WORKSHOP ON METHODOLOGIES FOR *NEPHROPS* REFERENCE POINTS (WKNEPHROPS; OUTPUTS FROM 2019 MEETING)

VOLUME 2 | ISSUE 3

ICES SCIENTIFIC REPORTS

RAPPORTS SCIENTIFIQUES DU CIEM

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ISSN number: 2618-1371 I © 2020 International Council for the Exploration of the Sea

ICES Scientific Reports

Volume 2 | Issue 3

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Recommended format for purpose of citation:

ICES. 2020. Workshop on Methodologies for *Nephrops* Reference Points (WKNephrops; outputs from 2019 meeting).
ICES Scientific Reports. 2:3. 106 pp. http://doi.org/10.17895/ices.pub.5981

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i Executive summary

The main objective of WKNephrops was to review reference points for a range of *Nephrops* stocks taking account of updated methods and new data (including discard survival rates). While good progress was made in terms of documenting and testing current methodologies for estimating reference points, for the most part further work is need before new reference points can be proposed and agreed.

The current approach for basing advice for fishing opportunities for Category 1 *Nephrops* stocks where on UWTV surveys and F_{MSY} harvest rates derived from per-recruit proxies based on either $F_{0.1}$, $F_{35\%}$ or F_{max} (dependent on the perceived stock productivity and apparent vulnerability to overfishing) has been in place since 2009. An evaluation and review of this approach is timely, particularly since issues have arisen for some stocks where the SCA population estimates differs substantially from the UWTV surveys. These differences in population estimates can be as much as an order of magnitude and this appears to be an issue of scaling rather than estimation error. Currently, there does not appear to be a sound explanation of why the two approaches differ so markedly. Work carried out at the meeting on some *Nephrops* FUs using the SCA approach in a semi-dynamic way suggested that the population signal in the survey was reflected in the catch data, this offers some reassurance that an integrated modelling approach with the surveys as a relative index may be appropriate.

Re-estimation of reference points was carried out for a number of *Nephrops* stocks and this showed that for most stocks there was little change in reference points over time, whereas for others there have been larger variations. The group did not recommend revising any reference points at this stage until further work has been carried out. For the Bay of Biscay stock (FU23–24) the group recommended that the discard survival rate should be revised and a 50% value should be used in future assessments and advice.

Another current issue is that new studies on discard survival raise concern about the discard survival assumptions used in the ICES assessments and advice. This is an issue of importance for advice users since as it affects the way the fisheries are managed, and there is a perception that differences in assumed and actual survival rates could lead to inaccurate ICES advice. A sensitivity analysis was carried out for several stocks at WKNephrops. It appeared that F_{MSY} proxies based $F_{0.1}$ and $F_{35\%}$ were relatively insensitive to the discard survival rate and that F_{MAX} was more sensitive to discard survival rates. Discard survival will affect the shape of the yield per recruit curve, and may influence the estimates of F_{MSY} and $F_{0.1}$ differently. Further work is required to understand the exact mechanisms. For fisheries where discards account for a very low percentage of the catch and $F_{0.1}$ or $F_{35\%}$ are used as the F_{MSY} proxy, discard survival is not likely to be important. Conversely, for stocks where F_{MAX} is used as the F_{MSY} proxy and which have a high discard percentage F_{MSY} may need to be re-estimated using the best available estimate of discard survival.

For stocks that have limited length frequency data and little or no UWTV surveys, the working group is considering a range of DLS methods that rely more heavily on life-history theory in the absence of data on stock abundance. These include length-based indicators, methods based on spawning potential ratio (SPR) and surplus production models such as SPiCT (Pedersen and Berg, 2016). These are established methods within ICES and it is appropriate to investigate their utility for *Nephrops*. As much of the analysis was being performed at the meeting it was not possible to draw any general conclusions. In one stock investigated, a variety of such data-limited methods gave different estimates of stock status which at face value indicates that reference

points are model-sensitive which means that choosing one approach may not be sufficiently robust for management purposes. It was important and useful to see such differences, as model uncertainty is typically under-estimated in ICES assessments.

There is still much work to do in relation to the assessment and derivation of reference points on *Nephrops* stocks. The move toward dynamic length-based models integrating the UWTV surveys is desirable and may help address the reference point issue. A number of integrated models of this type are already available and include, Stock Synthesis, CASAL, LIME and Gadget. While some work is ongoing on some of these models, a co-ordinated work plan setting out a systematic approach to the development, testing and application of the methods might be beneficial in the medium term. Where data-limited methods are being examined there may be value in testing these on data-rich stocks to gain an understanding of their performance where stock status is better understood so that the choice of method to apply is well informed.

ii Expert group information

Expert group name	Workshop on Methodologies for *Nephrops* Reference Points (WKNephrops)
Expert group cycle	Annual
Year cycle started	2019
Reporting year in cycle	1/1
Chair	Michael Bell, UK
Meeting venue and dates	25–29 November 2019, Lisbon, Portugal (12 participants)

1 Introduction

1.1 Terms of Reference

The Workshop on Methodologies for *Nephrops* Reference Points (WKNephrops), chaired by Michael Bell*, UK and attended by one Invited Expert, Robin Cook, UK, will be established and will meet in Lisbon, Portugal 25–29 November, 2019 to evaluate reference point estimation methods for stocks with UWTV surveys.

The workshop will work to:

a) Review the methodology and performance of the current approaches to estimating reference points for Category 1 *Nephrops* stocks.
b) Based on a) develop a standard method and apply this method to estimate reference points (MSY, ranges, precautionary and limit) for fishing pressure and stock size for all *Nephrops* stocks which have sufficient data.
c) Evaluate the utility of other modelling frameworks to assess and provide reference points for *Nephrops* stocks (e.g. length-based models, VPA type models and production models).
d) For *Nephrops* stocks which are more data-limited, propose a consistent methodology to determine stock status and provide catch advice taking into account available data and knowledge from other areas.
e) In cases where transitioning from PA advice to MSY advice results in significant changes in the advice consider the need for a gradual approach by means of a Harvest Control Rule.

WKNephrops will report by 31 December 2019 for the attention of the Advisory Committee.

1.2 Background

Sound methods that reliably produce high-quality reference point estimates for *Nephrops* in the ICES area are needed given the outcomes of recent benchmarks (e.g. WKNEP, ICES, 2016). ICES delivers advice for 29 *Nephrops* stocks using a range of data-rich and data-limited methodologies which are generally bespoke to *Nephrops* issues. *Nephrops* fisheries themselves have a high commercial value; some stocks have strong mixed-fishery interactions and therefore reliable science and advice is of paramount importance.

The current ICES method for assessing and providing catch advice based on UWTV surveys has been in place since 2009 (ICES, 2009). A review is timely for a number of reasons:

- New studies on discard survival raise concern about the discard survival assumptions used in the ICES assessments and advice.
- The number of Cat 1 stocks and the time-series of their dynamics has increased since 2019.
- The length-based yield per recruit methods have developed since 2009.
- When reviewing the data and methods for three stocks proposed to be Category 1, WKNEP 2016 had an issue in reconciling some of the data and methods for generating reference points. The proposed MSY reference points suggested that fishing could dramatically increase despite some histories of fishery reduction and concern over stock status. The benchmark recommended a workshop be convened to explore these issues and

to derive appropriate HCRs for transitioning between data-limited and data-rich categories.

1.3 Conduct of the meeting

The list of participants and agenda for the workshop are presented in Annex 1 and Annex 2, respectively. The various presentations given by the participants are available on SharePoint. As noted by the reviewer in Section 6, there was limited work completed in advance of the meeting although there was significant progress during and after the meeting. Further work will be needed before new reference points can be proposed and fully reviewed for the most part. The ACOM leadership assisted in compiling the final meeting report.

2 Stock-by-stock review of reference points

We present here a summary table of all the *Nephrops* Functional Units (Figure 2.1) with their reference points and assessment methods (Table 2.1). After this, the specific work done during WKNephrops on each FU is presented more in detail.

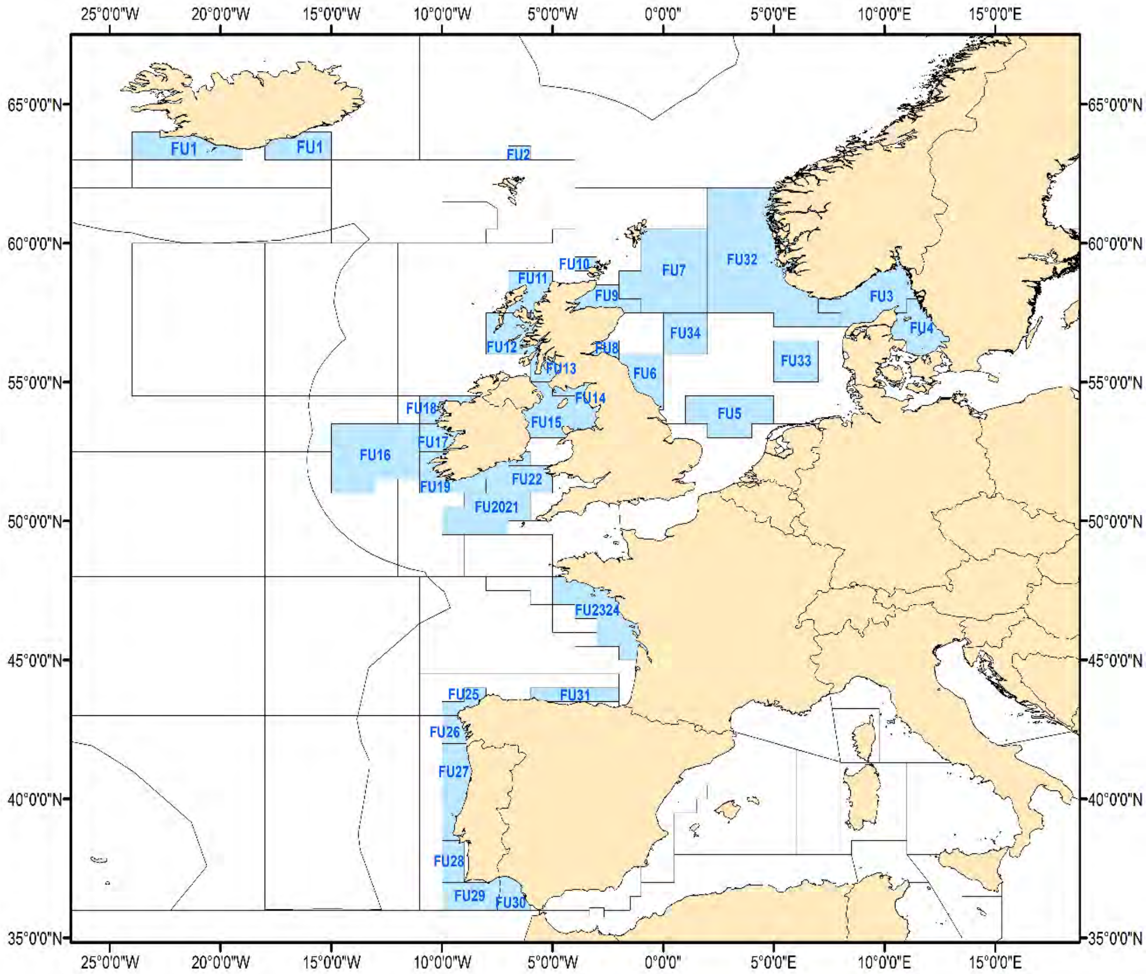


Figure 2.1. ***Nephrops*** **Functional Units map.**

Table 2.1. Reference points summary table for *Nephrops* Functional Units.

FU	Category	Reference points								Advice in 2019	Assessment type	References
		MSY-$B_{trigger}$	Basis	F_{MSY}	Basis	F_{lower}	Basis	F_{upper}	Basis			
FU3–4	1	Not defined		7.9%	Harvest ratio F_{max} sexes combined, proxy based on SCA	5.6%	5% reduction in yield compared with F_{MSY} proxy	7.9%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: WGNSSK ICES (2011) Assessment: WGNSSK ICES (2019)
FU6	1	858 million	Lowest observed UWTV abundance	8.12%	$F_{35\%SPR}$ males, proxy based on SCA	7.0%	5% reduction in yield compared with F_{MSY} proxy	8.12%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: WGNSSK ICES (2010) Assessment: WGNSSK ICES (2019)
FU7	1	2767 million	Lowest observed UWTV abundance (1992-2010)	7.5%	Harvest ratio $F_{0.1}$ sexes combined, proxy based on SCA	6.6%	5% reduction in yield compared with F_{MSY} proxy	7.5%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: WGNSSK ICES (2010); WGNSSK ICES (2015) Assessment: WGNSSK ICES (2019)
FU8	1	292 million	Lowest observed UWTV abundance (1993–2010)	16.3%	Harvest ratio F_{max} sexes combined, proxy based on SCA	10.6%	5% reduction in yield compared with F_{MSY} proxy	16.3%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: WGNSSK ICES (2010); WGNSSK ICES (2012) Assessment: WGNSSK ICES (2019)

FU	Category	Reference points								Advice in 2019	Assessment type	References
		MSY-$B_{trigger}$	Basis	F_{MSY}	Basis	F_{lower}	Basis	F_{upper}	Basis			
FU9	1	262 million	Lowest observed UWTV abundance (1993–2010)	11.8%	Harvest ratio $F_{35\%SPR}$ sexes combined, proxy based on SCA	9.1%	5% reduction in yield compared with F_{MSY} proxy	11.8%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: WGNSSK ICES (2010); WGNSSK ICES (2012) Assessment: WGNSSK ICES (2019)
FU10	4	Not defined		Not defined		Not defined		Not defined		ICES precautionary approach: advice for 2016 + 20%	Data-limited method for *Nephrops*	Assessment: WGNSSK ICES (2018)
FU11	1	540 million	Lowest observed UWTV abundance	10.8%	Harvest ratio $F_{35\%SPR}$ sexes combined, proxy based on SCA	8.4%	5% reduction in yield compared with F_{MSY} proxy	10.8%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: EU request on F_{MSY} ranges ICES (2016) Assessment: WGCSE ICES (2019)
FU12	1	1020 million	Lowest observed UWTV abundance (1995-2010)	11.7%	Harvest ratio $F_{35\%SPR}$ sexes combined, proxy based on SCA	9.3%	5% reduction in yield compared with F_{MSY} proxy	11.7%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: EU request on F_{MSY} ranges ICES (2016) Assessment: WGCSE ICES (2019)

FU	Category	Reference points								Advice in 2019	Assessment type	References
		MSY-$B_{trigger}$	Basis	F_{MSY}	Basis	F_{lower}	Basis	F_{upper}	Basis			
FU13	1	580 million (Firth of Clyde) 160 million (Sound of Jura)	Lowest observed UWTV abundance (Firth of Clyde) Lowest observed UWTV abundance (Sound of Jura)	15.1% (Firth of Clyde) 12.0% (Sound of Jura)	Harvest ratio F_{max} sexes combined, proxy based on SCA Harvest ratio $F_{35\%SPR}$ sexes combined, proxy based on SCA	9.9% (Firth of Clyde) 9.4% (Sound of Jura)	5% reduction in yield compared with F_{MSY} proxy	15.1% (Firth of Clyde) 12.0% (Sound of Jura)	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: EU request on F_{MSY} ranges ICES (2016) Assessment: WGCSE ICES (2019)
FU14	1	350 million	Lowest observed UWTV abundance	11.0%	Harvest ratio $F_{0.1}$ sexes combined, proxy based on SCA	9.1%	5% reduction in yield compared with F_{MSY} proxy	11.0%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: EU request on F_{MSY} ranges ICES (2016) Assessment: WGCSE ICES (2019)
FU15	1	3 billion	Minimum abundance observed based on a scaled trawl survey index	18.2%	Harvest ratio F_{Max} sexes combined, proxy based on SCA	12.4%	5% reduction in yield compared with F_{MSY} proxy	18.2%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	Ref. points: EU request on F_{MSY} ranges ICES (2016) Assessment: WGCSE ICES (2019)
FU16	1	Not defined		6.2%	Harvest ratio $F_{0.1}$ sexes combined, proxy based on SCA	5.0%	5% reduction in yield compared with F_{MSY} proxy	6.2%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	WGCSE ICES (2019)

