard proportion (dead discards as a fraction of dead removals), $\overline{w_{land}}$ is the mean individual weight in the landings, $\overline{w_{disc}}$ is the mean individual weight in the discards, and sd is the discard survival (Table 6.4).

When discards are assumed to be zero, catch options are derived from:

$$Wanted\ catch = R \times (1 - dr) \times \overline{w_{land}} \quad (18)$$

$$Unwanted\ catch = R \times dr \times \overline{w_{disc}} \quad (19)$$

where *dr* is total discard rate. "Wanted" and "unwanted" catch are the terms adopted by ICES to describe the components of the catch that would be landed or discarded (respectively) in the absence of the EU landing obligation.

The dead discard rate is calculated from the total discard rate and discard survival as follows:

$$ddr = \frac{(1-sd)\times dr}{1-sd\times dr} \quad (20)$$

Table 6.4. Name, abbreviation, and description of variables used to provide catch options when discarding occurs.

Variable name	Abbreviation	Description
Total number of removals	R	Derived as the product of the abundance and harvest rate.
Mean weight in landings	$\overline{w_{land}}$	Derived from sampling data. Either a short-term (three years) or long-term average.
Mean weight in discards	$\overline{w_{disc}}$	Derived from sampling data. Either a short-term (three years) or long-term average.
Total discard proportion	dr	Derived from sampling data. Usually short-term (three years) average. Total number discarded as a proportion of total catch in number.
Dead discard proportion	ddr	Derived from sampling data. Calculated from total discard proportion and an assumption of discard survival (sd)
Discard survival	sd	FU dependent assumption (see Section 6.7). Proportion by number of discarded individuals which survival the discarding process.

When catch options are based on survey estimates, additional uncertainties related to mean weight in the landings, discard rates, and discard survival also arise. The variability in mean weight and discarding is a key uncertainty in the derivation of catch options. The procedure outlined in the benchmarks (ICES, 2009, 2013a) is to use a multiannual average to dampen variability.

6.7 Discard survival

The immediate survival rate of discarded *Nephrops* is highly variable and depends on a number of factors, including the amount of damage incurred during capture and post-capture handling, air temperature, and the level of predation by seabirds, fish, and other marine predators during their return to the seabed. The type of ground to which the *Nephrops* are returned will affect their long term survival, as *Nephrops* have specific sediment requirements for the construction of burrows. The probability of being returned to a suitable habitat will, therefore, depend upon the fishery practice and the spatial structure of the particular grounds.

Trawl discard survival estimates range from 20–40% in Scottish waters (Wileman *et al.*, 1999) to 45–65% in the Bay of Biscay (Méhault *et al.*, 2011), while a recent study in the Clyde using a short tow duration (catching for the live market) obtained much higher survival rates of ca. 80% (Albalat *et al.*, 2015). Across most functional units, tow durations are relatively lengthy with high catch volumes; this results in pro-

longed sorting on deck and, hence, discard survival rates are considered to be relatively low.

The process of sorting catch differs between fisheries. Catches may be sorted while steaming between tows and hence *Nephrops* may be discarded onto unsuitable habitat. In this situation, *Nephrops* are unlikely to find a suitable refuge and are at a much higher risk of predation mortality (Harris and Ulmestrand, 2004). Discards on large homogeneous grounds like Fladen (FU 7) are more likely to have a higher survival rate than when discarding on patchier grounds like Devil's Hole (FU 34) or Botney Gut (FU 5). Understanding and experience of the individual fisheries are therefore used in combination with the estimates from the published studies to derive FU-specific discard survival rates.

Discard survival of creel-caught *Nephrops* is much higher than that of trawl-caught *Nephrops*. Studies conducted in northern European waters (Chapman, 1981; Harris and Ulmestrand, 2004) suggest that with good post-capture handling, the immediate discard mortality of creel-caught *Nephrops* could be almost zero. In creel fisheries, the catch is sorted during the creel-hauling process and discarded *Nephrops* are returned to the same location where caught, therefore increasing the chances of survival. On this basis, a 100% creel-discard survival rate is used for *Nephrops* in Division 6.a.