FU	Category	Reference points								Advice in 2019	Assessment type	References
		MSY-$B_{trigger}$	Basis	F_{MSY}	Basis	F_{lower}	Basis	F_{upper}	Basis			
FU17	1	540 million	2008 UWTV abundance	8.5%	Harvest ratio $F_{0.1}$ sexes combined, proxy based on SCA	7.4%	5% reduction in yield compared with F_{MSY} proxy	8.5%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	WGCSE ICES (2019)
FU19	1	430 million	5% interval on the probability distribution of abundance for the time-series 2011–2015, assuming a normal distribution	9.3%	Harvest ratio $F_{0.1}$ sexes combined, proxy based on SCA	8.3%	5% reduction in yield compared with F_{MSY} proxy	9.3%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	WGCSE ICES (2019)
FU2021	1	Not defined		6.0%	Harvest ratio $F_{0.1}$ sexes combined, proxy based on SCA	5.9%	5% reduction in yield compared with F_{MSY} proxy	6.0%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	WGCSE ICES (2019)
FU22	1	900 million	5% interval on the probability distribution of abundance for the time-series 2006–2015, assuming a normal distribution.	12.8%	$F_{35\%SPR}$ for combined sexes, proxy based on SCA	10.2%	5% reduction in yield compared with F_{MSY} proxy	12.8%	F_{MSY} proxy as upper bound	F range from EU multiannual plan	UWTV survey linked to length-based SCA	WGCSE ICES (2019)
FU23–24	1	Not defined		7.7%	F_{MSY} based on the average realized harvest rates of functional units with an observed history of sustainable exploitation, while also taking into account the low harvest rates applied to the FUs 23–24 stock in the recent past	Not defined		Not defined		MSY approach	UWTV survey	WKNEP; ICES (2017)

FU	Category	Reference points								Advice in 2019	Assessment type	References
		MSY-$B_{trigger}$	Basis	F_{MSY}	Basis	F_{lower}	Basis	F_{upper}	Basis			
FU25	3	Not defined		0.17	$F_{0.1}$ average across sexes, proxy based on length-based yield per recruit analysis linked to mean length-based estimators (Z)	Not defined		Not defined		ICES precautionary approach: zero TAC advice	Trends from commercial CPUE	Ref. points: WKProxy ICES (2016) Assessment: WGBIE ICES (2019)
FU26–27	3	Not defined		0.16	$F_{0.1}$ average across sexes, proxy based on length-based yield per recruit analysis linked to mean length method	Not defined		Not defined		ICES precautionary approach: zero TAC advice	Trends from commercial CPUE	Ref. points: WGBIE ICES (2019) Assessment: WGBIE ICES (2019)
FU28–29	3	Not defined		0.23 males 0.24 females	$F_{0.1}$, proxy based on length-based yield per recruit analysis linked to mean length method	Not defined		Not defined		ICES precautionary approach: advice 2019 x index ratio from standardized commercial CPUE	Trends from standardized commercial CPUE	Ref. points: WGBIE ICES (2017) Assessment: WGBIE ICES (2019)
FU30	3	Not defined		Not defined		Not defined		Not defined		ICES precautionary approach: advice 2019 x index ratio from UWTV, uncertainty cap applied	UWTV survey	Assessment: WGBIE ICES (2019)
FU31	3	Not defined		0.28 males 0.47 females	$F_{0.1}$, proxy based on length-based yield per recruit analysis linked to mean length-based estimators (Z)	Not defined		Not defined		ICES precautionary approach: zero TAC advice	Trends from commercial CPUE	Ref. points: WKProxy ICES (2016) Assessment: WGBIE ICES (2019)

FU	Category	Reference points								Advice in 2019	Assessment type	References
		MSY-$B_{trigger}$	Basis	F_{MSY}	Basis	F_{lower}	Basis	F_{upper}	Basis			
FU32	4	Not defined		Not defined		Not defined		Not defined		ICES precautionary approach: advice for 2018 and 2019 + 20%	Data-limited method for *Nephrops*	Assessment: WGNSSK ICES (2019)
FU33	4	Not defined		Not defined		Not defined		Not defined		ICES precautionary approach: advice for 2016 + 20%	Data-limited method for *Nephrops*	Assessment: WGNSSK ICES (2019)
FU34	4	Not defined		Not defined		Not defined		Not defined		ICES precautionary approach: advice for 2016 + 20%	Data-limited method for *Nephrops*	Assessment: WGNSSK ICES (2019)

2.1 Performance and methods for reference points estimation

2.1.1 Variation in F_{MSY} estimates over time for stock around Scotland

The opportunity was taken to explore whether there had been major changes in the reference points for FUs 7–9 and 11–13 since they were last calculated (ICES, 2012; ICES, 2015a,b & c). The same approach has been taken here as used at WKMSYREF in 2015 which derived the current reference points for FUs 11–13:

i. the separable length cohort analysis (SLCA) is applied to a three year rolling average catch length composition data assuming that the catch corresponds to dead removals with 25% discard survival over the full time-series of available data;
ii. for the purposes of the yield-per-recruit analysis, yield corresponds to landings;
iii. ‘annual’ F_{MSY} values are estimated (based on each SLCA & subsequent per-recruit analysis) with F_{MSY} lower defined as the F (below F_{MSY} resulting in 95% of the yield-per recruit at F_{MSY};
iv. an average of the last five F_{MSY} estimates is used for comparison to current ICES F_{MSY} values.

All analysis was conducted in R using the *nepref* package (v 0.2.2).

Note that unlike FUs 11–13, the current ICES agreed reference points for FUs 7–9 are not the result of a five value averaging process.

FUs 9, 11 and 12 show little variation in estimates over time (Figure 2.1.1), and although FU 7 shows quite substantial variation, the average of the most recent five estimates is very similar to the currently used ICES value of F_{MSY}. FUs 8 and 13 also show some variability over time with a trend in recent years resulting in the five year average being somewhat different to the current ICES estimates (lower in FU8 and higher in FU13).

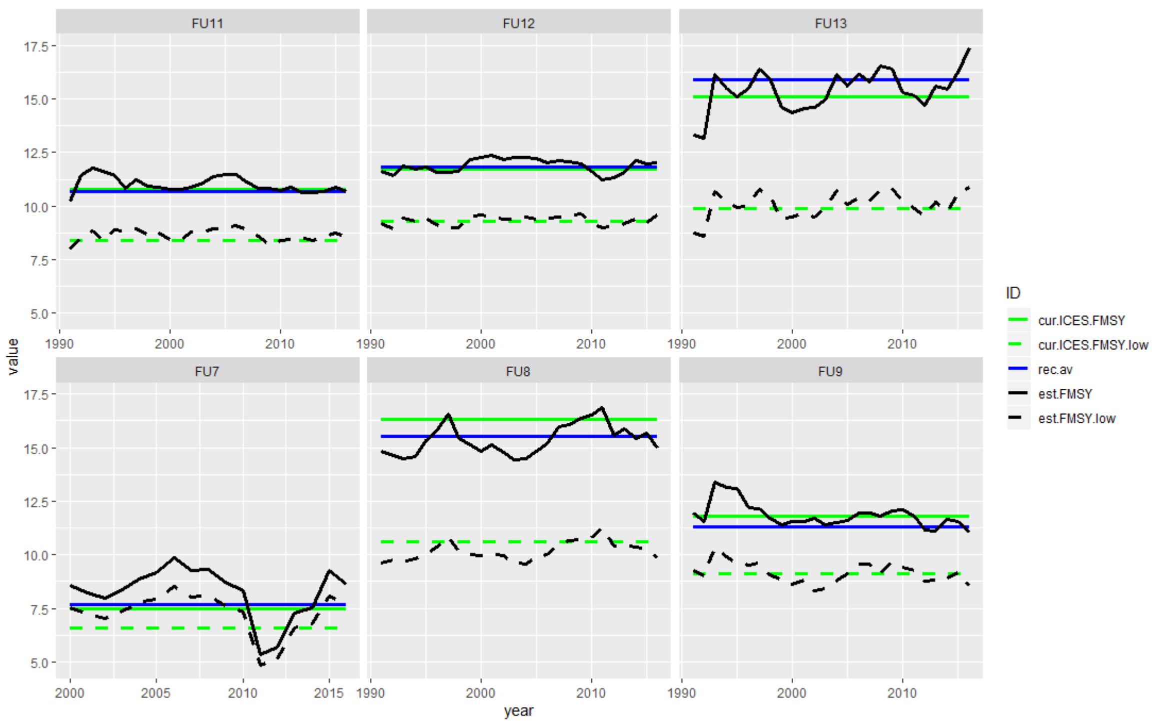


Figure 2.1.1. Comparison of current ICES F_{MSY} harvest rate (green) with F_{MSY} estimates derived from SLCA over time (black). Blue represents average of most recent five F_{MSY} estimates. Dashed lines represent $F_{MSY\ lower}$.

2.1.2 Sensitivity to discard survival assumptions for stocks around Scotland

Some limited exploration of the sensitivity of the estimated reference point to the discard survival assumption was carried out. A single three-year average of catch-at-length data (2016–2018) from FU 8 was used in the analysis. FU 8 was chosen, as one of the few Scottish FUs with a significant proportion of discards. The SLCA and subsequent per-recruit analysis were carried out over a range of discard survival assumptions (0 to 1 in increments of 0.1). The resulting estimates of the per-recruit reference points are shown in Figure 2.1.2.

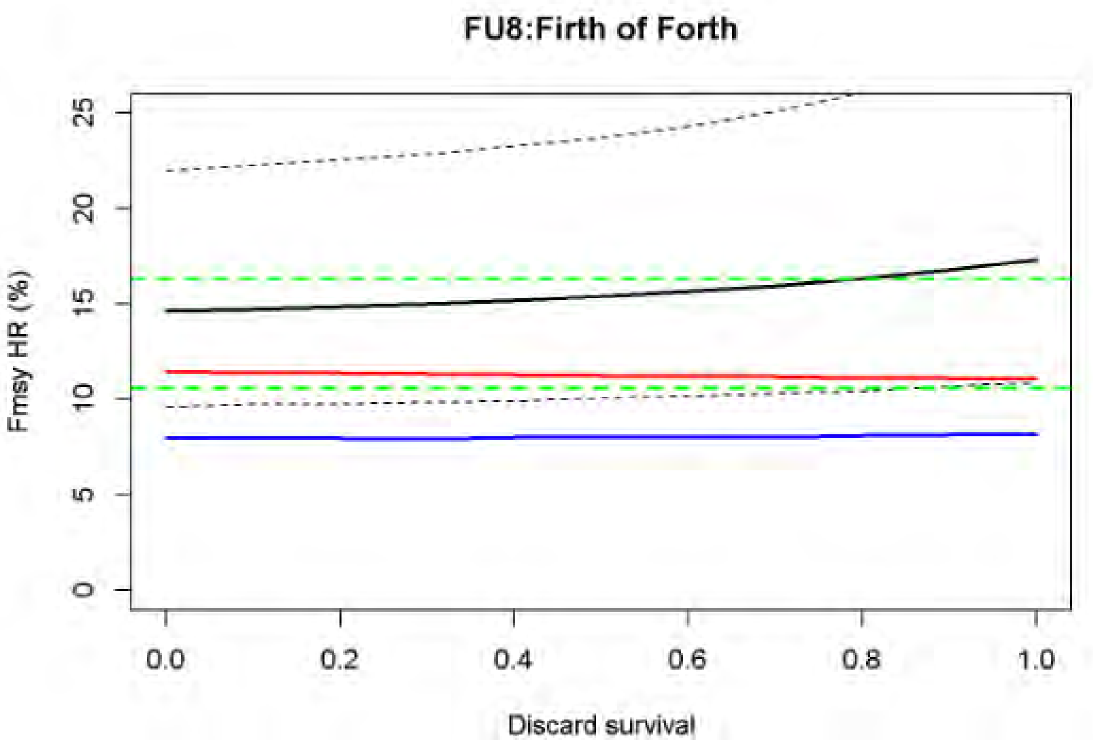


Figure 2.1.2. FU 8: Firth of Forth. Variability of estimated F_{MSY} harvest rate with discard survival (F_{max} = solid black line). Lower black dashed line: HR at 95% max YPR (at F_{MSY}). Upper black dashed line: HR at 95% maxYPR (above F_{max}). Green: current values of F_{MSY} and F_{MSY_lower}; Red: F35%; Blue: $F_{0.1}$.

For FU 8, increasing the discard survival results in an increase in the estimate of F_{max} (used as the F_{MSY} proxy for this stock), a small decline in $F_{35\%}$ and virtually no change in the $F_{0.1}$ estimate (which typically tends to be a much less sensitive reference point). This also appeared to be the general pattern for other FUs considered at the meeting.

The relationship between discard survival and estimated reference points is complex. The SLCA is currently applied to a three-year average of dead catch-at-length, so changes in the discard survival assumption will have an effect on the estimated fishery selectivity/mortality parameters and the estimated dead discard ogive. These parameter estimates are likely to be sensitive to the size range of discards compared to landings, their sex composition and the overall magnitude of discards. Although the expectation would be for a higher estimated fishery selectivity L_{50} and steeper ogive at higher discard survival, given the noise in the landings and discards length composition data and the likely correlation between parameter estimates this may not always be the case. For some FUs only a single estimated parameter may be influenced by the change is discard survival assumption, but in others the estimate of multiple parameters may be affected. These changes have most impact on the selectivity/mortality of individuals at smaller sizes and it is within these sizes (ages) that maturity occurs. Mature females have lower natural mortality and growth than immature individuals and the size at maturity relative to fishery selectivity impacts the estimated values of reference points. The particular biological characteristics of *Nephrops* therefore add to the difficulty in interpreting the impact of changing the discard survival assumption.

The $F_{0.1}$ reference point typically tends to be a more stable reference point than F_{max}. For FU 8 the change in $F_{0.1}$ over the range of assumed discard survival is almost imperceptible. However, given that the changes are so small, it may be that any systematic effect is not clearly distinguishable due to model discretisation error. This may also be the case for estimates of $F_{35\%}$ where there is little overall change in estimated fishery selectivity. It may be worth exploring the sensitivity further using a finer discretisation of age classes in the length-dependent YPR and/or finer increments in the F range used for estimating the reference points.

Further work is clearly required to better understand the processes contributing to the observed relationship between estimated reference points and discard survival assumption. The sensitivity would be best explored for FUs with high discard rates as in stocks with a low discard rate, the impact of different assumptions about survivability is likely to be lost in the error introduced by the numerical discretisation process. It may be worth simplifying any additional analysis such that it is conducted in two stages: i) sensitivity of SLCA estimated parameters to discard survival assumption and ii) a more thorough sensitivity analysis of the per-recruit analysis with systematic variation of input parameters (potentially initially on a single sex basis for simplicity). Furthermore, alternative approaches to modelling the fishery selection and discard process may also be useful and may make interpreting the results more straightforward.

2.1.3 Recalculation of reference points for stocks around Ireland

F_{MSY} reference points had been previously calculated for FU16, FU17, FU19, FU22 (ICES, 2015) and FU2021 (ICES, 2016) using Dobby's Separable Length Cohort Analysis (SLCA). In order to use the most updated data available, WKNephrops decided to recalculate these reference points. The new data available include length frequency data raised to international landings from 2012 to 2018 for all the Functional Units. The inclusion of the most recent years into the analysis increases the quality of the assessment, especially for FU2021, whose previous F_{MSY} reference points calculations used only two years of length frequency data.

The same methodology as in ICES, 2015 was followed, using SLCA to calculate F_{MSY} reference points with length frequency data of three years' periods, and then averaging the latest five periods (2012–2014, 2013–2015, 2014–2016, 2015–2017 and 2016–2018). The life-history parameters used as inputs for the model were the same as in previous calculations and the same rationale F_{MSY} were considered appropriate for the new F_{MSY} proxy reference points (Table 2.1.1). R (version 3.6.1, 64-bit), RStudio (version 1.1.463) and Dobby's *nepref* R package (version 0.2.2) were used in this process. Full code and input files are available at WKNephrops 2019 SharePoint.

Table 2.1.1. Life-history parameters, current F_{MSY} reference points and new proposed F_{MSY} reference points for each Functional Unit.

	FU16	FU17	FU19	FU2021	FU22
Life-history parameters					
VBGF: L_∞ Mal	75	60	68	68	68
VBGF: L_∞ Fem	60	56	49	49	49
VBGF: K Mal	0.14	0.16	0.17	0.17	0.17
VBGF: K Fem	0.1	0.08	0.1	0.1	0.1
Weight–length: a Mal	0.00009	0.000322	0.000322	0.000322	0.000322
Weight–length: b Mal	3.55	3.207	3.207	3.207	3.207
Weight–length: a Fem	0.00009	0.000684	0.000684	0.000684	0.000684
Weight–length: b Fem	3.55	2.963	2.963	2.963	2.963
Nat. Mortality Mal	0.3	0.3	0.3	0.3	0.3
Nat. Mortality Fem	0.2	0.2	0.2	0.2	0.2
Mat. Ogive 25 Fem	29	22	24	22	22
Mat. Ogive 50 Fem	29	23	24	22	22
Mat. Ogive 25 Mal	29	22	24	22	22
Mat. Ogive 50 Mal	29	23	24	22	22
F_{MSY} reference points					
Rationale F_{MSY}	$F_{0.1}$ combined sexes	$F_{0.1}$ combined sexes	$F_{0.1}$ combined sexes	$F_{0.1}$ combined sexes	$F_{35\%\ SPR}$ combined sexes
Current F_{MSY}	6.2%	8.5%	9.3%	6.0%	12.8%
Current $F_{MSY\ lower}$	5.0%	7.4%	8.3%	5.9%	10.2%
Re-estimated F_{MSY}	4.9%	8.1%	7.0%	6.5%	12.1%
Re-estimated $F_{MSY\ lower}$	4.4%	7.1%	6.0%	5.7%	8.8%

2.1.4 Sensitivity analysis: Discard survival rate for stocks around Ireland

The discard survival rate used in FU17, FU19, FU2021 and FU22 is currently set at 0.25. However, a recent study in FU17 suggests that this survival rate could be set at 0.64 (BIM, 2017). In order to quantify the effect of different discard survival rates on the calculation of reference points, WKNephrops decided to carry out a sensitivity analysis by running the SCLA model for different discard survival rates. Here we present the results of this analysis for FU16, FU17, FU19, FU2021 and FU22. Note that discards are assumed to be negligible for FU16 stock assessment.