7 UWTV surveys as ecosystem surveys

Annika Clements

Although UWTV surveys only target established *Nephrops* grounds, they offer the potential to (a) provide data to assess the condition of such grounds, e.g. detection of trawl marks, and (b) provide data on co-occurring benthic species. Currently, surveys routinely record the presence of trawl marks and sea pen species (*Virgularia mirabilis*, *Pennatula phosphorea*, and *Funiculina quadrangularis*) for each minute of video footage analysed for burrow counts. ICES UWTV surveys have routinely recorded sea pen species since 2012, following a special request from OSPAR in 2011. Other species (including additional conspicuous burrow-forming species, epibenthic sessile species, and fish) are also noted but often in an inconsistent manner due to the focus on *Nephrops* burrow system counting and limited resources to review footage for additional species.

UWTV survey data have been considered by the Scottish Government (Allan *et al*., 2012) and Joint Nature Conservation Committee (JNCC, 2014) as an aid in identifying suitable habitats for potential designation as marine protected areas (MPAs) in Scotland or marine conservation zones (MCZs) in UK offshore waters. In particular, the identification of "sea pen and burrowing megafauna communities", which are on the OSPAR list of threatened and/or declining species and habitats, has made use of UWTV data[1].

Specifically, for the purposes of JNCCs assessments, "all stations recording a mean *Nephrops* burrow system density ≥ 0.2 burrows m^{-2} have been accepted as demonstrating the presence of sea pen and burrowing megafauna communities" (JNCC, 2014). Reference is also made to the presence of sea pen species determined from UWTV survey data, as reported in Allan *et al*. (2012), and the challenges of assessing abundance from existing UWTV data.

In an analysis of habitat evidence to identify alternative MCZ sites for "subtidal mud" habitats and component sea pen and burrowing megafauna communities in the Irish Sea (Clements, 2016), the JNCC-recommended threshold of *Nephrops* burrow system density (≥ 0.2 burrows m^{-2}) was applied to historical FU 15 UWTV data and all records of sea pens were extracted (from survey notes and database entries) as shown in Figure 7.1 and 7.2.

[1] OSPAR definition of "Sea-pens and burrowing megafauna" habitat: "Plains of fine mud, at water depths ranging from 15-200m or more, which are heavily bioturbated by burrowing megafauna with burrows and mounds typically forming a prominent feature of the sediment surface. The habitat may include conspicuous populations of sea-pens, typically Virgularia mirabilis and Pennatula phosphorea. The burrowing crustaceans present may include Nephrops norvegicus, Calocaris macandreae or Callianassa subterranea. In the deeper fiordic lochs which are protected by an entrance sill, the tall seapen Funiculina quadrangularis may also be present."