The effect of the change on discard survival rates varies between the different rationales analysed (Figure 2.1.3). For $F_{0.1}$, $F_{0.1\ lower}$ and $F_{35\%}$ higher survival rates give slightly lower harvest rates or have no effect. For $F_{35\%\ lower}$, F_{max} and $F_{max\ lower}$ higher survival rates give slightly higher harvest rates or have no effect. For $F_{0.1\ upper}$, $F_{35\%\ upper}$ and $F_{max\ upper}$ higher survival rates give higher harvest rates.

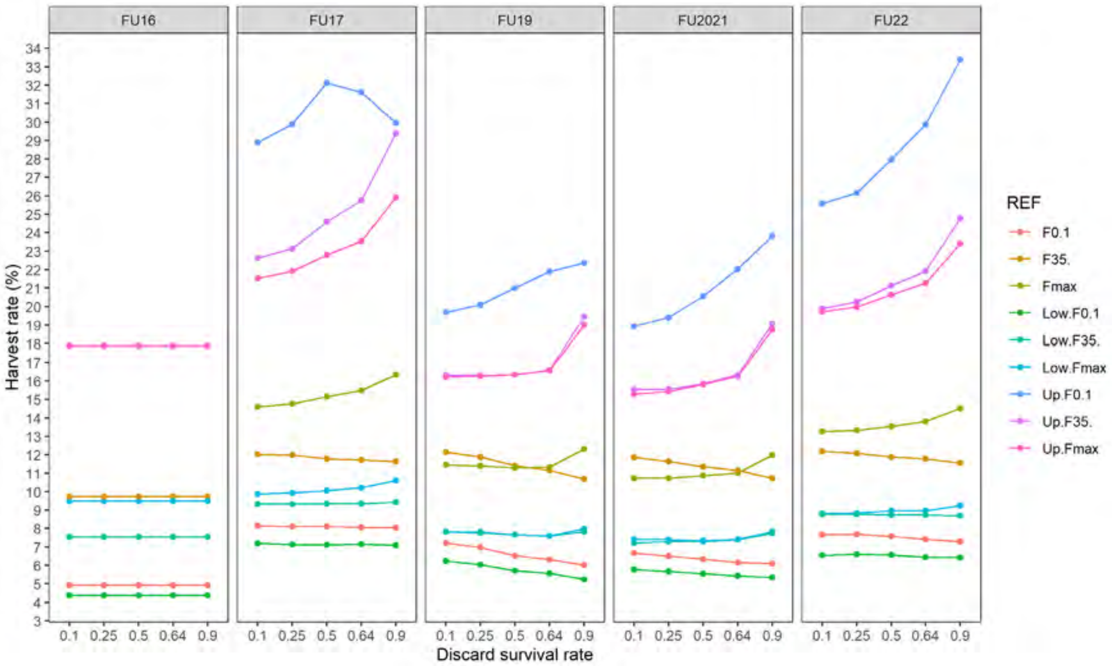


Figure 2.1.3. Sensitivity analysis for different discard survival rates and their effect on the proposed harvest rates for each Functional Unit. Coloured lines refer to different rationales. Note that discards are assumed to be negligible for FU16 stock assessment.

However, the differences on the final harvest rates between using 0.25 or 0.64 as discard survival rates are minimum for the rationales currently used (Table 2.1.3). Therefore, WKNephrops decided not to update the currently used discard survival rate of 0.25.

Table 2.1.2. Sensitivity analysis for 0.25 and 0.64 discard survival rates and their effect on F_{MSY} and $F_{MSY\ lower}$ for each Functional Unit.

	FU16		FU17		FU19		FU2021		FU22	
Rationale F_{MSY}	$F_{0.1}$		$F_{0.1}$		$F_{0.1}$		$F_{0.1}$		$F_{35\%\ SPR}$	
Discard survival rate	0.25	0.64	0.25	0.64	0.25	0.64	0.25	0.64	0.25	0.64
F_{MSY}	4.9	4.9	8.1	8.1	7.0	6.3	6.5	6.2	12.1	11.8
$F_{MSY\ lower}$	4.4	4.4	7.1	7.2	6.0	5.6	5.7	5.4	8.8	8.7

2.1.5 Re-estimation of F_{MSY} for Bay of Biscay FU23–24

Stock summary

In the Bay of Biscay, *Nephrops* grounds correspond to muddy areas: the first one, which is the largest one, is in Division 8.a and is called “la grande vasière”, the second one in Division 8.b is called “vasière de la Gironde” (Bourillet *et al.*, 2006; Dubrulle *et al.*, 2005). The overall area extends for 11 676 km² of surface if only the typical muddy strata are taken into account whereas more recent studies from 2016 onwards (standardized UWTV surveys since the benchmark workshop in 2016) suggest to incorporate in the whole area some rough sea grounds crossed by muddy channels and also included in the external outline of the Central Mud Bank (surface increasing up to 16 164 km²).

The stock is almost exclusively exploited by French trawlers whereas the creel targeting fishery remains minor. The major part of vessels come from the Southern Brittany (districts of Le Guilvinec, Lorient, Concarneau) harvesting around ²/₃ of the total catches in the Northern part of the central mud bank. The Breton fleet is *Nephrops* directed depending a lot on the species during the whole year whereas vessels outside Brittany are more multi-purpose. Landings generally fluctuated in the range 3000–4000 t per year with a recent peak of 4200 t in the middle of 2010s and a minimum level of 2125 t in 2018 corresponding to the lowest value throughout the historical time-series.

Discards represent most of the catches of the smallest individuals. The average weight of discards per year in the period up to early 2000s (not routinely sampled) is about 1551 t whereas discard estimates of the recent sampled years (2003–2018) reached a higher level of 2018 t. This change in the amount of discards could be due to the restriction of individual quotas, the strength of some recruitments in the middle of 2000s and the change in the MLS (which tends to increase the discards), although improvements in the selectivity pattern should tend to reduce the discards. The relative contribution of each of these three factors remains unknown. In 2018, 152 million individuals were estimated to have been discarded (1627 t) and the discard rate moved upwards (65% against 55% in 2016 and 58% in 2017).

For many years the advice was biennial. The stock was classified under category 3 and only trends of the yearly assessment were taken into account for the advice. The UWTV survey routinely carried out since 2014 was validated as standard assessment method by the 2016 benchmark workshop (WKNEP). As consequence of that, the advice became yearly and the stock was categorised in group 1. Nevertheless, no biological reference points are known for the stock. It was considered appropriate to convene a study group to propose methods for deriving advice from direct absolute measurements of stock abundance, in general and for *Nephrops* measured by UWTV surveys in particular.

DataBiological parameters

Table 2.1.3 sums up the main input biological parameters at the aim of obtaining the stock reference points. As consequence, a preliminary exemption to the landing obligation for the *Nephrops* fishery due to high survival was granted for the period 2016–2018.

Table 2.1.3. *Nephrops* in FUs 23–24 Bay of Biscay (8.a,b). Input data and parameters.

INPUT PARAMETERS		
Parameter	Value	Source
Discard Survival	0.30	Gueguen and Charuau, 1975; Charuau et al., 1982
	0.50	Mérillet et al., 2018
MALES		
Growth - K	0.140	after Conan and Morizur, 1979 ; plus unpublished data
Growth - L(inf)	76	"
Natural mortality - M	0.3	Morizur, 1982
Size at maturity (knife-edged)	26.3 mm CL	unpublished data (WKNEPH 2006)
Length/weight - a	0.00039	Conan, 1978
Length/weight - b	3.180	"
FEMALES		
Immature Growth		
Growth - K	0.140	after Conan and Morizur, 1979 ;Verdois et al., 2001
Growth - L(inf)	76	"
Natural mortality - M	0.3	Morizur, 1982
Size at maturity	22.43 mm females	
	26.32 mm males	
Mature Growth		
Growth - K	0.110	after Conan and Morizur, 1979 ;Verdois et al., 2001
Growth - L(inf)	56	"
Natural mortality - M	0.2	based on Morizur, 1982 ; assuming lower rate for mature females
Length/weight - a	0.00081	Conan, 1978
Length/weight - b	2.970	"

Discard Survival rates

The main change throughout the recent time-series involves in the survival rate of discarded *Nephrops*. It is currently suggested that the historical value of 30% based on experiments undertaken during 1970s (Charuau *et al.*, 1982) will be replaced by a higher one of 50% (Mérillet *et al.*, 2018) mainly after the quick evacuation system on deck for discarded individuals became compulsory (1st January 2017). As consequence, a preliminary exemption to the landing obligation for the *Nephrops* fishery due to high survival was granted for the period 2016–2018. Table 2.1.4 provides the updated information by season and for the whole year.

Table 2.1.4. *Nephrops* in FUs 23–24 Bay of Biscay (8.a,b). Survival rates (%) and their 95% confidence intervals [square brackets] at the end of the 14-days monitoring period for the two sorting scenarios and control (in Mérillet *et al.*, 2018).

Survival rates (%) and their 95% confidence intervals [in square brackets] at the end of the 14 days monitoring period for the two sorting scenarios and control.

Season	Standard scenario	Discarding chute scenario	Control
Spring	35.4 [15.3; 55.5]	42.3 [26.6; 57.9]	86.3
Summer	36.4 [30.3; 42.5]	56.5 [49.3; 63.7]	61.8
Autumn	39.2 [17.5; 60.9]	54.9 [31.5; 78.3]	69.5
Global	36.9 [20.9; 52.9]	51.2 [30.9; 71.5]	69.3 [45.7; 93.0]

UWTV survey results

During the WGBIE (May 2019, Lisbon) and WGNEPS (November 2019, Split) meetings, UWTV survey's 2014–2019 (named LANGOLF-TV) collected data as well as investigations for the stock assessment and advice were presented. The survey has been conducted owing to European funding project (named FEAMP) for partnership between scientists and fishery industry. In the beginning of the time-series, the survey was planned in various periods within year (late September 2014, late July 2015) due to constraints of the schedule time for the Irish vessel and equipment hired for the cruise. From 2016 onwards, the survey period is fixed in late April/early May. The choice of the survey season does not affect the output information consisting in counted burrows independent from the *Nephrops* availability maximised during spring and summer. Nevertheless, it may impact assessment and advice scheme: as the latest deadline for the annual advice is fixed in the middle of the autumn, the survey has to be carried out during spring/early summer. Table 2.1.5 summarizes information from the UWTV survey for the period 2014–2019 (*In bold=input information for the SCA model projections*).

Table 2.1.5. *Nephrops* in FUs 23-24 Bay of Biscay (8.a,b). Information from the UWTV surveys 2014–2019.

Year of survey	Number of stations		Historical area			Benchmarked area		
	Historical area[1]	Benchmarked area[2]	Nb burrows (10^9)	Nb/m²	CV (%)	Nb burrows (10^9)	Nb/m²	CV (%)
2014	156	-	4.165	0.357	5.82	-	-	-
2015	96	-	3.631	0.311	8.25	-	-	-
2016	160	196	3.633	0.311	7.86	4.167	0.258	7.84
2017[3]	94	124	2.850	0.244	9.85	3.373	0.209	9.87
2018[4]	148	184	3.365	0.288	8.44	3.788	0.234	8.30
2019[5]	116	145	3.560	0.305	8.59	**4.113**	0.254	8.34

LFDs for landings and discards

French sampling plan at auction started in 1984, but only from 1987 onwards the data can be used on quarterly basis. Since 2003, additional database of landings was also provided by sampling routinely performed on board under the European DCF aiming for discard estimates. As the landed fraction of *Nephrops* is usually size graded the sampling plan is time and commercial category vs. size stratified.

Discard data by sampling on board are available for 1987, 1991, 1998, and from 2003. Since 2003, discards have been estimated from sampling catch programmes on board *Nephrops* trawlers (646 trips and 1787 hauls have been sampled over 16 years). The total number of trips usually not well known in the past is more accurately provided for the recent years and can be reliably used as raising factor for discards. Nevertheless, the number of trips mostly represented by the number of sales at auction is heterogeneous as in the northern part of the Bay of Biscay the boats conduct daily trips whereas in the southern part trips last 2–3 days with a more multi-purpose profile of catches. Averaged data from years 2016–2018 are input for the SCA model projections (Table 2.1.6; Figure 2.1.4).

[1] Historical area covered by the former trawl survey LANGOLF (years 2006-2013). Surface=11 677 km².

[2] Benchmarked area validated by the benchmark workshop 2016 which upgraded the NEP23–24 stock (category 3 to 1). This area included the historical one (see above) and added a supplementary stratum (rough sea bottom). Surface=16 164 km².

[3] In 2017, ≈28 000 km² of total surface were investigated accordingly to WGNEPS 2016 recommendations aiming to accurately define the actual edge of the stock polygon.

[4] In 2018, ≈13.6% of additional area were covered although only 0.7% of supplementary burrows were found (215 total stations; among them 184 in the benchmarked area).

[5] In 2019, ≈5.8% of additional area were covered corresponding to 3.5% of supplementary burrows (152 total stations; among them 145 in the benchmarked area).

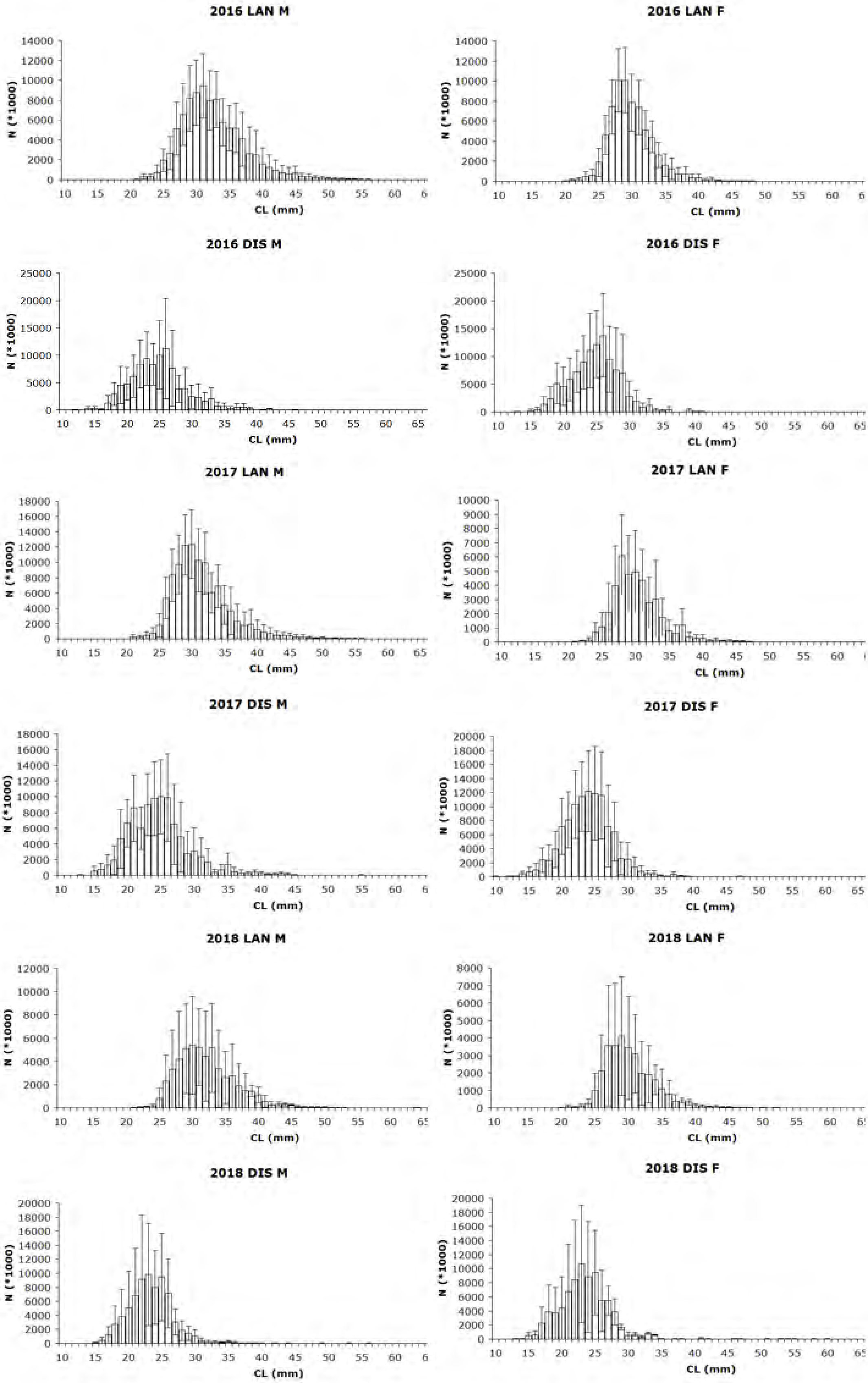


Figure 2.1.4. NEP2324. LFDs for landings and discards by sex. Years 2016–2018.

Table 2.1.6. *Nephrops* in FUs 23–24 Bay of Biscay (8.a,b). Information for LFDs of landings and discards by sex. Years 2016–2018.

Year	Males				females			
	LAN		DIS		LAN		DIS	
	number(10^6)	CV(%)	number(10^6)	CV(%)	number(10^6)	CV(%)	number(10^6)	CV(%)
2016	92.932	13.46	95.467	25.20	68.439	13.90	105.506	24.97
2017	103.990	18.78	95.219	25.52	39.512	24.15	105.381	19.36
2018	53.186	12.92	72.779	19.80	30.278	15.05	79.564	20.28

The Separable Cohort Analysis (SCA- model performed by Ewen Bell, Cefas), used for calculating MSY reference points for category 1 *Nephrops* stocks and two different discard survival estimates was explored (see settings in Table 2.1.7).

Table 2.1.7. *Nephrops* in FUs 23–24 Bay of Biscay (8.a,b). Settings for the SCA model.

LFDs (three years average)	2016–2018
TV abundance (10^3 individuals) (last year's survey)	2019
Discard survival	30% (Charuau *et al.*, 1982) 50% (Mérillet *et al.*, 2018)
Surv.time	0.416667
TV.sel	16.5–17
Alpha (high weight or low weight for UWTV)	0.2/0.00001
f.range	c(0, 0.01, seq(0.05, 4, 0.05))
discard.weight	c(1)
initial.parameters (s-shaped Selection)	c(8.,22., 1.2,0.4,0.3)
initial.parameters (domed Selection)	c(8.,22.,1.2,0.4,0.3,1.1,1.1,0.5)

Results

Eight different runs were carried out considering the number of individuals of the population from the 2019s UWTV survey (4113 millions of burrows; Table 2.1.5) with high or weak weight. The two survival rates (30% and 50%) were tested. Additionally, sigmoid and domed selection pattern was explored for each case. All results are presented in Table 2.1.8 and Figures 2.1.5–2.1.6.

Results show better fit when s-shaped selection pattern was applied. Slight differences appear under the two different scenarios of discard survival rate. However, accordingly to the investigations performed during the benchmark workshop of 2016, there is a considerable discrepancy between the population estimates from the model when constraint vs. UWTV abundance is imposed or not. Thus, the ratio between the abundance predicted by a constrained SCA vs. UWTV survey and a simple LCA on LFDs was in the range 5.6–6.2 (domed selection for SR=30% provided some completely unlikely results). The perception of the stock status is radically different under the two UWTV weight options (overexploited with option LFDs, weakly harvested with option UWTV).

Under the s-shaped selection profile, runs no constrained by the number of burrows (abbreviated by runs LFDs) reveal a highly harvested stock (on two sexes combined F_{sq}=0.645 for SR=30% or F_{sq}=0.672 for SR=50% against respectively F_{max}=0.194 for SR=30% or F_{max}=0.202 for SR=50%). Weak differences are obtained between the two SR values with higher F_{sq} and F_{max} for the currently more plausible scenario SR=50%. Status quo harvest rate (HR_{sq}) is estimated at 33.9% for SR=30% or 28.6% for SR=50% (sex combined) whereas the current reference point is HR=7.7% (since the benchmark workshop 2016).

Runs including constraint vs. the number of burrows (abbreviated by runs UWTV) stress a point on the under-exploitation of the stock (on two sexes combined F_{sq}=0.103 for SR=30% or F_{sq}=0.085 for SR=50% against respectively F_{max}=0.195 for SR=30% or F_{max}=0.200 for SR=50%). HR_{sq} with this option is equal to 6.0% (SR=30%) or 4.6% (SR=50%) i.e. the reference point HR=7.7%.

Table 2.1.8. *Nephrops* in FUs 23–24 Bay of Biscay (8.a,b). Results of the SCA model under different options (survival rate [SR], weak or high weight for the 2019s UWTV survey [LFDs or UWTV], s-shaped or domed selection).

SR=0.30 (removals=258.692)									
s-shaped selection						domed selection			
		males	females	combined		males	females	combined	
	population			763.399				5578.818	
LFDs	F0.1	0.118	0.101	0.129	10.0%	0.352	0.180	0.277	17.6%
	F35%	0.157	0.177	0.161	12.2%	0.335	NA	0.273	17.4%
	Fmax	0.196	0.177	0.194	14.1%	0.454	0.180	0.317	20.3%
	Fsq	0.783	0.507	0.645	33.9%	0.113	0.045	0.079	4.7%
	population			4304.350				4313.214	
UWTV	F0.1	0.141	0.116	0.128	10.2%	0.340	0.185	0.264	17.7%
	F35%	0.165	0.166	0.159	12.4%	0.327	0.198	0.264	17.7%
	Fmax	0.214	0.178	0.195	15.0%	0.453	0.251	0.355	24.3%
	Fsq	0.122	0.083	0.103	6.0%	0.126	0.066	0.096	6.0%
SR=0.50 (removals=196.407)									
s-shaped selection						domed selection			
		males	females	combined		males	females	combined	
	population			686.418				662.335	
LFDs	F0.1	0.124	0.104	0.101	8.1%	0.138	0.090	0.114	8.9%
	F35%	0.165	0.182	0.168	12.4%	0.138	0.180	0.152	11.2%
	Fmax	0.206	0.208	0.202	14.2%	0.231	0.210	0.190	13.3%
	Fsq	0.825	0.520	0.672	28.6%	0.923	0.600	0.761	29.7%
	population			4299.022				4309.667	
UWTV	F0.1	0.143	0.115	0.127	10.1%	0.370	0.193	0.289	17.9%
	F35%	0.158	0.163	0.157	12.3%	0.332	0.196	0.271	16.7%
	Fmax	0.220	0.186	0.200	15.2%	0.498	0.201	0.356	22.1%
	Fsq	0.102	0.068	0.085	4.6%	0.128	0.050	0.089	4.6%

Additional explorations were carried out involving in SCA runs with different values of natural mortality M by sex. Using M≥0.7 for males (current M=0.3) and M≥0.5 for mature females (current M=0.2) induces a convergence between the two ways (runs LFDs and UWTV). The demographic pattern of the species suggests that such scenarios should be unlikely. High predation M for the Bay of Biscay stock seems not plausible: recent studies (Voisin, 2019) show the absence of significant interaction between adult hake (piscivorous predator) and *Nephrops* whereas competition between juvenile hake and *Nephrops* seems more obvious.

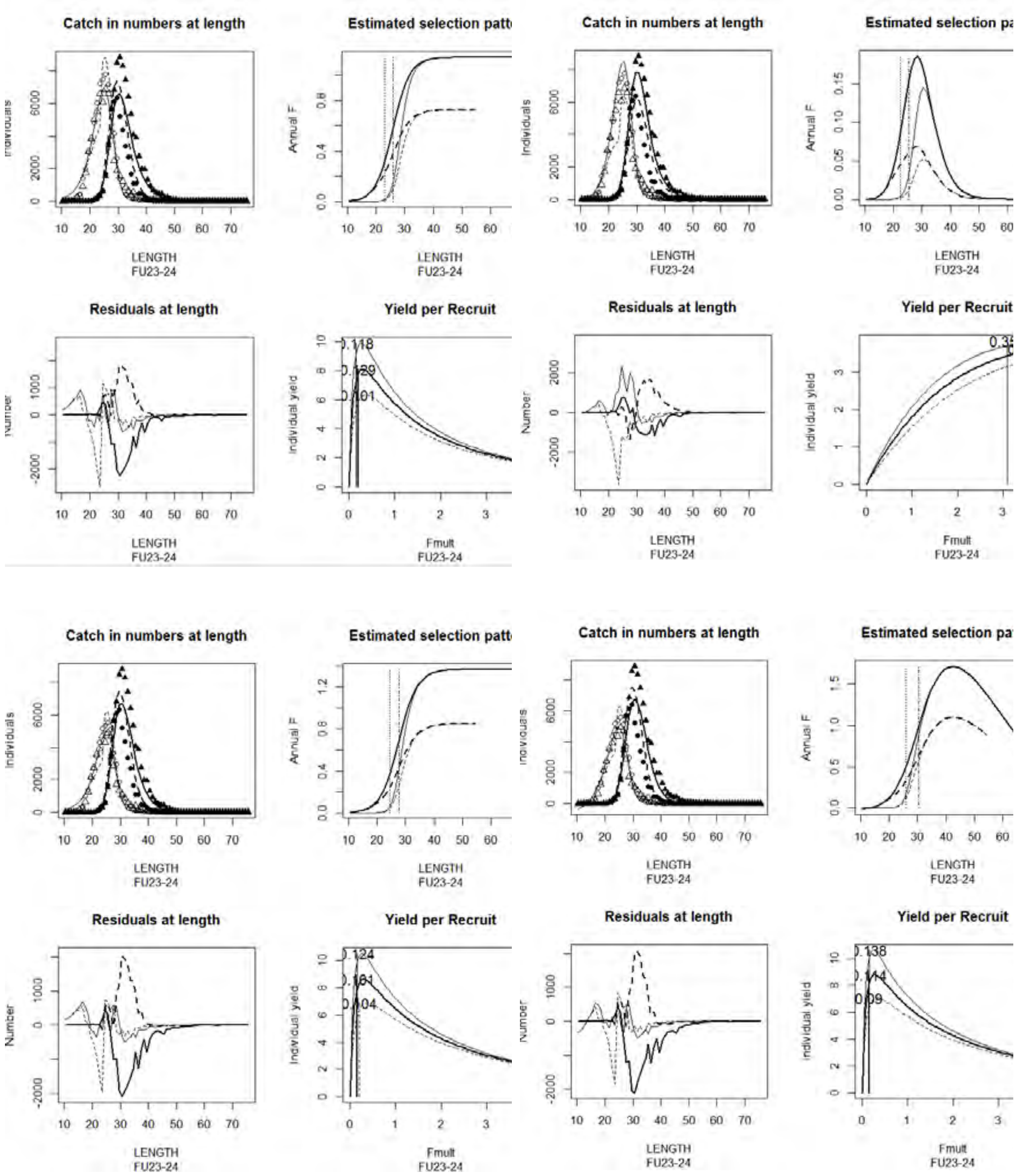


Figure 2.1.5. NEP2324. Results of the SCA model runs no constrained by the UWTV survey (runs LFDs). Survival rate (SR) of 30% (above) or 50% (below). S-shaped (left) or domed (right) selection pattern.

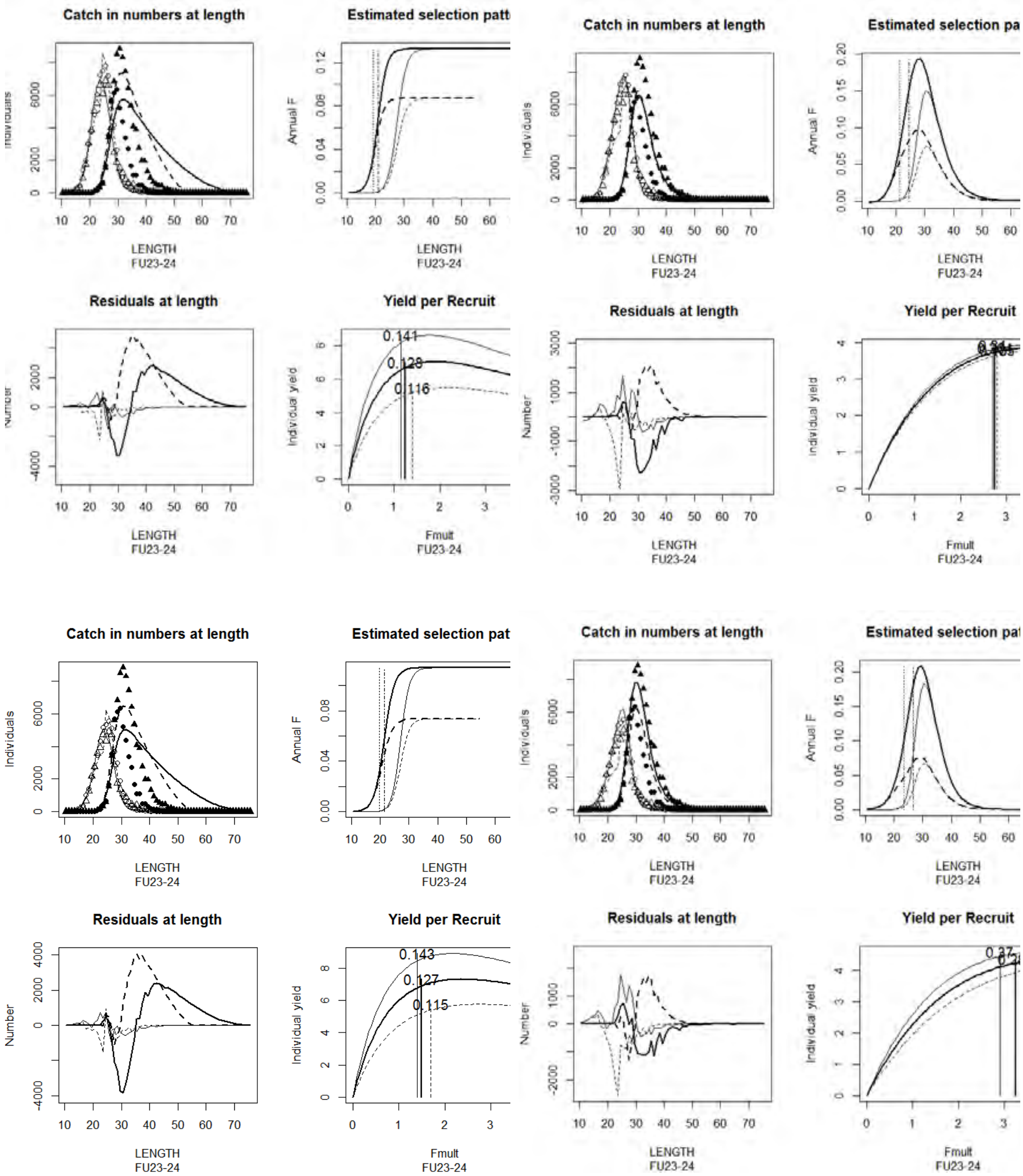


Figure 2.1.6. NEP23-24. Results of the SCA model runs constrained by the UWTV survey (runs UWTV). Survival rate (SR) of 30% (above) or 50% (below). S-shaped (left) or domed (right) selection pattern.

Conclusion

There is uncertainty in the assumed values of natural mortality and in the growth parameters for *Nephrops* stocks. Regarding to natural mortality, there are indications that it may be higher for some *Nephrops* stocks than usually assumed. It is very difficult to estimate the individual growth parameters using the traditional age methods as it is usually observed for crustaceans. VB parameters for FU23–24 stock were estimated a long time ago.

The SCA model (runs LFDs or UWTV) gives very divergent stock estimates. Factors as the uncertainty of the natural mortality and growth parameters can affect the shape of the catch-at-length distribution and can produce different magnitudes of stock abundance. As the WK was not conclusive at the aim of defining new reference points exclusively based on the SCA outputs it is cautiously considered optimum to keep the current reference value of HR=7.7% as the scenarios under $F_{0.1}$ provide obviously irrelevant results.

The survival rate was revised and a 50% value will be considered in future assessments and advice. The impact of this revised survival rate on the estimation of reference points is currently estimated to be relatively small according to the SCA model.

2.2 Reference points from surplus production models for FU17

2.2.1 Introduction

Nephrops stock in FU17 is considered as category 1 by ICES for purposes of stock assessment and management (Marine Institute, 2018). Stocks classified as category 1 correspond to the ones with quantitative assessment: full analytical assessment and forecast or assessment based on production models (ICES, 2018). For stocks classified as categories 1 and 2, the advice is provided according to management plans and strategies, however when those are considered 'not precautionary', the advice is given based on the ICES MSY approach (ICES, 2018). This last approach has been the basis of the advices for this species since 2011, with per-recruit proxies derived from length cohort analysis being proposed as F_{MSY} proxies for several functional units, including FU17 (ICES, 2017). Observing one of the aims of the WKNephrops 2019: 'c) Evaluate the utility of other modelling frameworks to assess and provide reference points for *Nephrops* stocks', reference points concerning the year 2018 were estimated for FU17 by the methodology described below.