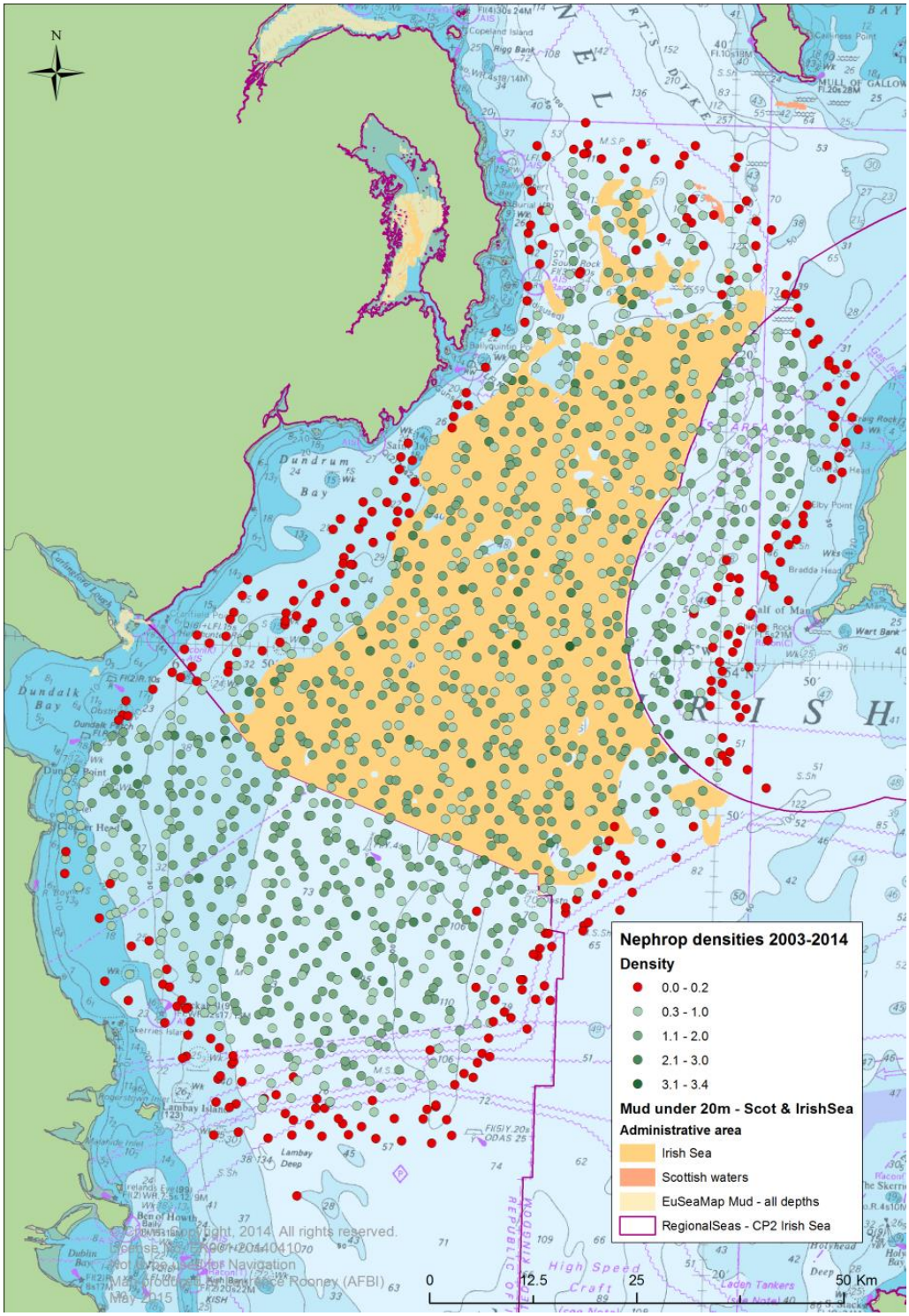

Figure 7.1. Potential "subtidal mud" including burrowing megafauna communities defined over FU 15 UWTV survey area using the *Nephrops* burrow system density ≥ 0.2 burrows m^{-2} threshold as recommended by JNCC (2014). Map produced by Lawrence Rooney (AFBI) © Crown copyright 2014.