2.2.2 Methods

Reference points for FU17 in 2018 were estimated by a 'non-equilibrium Schaefer surplus production model' as in Hilborn and Waters (1992) and Haddon (2011). The input data were annual removals (landings + discard) and abundance estimates from UWTV surveys. Such reference points were compared to the ones derived during the workshop for the same FU by methodology currently used on *Nephrops* stock assessment in ICES area: Dobby's Separable Length Cohort Analysis (SLCA), as well as to the ones estimated by ICES in 2018 (Marine Institute, 2018).

2.2.3 Results

Reference Points

The parameters and reference points estimated for the Aran Grounds (FU17) using the methodology abovementioned (non-equilibrium Schaefer surplus production model) can be seen at Table 2.2.1 below.

Table 2.2.1. Carrying capacity (K), growth intrinsic rate (r) and reference points / 2018 estimated for FU17 by a non-equilibrium Schaefer surplus production model using as input data annual removals (2002–2018) and abundance estimates from UWTV surveys.

Parameters
K = 15 774.32796 tonnes
r = 0.262427344
Reference Points
MSY = 1034.90 tonnes
B_{MSY} = 7887.16 (~ 418.20 million individuals)
F_{MSY} = 0.13121
H_{MSY} = 12.2970 %

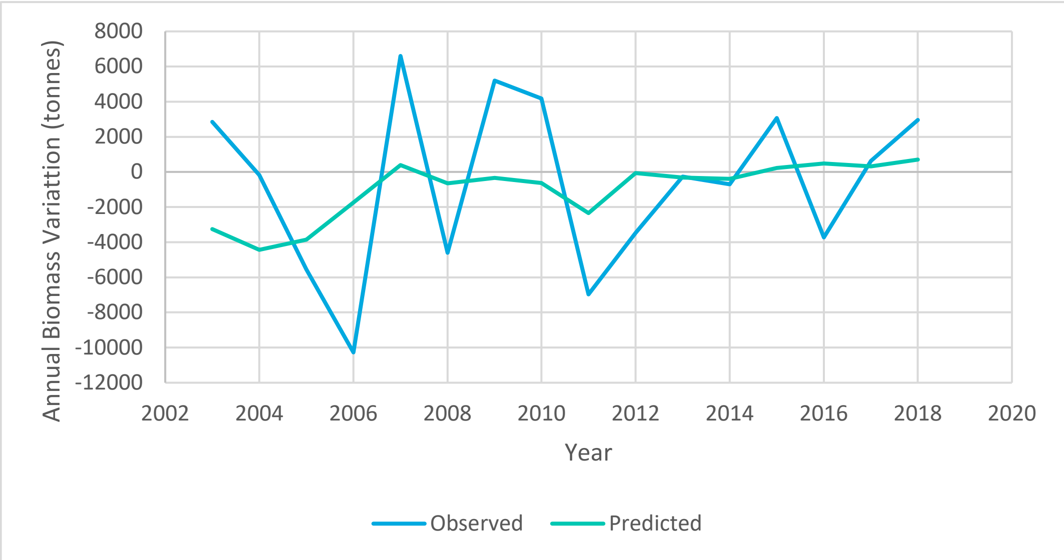


Figure 2.2.1. Plot of the of the observed annual variation of biomass estimates from UWTV surveys vs fitted values from the non-equilibrium Schaefer surplus production model for FU17.

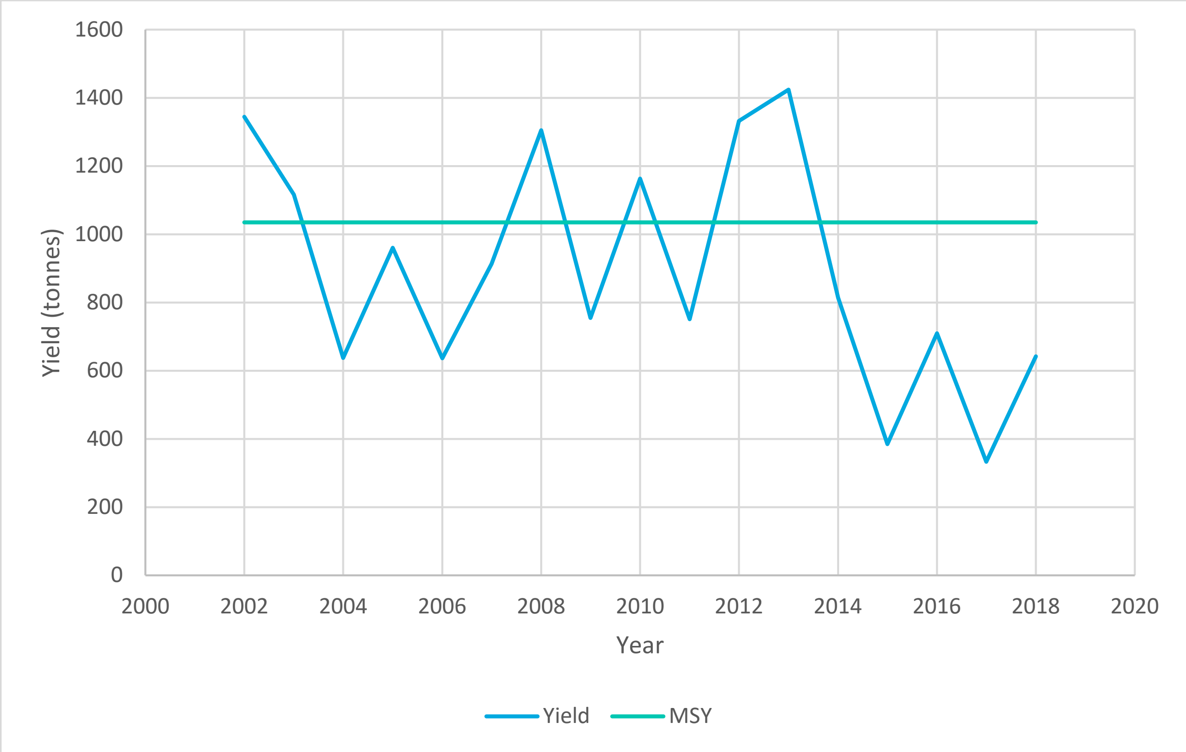


Figure 2.2.2. Plot of annual removals (yield) vs the estimated maximum sustainable yield for Aran Grounds (FU17) in 2018.

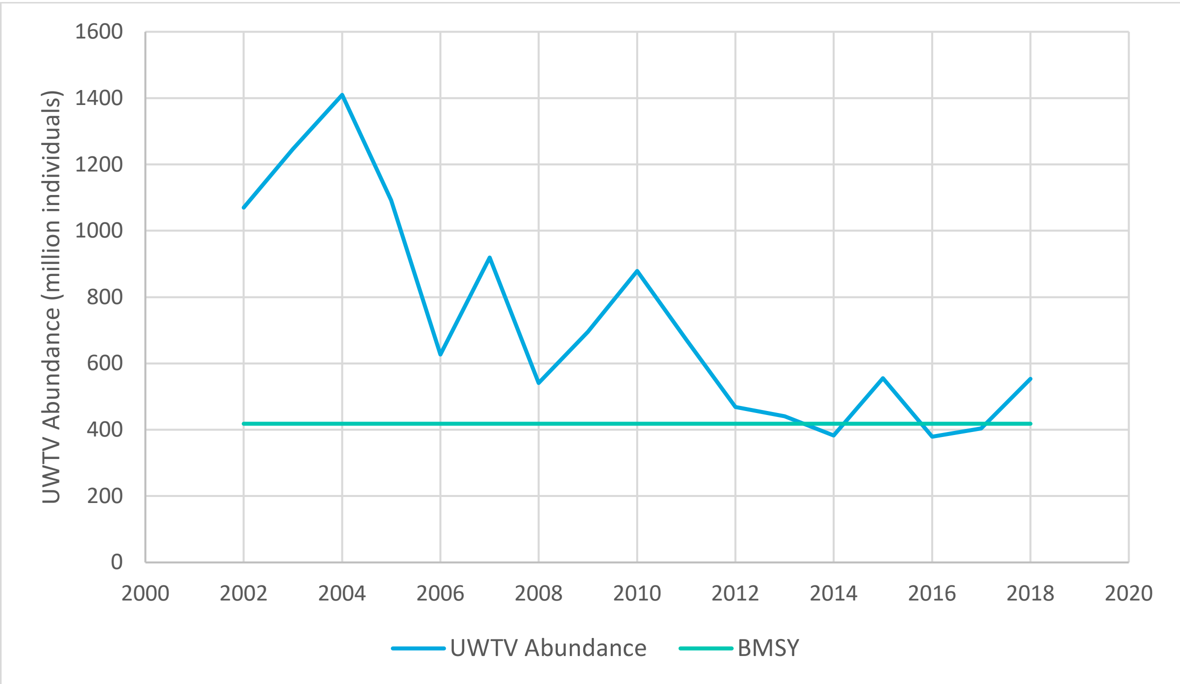


Figure 2.2.3. Plot of abundance annual estimates from UWTV surveys vs estimated BMSY for Aran Grounds (FU17) in 2018.

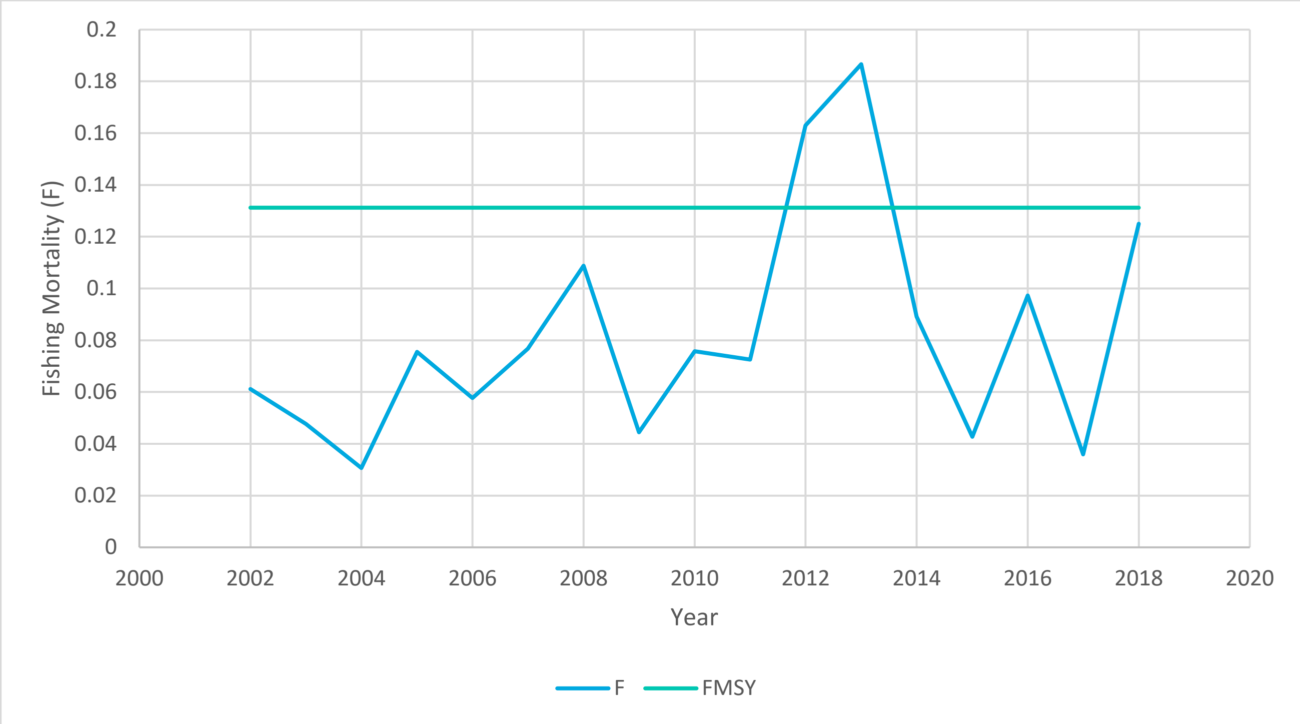


Figure 2.2.4. Plot of annual instantaneous rate of fishing mortality vs estimated F_{MSY} for Aran Grounds (FU17) in 2018.

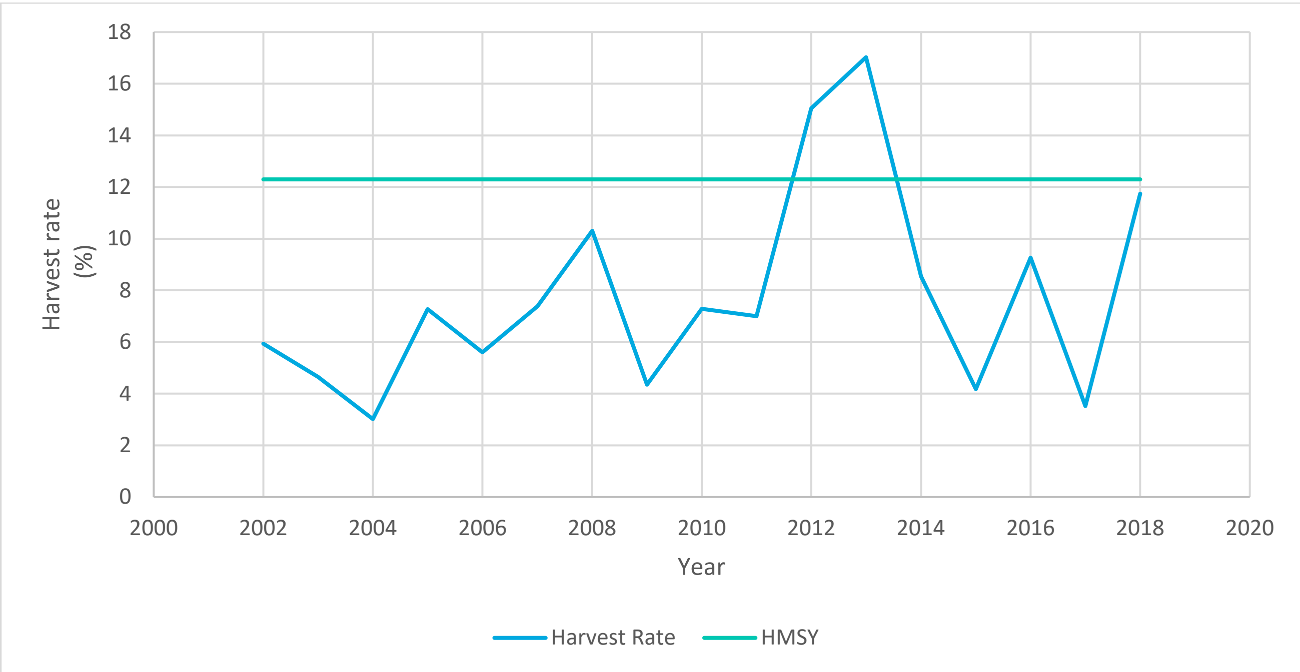


Figure 2.2.5. Plot of annual harvest rate estimates vs estimated H_{MSY} for Aran Grounds (FU17) in 2018.

2.2.4 Final considerations

The value of the harvest rate at F_{MSY} estimated by Separable Length Cohort Analysis (SLCA) during the workshop was 8.1%, which was lower than the estimate using the non-equilibrium Schaefer surplus production model (= 12.30%, see Table 4). However, the SLCA value is an average of annual estimates (based on length frequency data of three years) of the previous five years. Perhaps, whether F_{MSY} will be estimated for the previous five years by non-equilibrium Schaefer surplus production model and these values will be averaged, similar values might be found.

The harvest rate at F_{MSY} estimated herein by non-equilibrium Schaefer surplus production model was also less conservative than the one used by ICES in 2018 (= 8.5%) (Marine Institute, 2018), which was estimated according to the ICES MSY approach, such as the SLCA estimate above-mentioned. It is important to emphasize that in spite of the estimates from the non-equilibrium Schaefer surplus production model being less conservative than the other ones treated herein, the trends are concerning, for example, 'Abundance – MSY $B_{trigger}$' in 2018 [see Figure 2.2.6 below extracted from the ICES Advice 2018 (Marine Institute, 2018)] and 'Abundance – B_{MSY}' from the approach used herein (Figure 2.2.3 above) are very similar since 2012 (perhaps they would be the same whether the uncertainty had been quantified in the non-equilibrium surplus production modelling): (i) the abundance has been below the MSY $B_{trigger}$ in the case of estimates based on ICES MSY approach and (ii) below or slightly above the B_{MSY} in the case of the approach used herein (non-equilibrium surplus production model). Both, possibly, would generate the same precautionary management response.

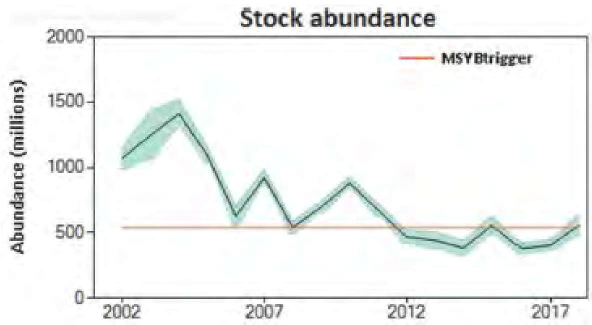


Figure 2.2.6. Plots of annual mortality (harvest rate) vs. estimated F_{MSY} and Abundance vs. estimated $MSYB_{trigger}$ for FU17 in 2018.

Observing this, with some adjustments, the non-equilibrium Schaefer surplus production model using as input data UWTV estimates of abundance (the basis of the stock assessment and management for category 1 stocks in ICES area) instead of standardized CPUE (a complicated issue in *Nephrops* fisheries) could be an alternative to other approaches.

2.3 Overview for FU 26–27

Stock summary

The *Nephrops* stock from FU 26 extends along the Atlantic area off the northwestern Spanish coast, south of Cape Finisterre, whereas FU 27 covers the Atlantic area off northern Portugal. The distribution of *Nephrops* in this area is limited to depths ranging from 90–500 m. These FUs are assessed together because landings could not be differenced before 1996.

Nephrops is caught in a mixed bottom-trawl fishery, which takes place throughout the year, with the highest *Nephrops* landings in spring and summer. The bottom-trawl fleet comprises three main components: baca trawl, high vertical opening trawl (HVO) and pair trawl, each targeting different species. Only the baca trawl catches *Nephrops*. Other targeted species include hake, anglerfish, megrim, horse mackerel, mackerel and a variety of other fish and cephalopods. *Nephrops* is considered as bycatch.

Landings and LPUE show a continuous decreasing trend since 1970s. This stock is currently classified by ICES as category 3 and the advice has been a recovery plan and zero catch since 2003 because the biomass is extremely low.

Data

Length composition of the catches is available for the period 1988–2018. In spite of the length frequency distribution sampling has been carried out by sex, only the length composition of males and females are available before this WK since 2008. There are no discards on this fishery and then landings correspond to catches. Table below shows the life-history parameters for these stocks:

Parameter	Value	Source
Discards survival	NA	Not applicable-Few discards (<1% on average)
MALES		
Growth-K	0.150	(Fernandez *et al.*, 1986)
Grouth-L(inf)	80	"
Natural mortality-M	0.2	"
Lenght/weight-a	0.00043	(Fariña, 1984)
Lenght/weight-b	3.160	"
FEMALES		
Inmature Growth		
Growth-K	0.160	(ICES, 1994)
Growth-L(inf)	70	"
Natural mortality-M	0.2	"
Size at maturity (mm CL)	26	(Fariña, 1996)
Mature Growth		
Growth-K	0.080	(ICES, 1994)
Grouth-L(inf)	65	"
Natural mortality-M	0.2	"
Lenght/weight-a	0.00043	(Fariña, 1984)
Lenght/weight-b	3.160	"

Methods

No method has been applied for FU2627 during this WK.

Roadmap for development

The length composition by sex for the 1988–2007 period will be recovered and different methods used in this WKNephrops will be applied next year before next WGBIE.

2.4 Data-limited approaches for FU 31

The stock is classified in the category 3.14 of Data Limited Stocks (DSL), i.e. stock with biomass/abundance trends-based assessment (commercial CPUE), with extremely low biomass and a zero catch advice (ICES, 2017).

FU 31 *Nephrops* catch has decreased a 98% since 1989 to 2016, from 177 t to 4 t (ICES, 2019a). CPUE decreased at 92% since 1990 to 2013, from 27 kg/day to 2.3 kg/day (ICES, 2019a).

ICES recommended zero catch advice since 2002 (ICES, 2019a). The fishery was closed (TAC zero) in the triennium 2017–2019 (Reg. UE 2017/127). ICES advice for the triennium 2020–2022 is also TAC zero (ICES, 2019a).

2.4.1 Data

1988–2016 annual catch–length distributions by sex from the commercial fishery. Also 2019 July length distribution from the *Nephrops* Sentinel fishery in FU 31. Both provided by Spain. Length distributions of the Sentinel could be slightly different from the rest because the females' catchability in July is the highest of the year (González Herraiz *et al.*, 2011). Discard in this FU is negligible; therefore, landings are equal to catches.

1988–2016 catches was not restricted by the existing TAC because catches were always much lesser than TAC (ICES, 2019a). 2019 catch was constricted to a special *Nephrops* quota for the FU 31 *Nephrops* Sentinel fishery of 700 kg (ICES, 2019b, Reg. EU 2019/1097).

2.4.2 Methods

Mean length-based estimators (Z)

Method

Section 2.2 in ICES (2015) presents the method, data and information requirements, assumptions, outputs expected, method of operation, testing, caveats and software to which the reader is referred for further details (ICES, 2016).

The method applied was the mean length-based mortality estimator in non-equilibrium situations (Gedamke and Hoening, 2006) extended from Beverton and Holt (1957) mean length mortality estimator. Taking into account previous trials (ICES, 2016) and in absence of an effort time-series that covers the whole period (1988–2019), THoG model was not applied.

Critic assumptions

Gedamke and Hoenig model assumes:

1. Recruitment is constant over time,
2. Growth is deterministic following a von Bertalanffy growth equation and is time-invariant, and
3. Selectivity is knife-edge above the length of full selectivity (L_c) and is time-invariant.

Data & Parameters

Data used were 1988–2016 and 2019 catch–length distributions by sex.

Table 2.4.1. Input parameters.

Parameter	Males	Reference	Females	Reference
von Bertalanffy k (yr^{-1})	0.15	ICES, 1994	0.1	ICES, 1994
von Bertalanffy L_∞ (mm)	86	Length distribution time series	65	Length distribution time series
Max age	13	Fariña et al, 2003	13	Fariña et al, 2003
Gedamke-Hoening & YPR				
stZ seed	0.3		0.3	
Natural mortality (M) (yr^{-1})	0.3	Exploratory analysis	0.2	Morizur, 1982
YPR estimation for reference points				
Von Bertalanffy t_0	0		0	
Length weight a	0.00043	Biological sampling from Fariña, 1984	0.00043	Biological sampling from Fariña, 1984
Length weight b	3.16		3.16	

Exploration

Lc

The model adds the length distributions of all years (1988–2016 and 2019) in an only length distribution for each sex (Figure 2.4.1) and after, identifies the length of full selectivity (L_c) for each sex (the mode of each distribution). The result was, for both, males and females, 40 mm of carapace length (CL). Figure 2.4.2 shows the L_c of 40 mm in each of the lengths distributions.

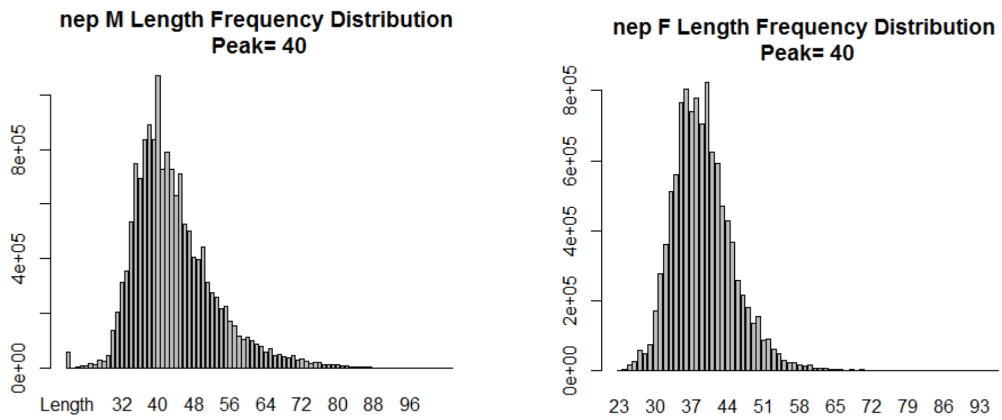


Figure 2.4.1. *Nephrops* FU 31. Length frequency distribution of males (left) and females (right) aggregated over all years (1988–2016 and 2019).

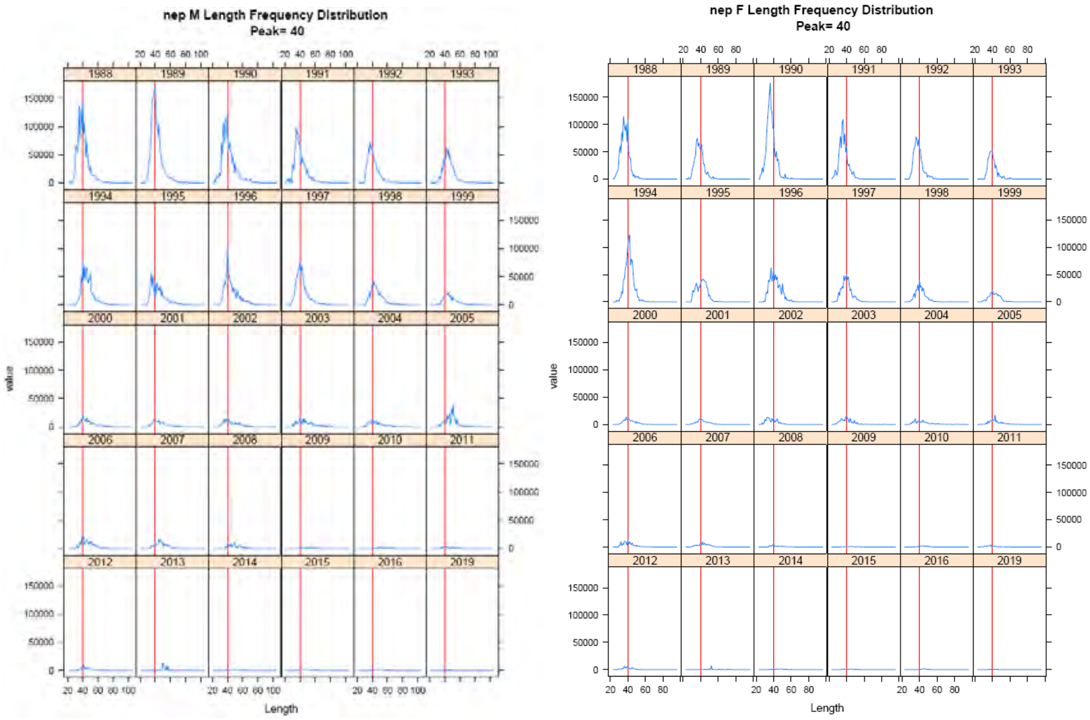


Figure 2.4.2. Length distributions (1988–2016 and 2019) with the L_c (red line). Left: males, right: females.

The model also calculates the L_c mean of the 30 length distributions for each sex, the average Lc for males was 42.4 mm CL and for females 39.83 mm CL.

Identification of the data period/s

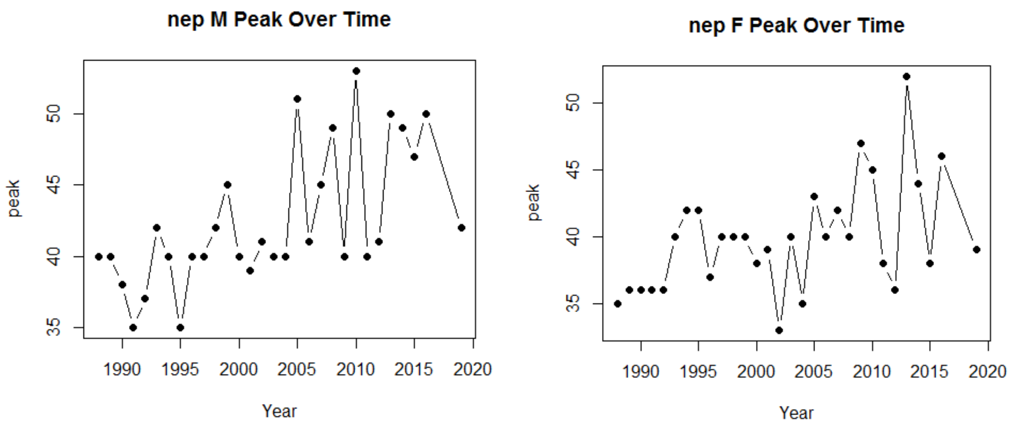


Figure 2.4.3. L_c by year and sex. Left: Males, right: Females.

Taking into account the changes of L_c over time per year and sex (Figure 2.4.3), two periods were identified in the L_c time-series for both sexes, therefore models that estimated two Z were used, trying different years as breaking point. No matter the year of break that were introduce as seed in the model, the result was always year of break 1997 for males and 1994 for females (Figure 2.4.4).

Results

Gedamke-Hoening

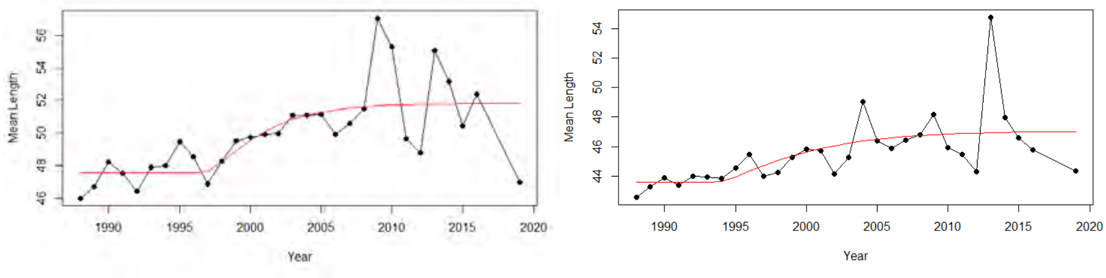


Figure 2.4.4. *Nephrops* in FU 31. Observed (black points and line) and fitted (red line) mean lengths (mm CL) by year for males (left) and females (right) (1988–2016 and 2019).

Table 2.4.2. Results.

Model	Parameter	1988-2016 & 2019 data (WKNEPH 2019)		2001-2002, 2004-2014 data (WKProxy 2015, ICES, 2016b)	
		Males	**Females**	**Males**	**Females**
Gedamke-Hoenig	Z1 estimate (yr^{-1})	0.53	0.45		
	Estimated year of change	*1997*	*1994*	0.19	0.13
	Z2 estimate (yr^{-1})	0.34	0.21		
	F1 (yr^{-1}) (Z1 estimated - external M)	0.23	0.25		
	Estimated year of change	*1997*	*1994*	-0.01	-0.07
	F2 (yr^{-1}) (Z2 estimated - external M)	0.04	0.01		
Yield Per Recruit Analysis (based on external M)	$F_{0.1}$	0.25	0.27	0.28	0.47

Year Per Recruit estimation for reference points

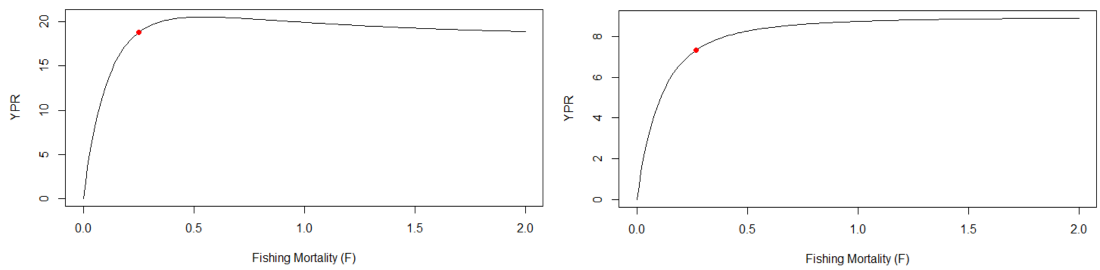


Figure 2.4.5. YPR estimation for reference points for males (left) and females (right).

Issues about reference points estimation

Despite Gedamke & Hoening method is for non-equilibrium situation, it is not very suitable for *Nephrops* of FU 31 because recruitment was not constant over time (see Figure 2.4.6). Moreover, the method could be quite sensitive to different values of the estimate Z seed.

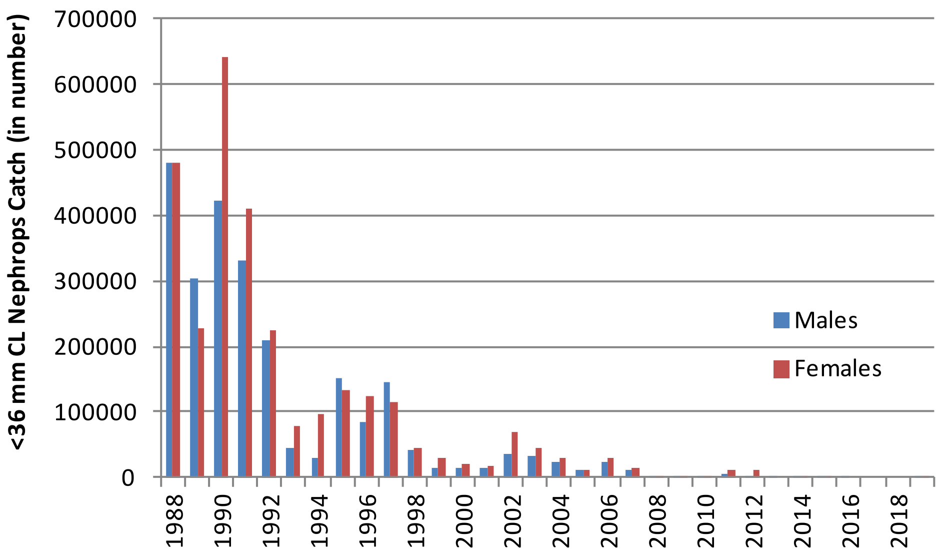


Figure 2.4.6. Proxy of recruitment in FU 31. Number of individuals with carapace length ≤35 mm in *Nephrops* catch.