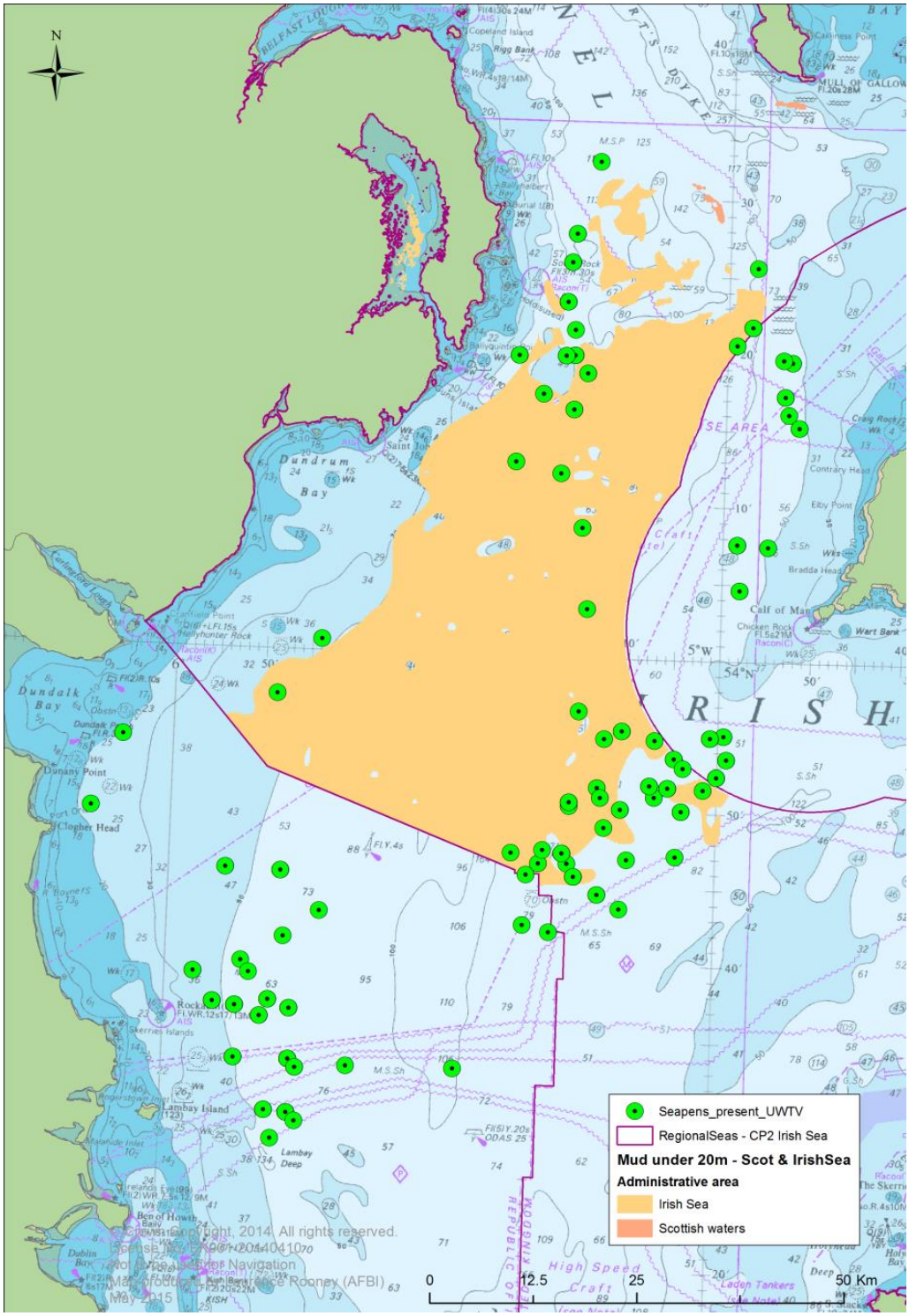

Figure 7.2. Sea pen distribution extracted from FU 15 UWTV records (2003–2014). Map produced by Lawrence Rooney (AFBI) © Crown copyright 2014.

There is the potential to derive semi-quantitative and fully quantitative abundance data for conspicuous epibenthic species and marine litter from UWTV footage. This may have a variety of applications for ecosystem assessments as well as the development and testing of potential condition indicators (e.g. for EU Marine Strategy Framework Directive) where these could be focused over *Nephrops* habitat. However, these data are not routinely collected or reported during UWTV surveys due to limited resources.

Many institutes collect CTD data routinely on UWTV sledges, which also provides a useful resource for oceanographic studies.

8 References

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9 List of acronyms

CCC: Lin's concordance correlation coefficient

CTD: Conductivity, temperature, and depth. A CTD device's primary function is to detect how the conductivity and temperature of the water column changes relative to depth.

HR: harvest rate

LCA: length cohort analysis

MCZ: marine conservation zone

MPA: marine protected area

SGNEPS: ICES Study Group on *Nephrops* Surveys

QC: quality control

SCA: separable cohort analysis

SLCA: separable length cohort analysis

STECF: Scientific, Technical and Economic Committee for Fisheries, European Commission

USBL: Ultra-short baseline

UWTV: Underwater television

VMS: vessel monitoring system

VPA: virtual population analysis

WKFRAME: ICES Workshop on Implementing the ICES FMSY framework

WGNEPS: ICES Working Group on *Nephrops* Surveys

YPR: yield-per-recruit

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