Moreover, there is the general uncertainty about the von Betalanffy parameters for *Nephrops* populations, since there not a standard method to estimated age in this species.

Taking into account the results of the Gedamke-Hoenig model, there are two periods in the time-series, one from 1988 to 1997 in males, and to 1994 in females, with smaller mean sizes, and a second one with higher mean sizes and variability (Figure 2.4.4). As the model assumes a constant recruitment, interprets high mean sizes as symptom of low fishing mortality (F) and vice versa (low mean sizes as high F), when, in this functional unit, high mean sizes are related with low recruitment (Figure 2.4.6).

Conclusion

This method is not the most suited for Functional Unit 31 since recruitment in this FU has not been constant in the time-series (Figure 2.4.6).

Length-based indicators and reference points: screening methods

Method

Section 2.1 in ICES (2015) presents the method, data and information requirements, assumptions, outputs expected, method of operation, testing, caveats and software to which the reader is referred for further details (ICES, 2016).

A set of length-based indicators was selected for screening catch/landings–length composition and classify the stocks according to conservation/sustainability, yield optimization and MSY considerations. These indicators require data on the stock catch/landings–length composition and life-history parameters and can be applied systematically to all data-limited stocks. The overall perception of stock status can be used to guide experts on the choices for parameters (initial values and/or ranges) used in other methods (e.g. C_{MSY}) (ICES, 2015).

The following Length Based Indicators (LBI) method shiny tool was used https://scott.shinyapps.io/LBIndicator_shiny/ .

Table 2.4.3. Selected indicators for LBI screening plots. Indicator ratios used for stock status assessment with traffic light system.

Indicator	Calculation	Reference point	Indicator ratio	Expected value	Property
$L_{max5\%}$	Mean length of largest 5%	L_{inf}	$L_{max5\%}$ / L_{inf}	> 0.8	Conservation (large individuals)
$L_{95\%}$	95th percentile		$L_{95\%}$ / L_{inf}		
P_{mega}	Proportion of individuals above L_{opt} + 10%	0.3–0.4	Pmega	> 0.3	
$L_{25\%}$	25th percentile of length distribution	L_{mat}	$L_{25\%}$ / L_{mat}	> 1	Conservation (immatures)
L_c	Length at first catch (length at 50% of mode)	L_{mat}	L_c/L_{mat}	> 1	
L_{mean}	Mean length of individuals > L_c	$L_{opt} = \frac{3}{3+M/k} \times L_{inf}$	L_{mean}/L_{opt}	≈ 1	Optimal yield
L_{max_y}	Length class with maximum biomass in catch	$L_{opt} = \frac{3}{3+M/k} \times L_{inf}$	L_{maxy} / L_{opt}	≈1	
L_{mean}	Mean length of individuals > L_c	$L_{F=M}$ = ($0.75L_c+0.25L_{inf}$)	L_{mean} / $L_{F=M}$	≥ 1	MSY

Critical assumptions

A length-based proxy for MSY is $L_{F=M} = 0.75L_c+0.25L_{inf}$ (where L_c is the length at 50% of mode) and the length of optimal yield is $L_{opt}=2/3L_{inf}$. The method assumes that input parameters are known, but life-history parameters L_{MAT}, L_{inf} may be uncertain for data-limited stocks.

Input data and parameters

Catch–length distributions and mean weight by length class in grammes.

Table 2.4.5. Input parameters.

Parameter	Males	Females
von Bertalanffy L_∞ (mm)	86	65
Length at maturity Lmat (mm)	25	28
M/K	2	2

Exploration

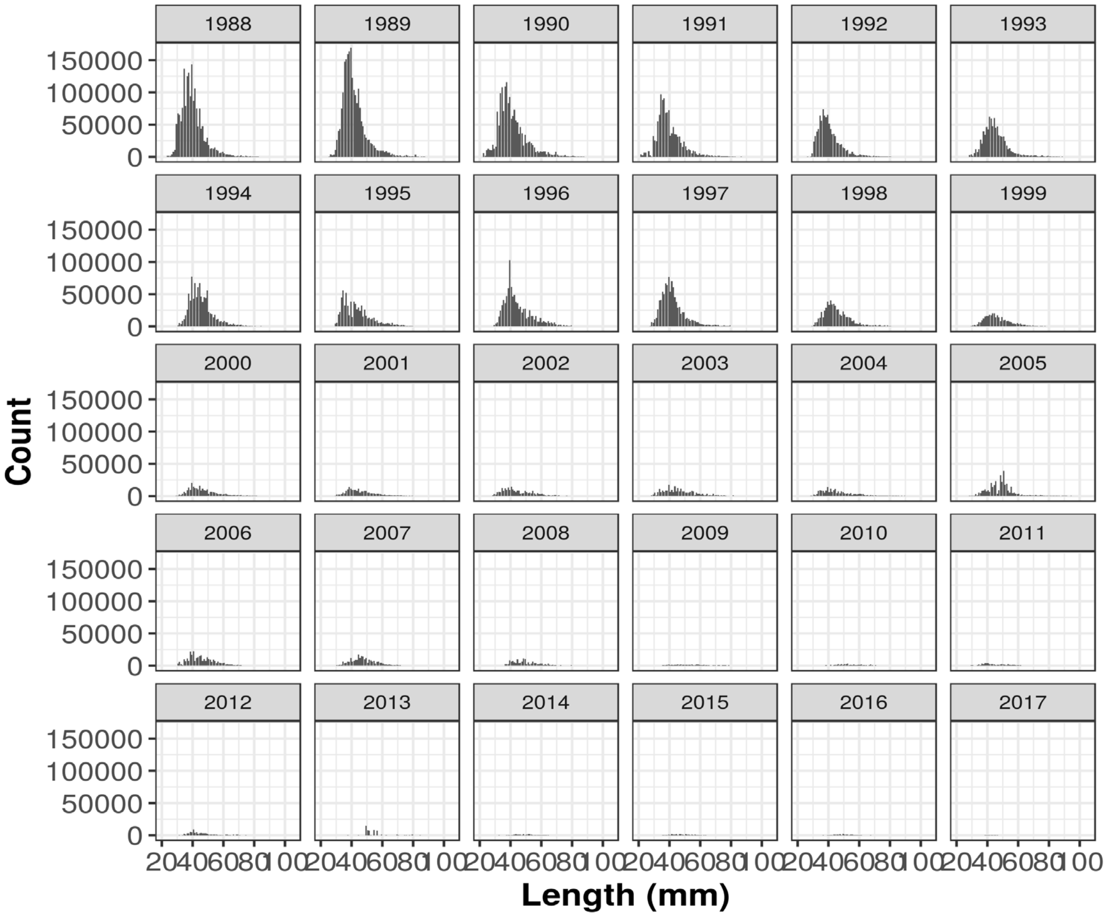


Figure 2.4.7. *Nephrops* FU 31 males. Binned length frequency distribution (1988–2016 and 2019). 1 mm carapace length classes. "2017" in the plot should be "2019".

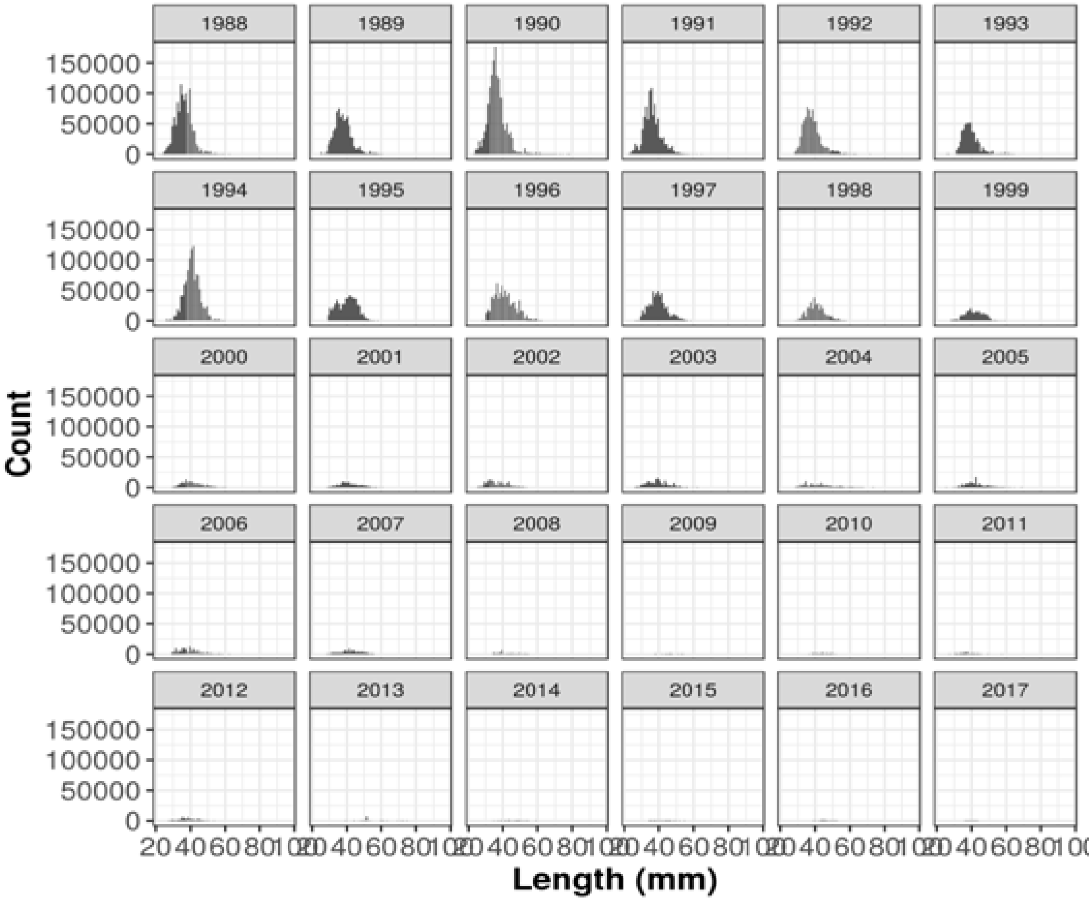


Figure 2.4.8. ***Nephrops*** **FU 31 females. Binned length frequency distribution (1988–2016 and 2019). 1 mm carapace length classes. "2017" in the plot should be "2019".**

Results

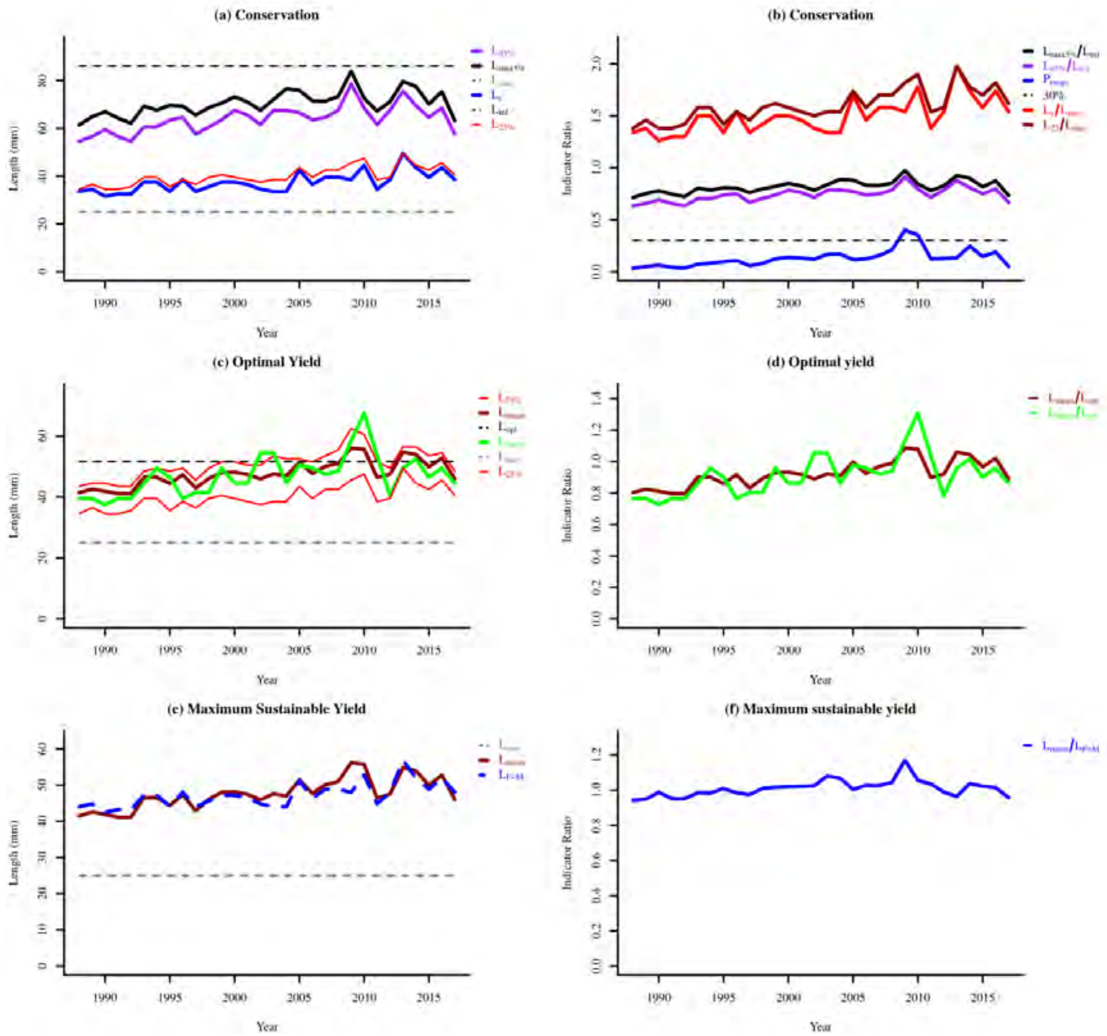


Figure 2.4.9. Males FU 31 length indicator trends.

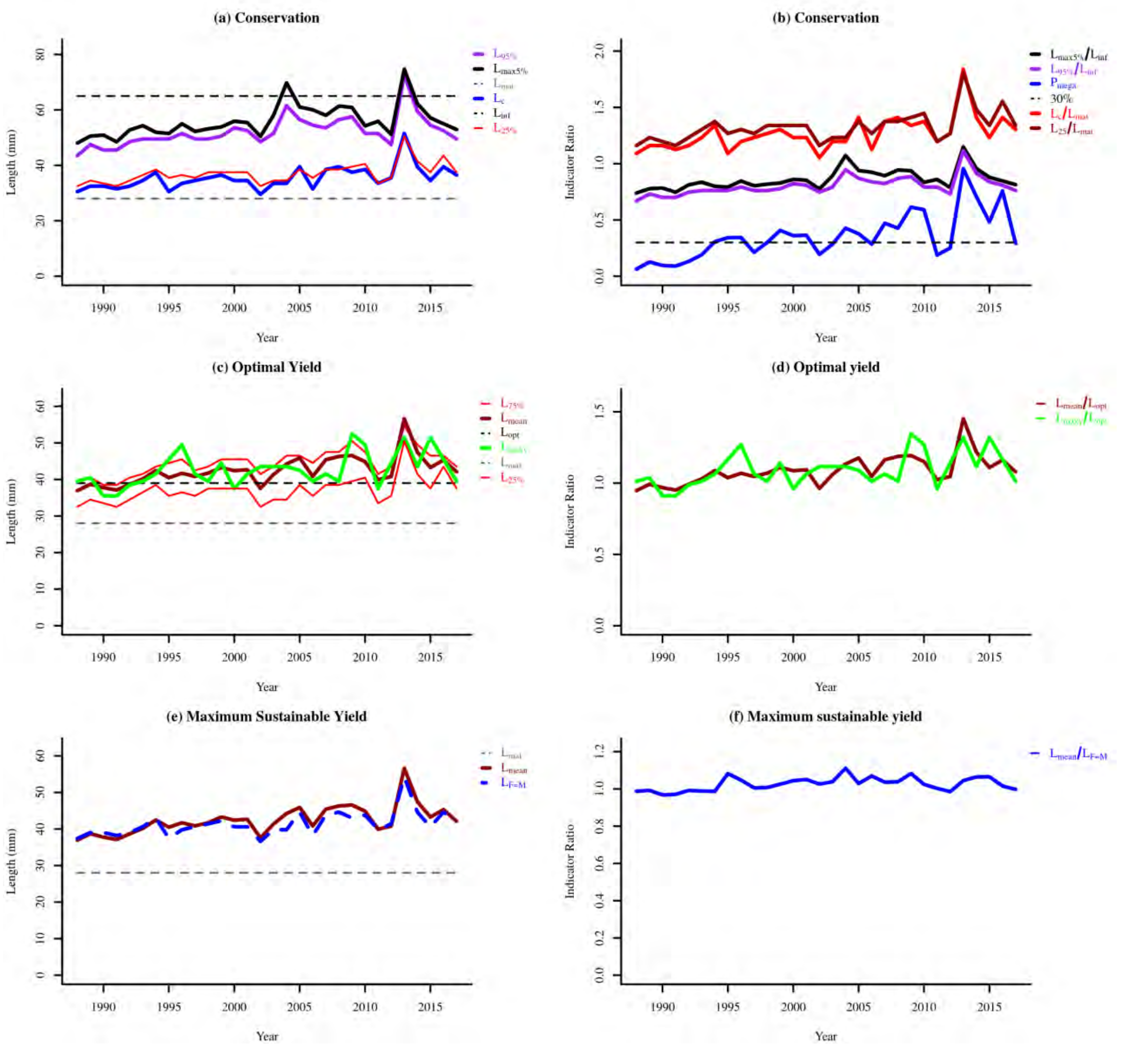


Figure 2.4.10. Females FU 31 length indicator trends.

Table 2.4.6. Indicator status for the most recent three years. Top: Males, bottom: Females.

MALES	Conservation				Optimizing Yield	MSY
	Inmatures		Large individuals			
Year	L_c / L_{mat}	$L_{25\%}$ / L_{mat}	$L_{max\ 5\%}$/ L_{inf}	P_{mega}	L_{mean} / L_{opt}	L_{mean} / $L_{F=M}$
Expected values	>1		>0.8	>0.3	≈ 1	≥ 1
2015	1.58	1.70	0.82	0.15	0.97	1.02
2016	1.74	1.82	0.88	0.19	1.02	1.01
2019	1.54	1.62	0.73	0.05	0.89	0.96

FEMALES	Conservation				Optimizing Yield	MSY
	Inmatures		Large individuals			
Year	L_c / L_{mat}	$L_{25\%}$ / L_{mat}	$L_{max\ 5}$ / L_{inf}	P_{mega}	L_{mean} / L_{opt}	L_{mean} / $L_{F=M}$
Expected values	>1		>0.8	>0.3	≈ 1	≥ 1
2015	1.23	1.34	0.88	0.48	1.11	1.07
2016	1.41	1.55	0.85	0.76	1.16	1.02
2019	1.30	1.34	0.81	0.29	1.08	1.00

The proportion of individuals above L_{opt} + 10% (P_{mega}) has been almost all the time-series of males and in the first years of the time-series of females (Figures 2.4.9 and 2.4.10) below the reference point (0.3).

Conclusion

The conservation of large males has been compromised all along the time-series. Males' fishery in 2019 has been over the optimum yield and the MSY.

Spawning Potential Ratio Method

Method

This method is also known as Spawning Per Recruit, Eggs Per Recruit and Proportion Lifetime Egg Production.

Section 2.3 in ICES (2015) presents the method, data and information requirements, assumptions, outputs expected, method of operation, testing, caveats and software to which the reader is referred for further details.

Traditional approaches compared size-based estimates of fishing mortality (Z, Beverton and Holt, 1956) with sized-based yield-per-recruit reference points (F_{max} or $F_{0.1}$, Beverton and Holt, 1957), both of which assumed knife edged selectivity at L_c. Alternative selectivity functions can be assumed if the yield-per-recruit analysis is based on length at relative age (Cadima, 2003), and the size-based yield-per-recruit can be extended to spawning biomass per recruit (http://nft.nefsc.noaa.gov/) (ICES, 2015).

The following Length Base Spawning Per Recruit method shiny tool was used http://barefooteco-logist.com.au/lbspr .

Critical assumptions

- Equilibrium-based method.
- Differences between observed and expected length distributions are due to variability of recruitment or mortality (i.e. method assumes constant recruitment and fishing pressure).
- Growth is adequately described by von Bertalanffy equation with known L_∞, CV[L_∞], M/κ, and t_0=0.
- Length structure of the catch is representative (*i.e.* not subject to biased sampling).
- Commercial selectivity follows a logistic curve (although the method is limited to this, and will take alternative forms, including domed selection; however, this requires knowledge of the shape of the selectivity curve, formation that may not be readily available in data-poor situations).

Input data and parameters

1988-2016 annual catch length distributions by sex from the commercial fishery. Also 2019 July length distribution from the *Nephrops* Sentinel fishery in FU 31.

Table 2.4.7. Input parameters.

Parameter	**Males**	**Females**
M/K	2	2
Linf	86	65
Lmat 50	25	28
Lmat 95	28.75	32.20
Options		
Smoother	no	no
SPR limit	0.2	0.2
SPR target	0.6	0.6

Exploration

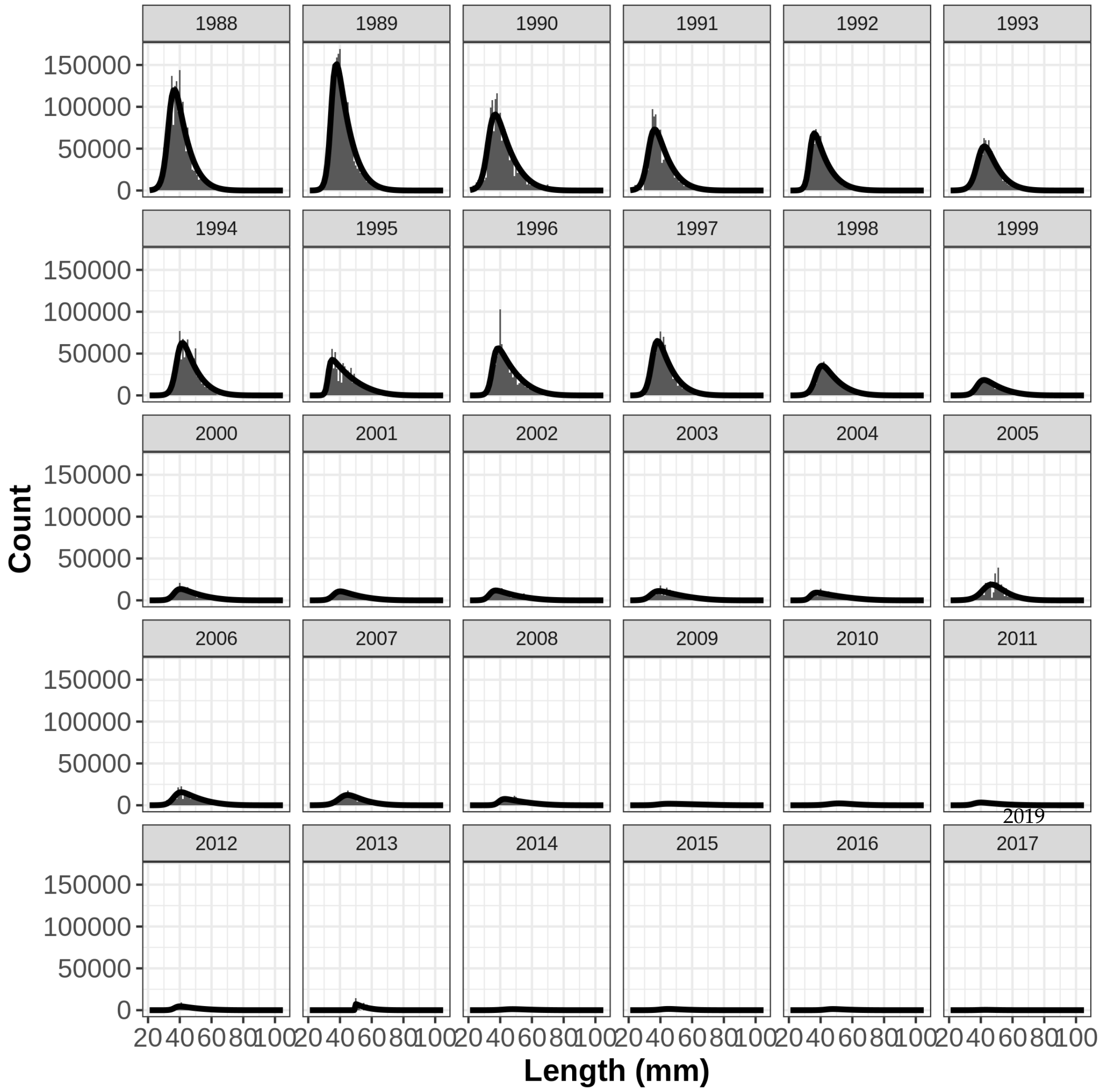


Figure 2.4.11. *Nephrops* FU 31 males. Binned length frequency distribution (1988–2016 and 2019). 1 mm carapace length classes.

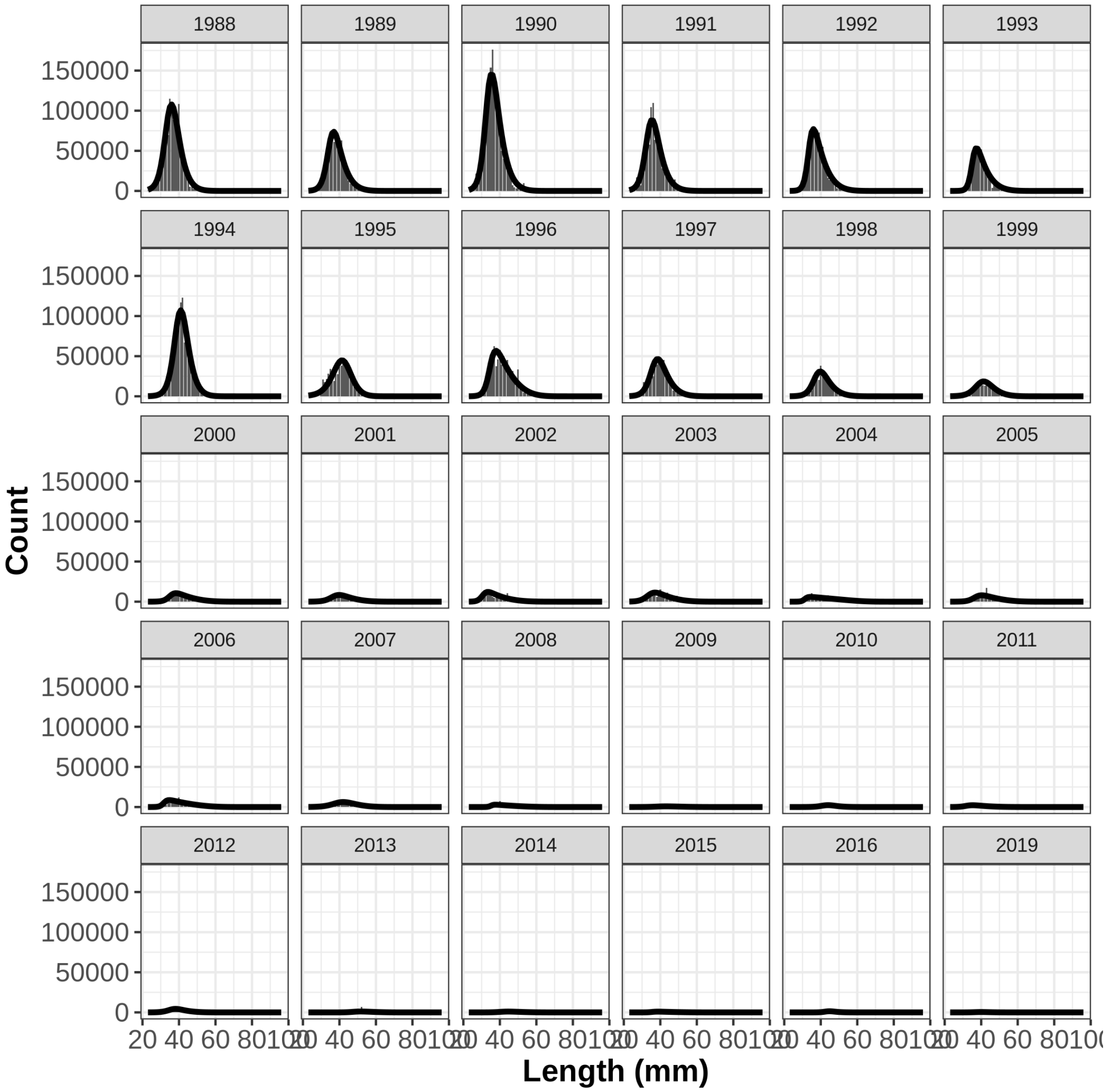


Figure 2.4.12. *Nephrops* FU 31 females. Binned length frequency distribution (1988–2016 and 2019). 1 mm carapace length classes.

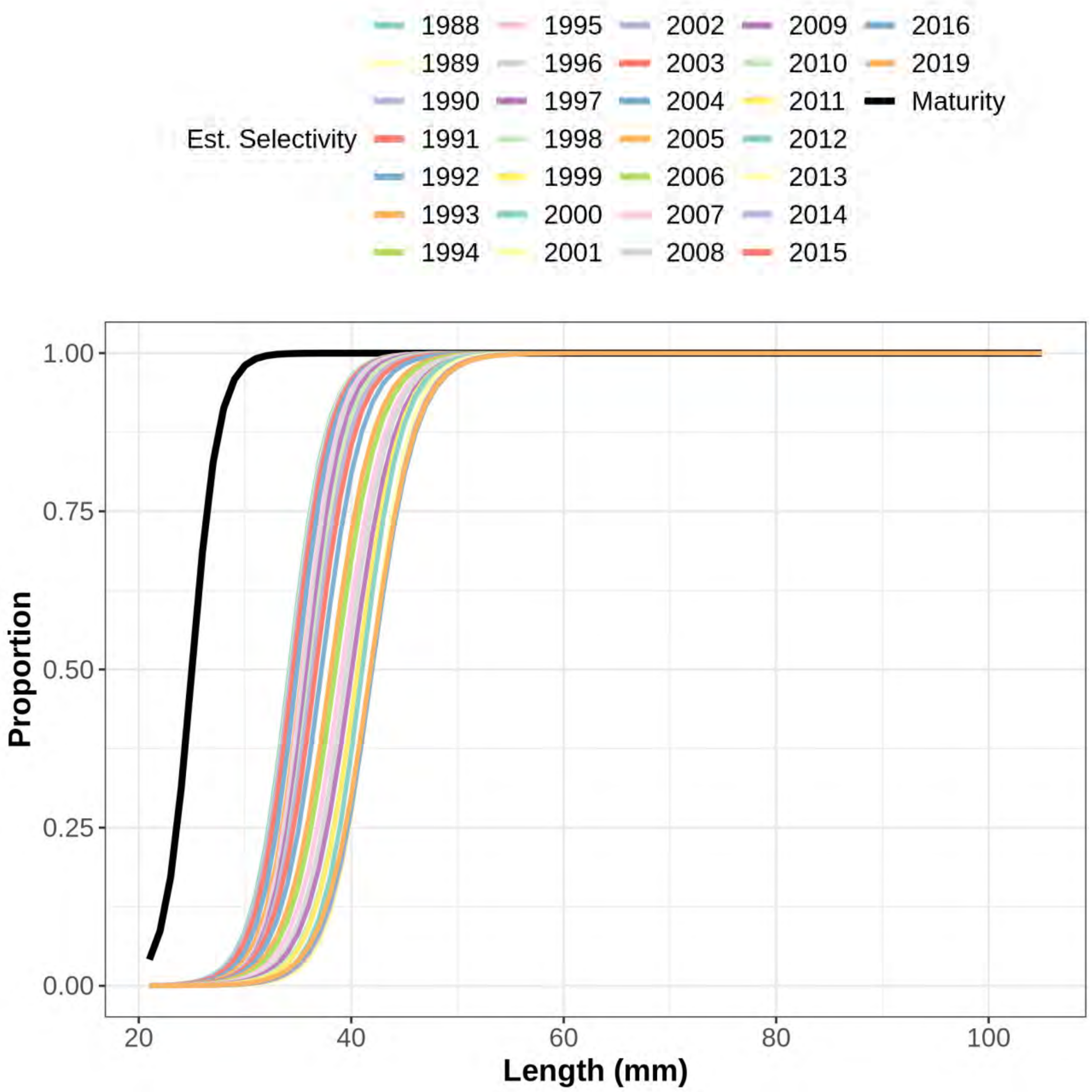


Figure 2.4.13. ***Nephrops*** **FU 31 males. Length at maturity ogive vs selection length ogive by year.**

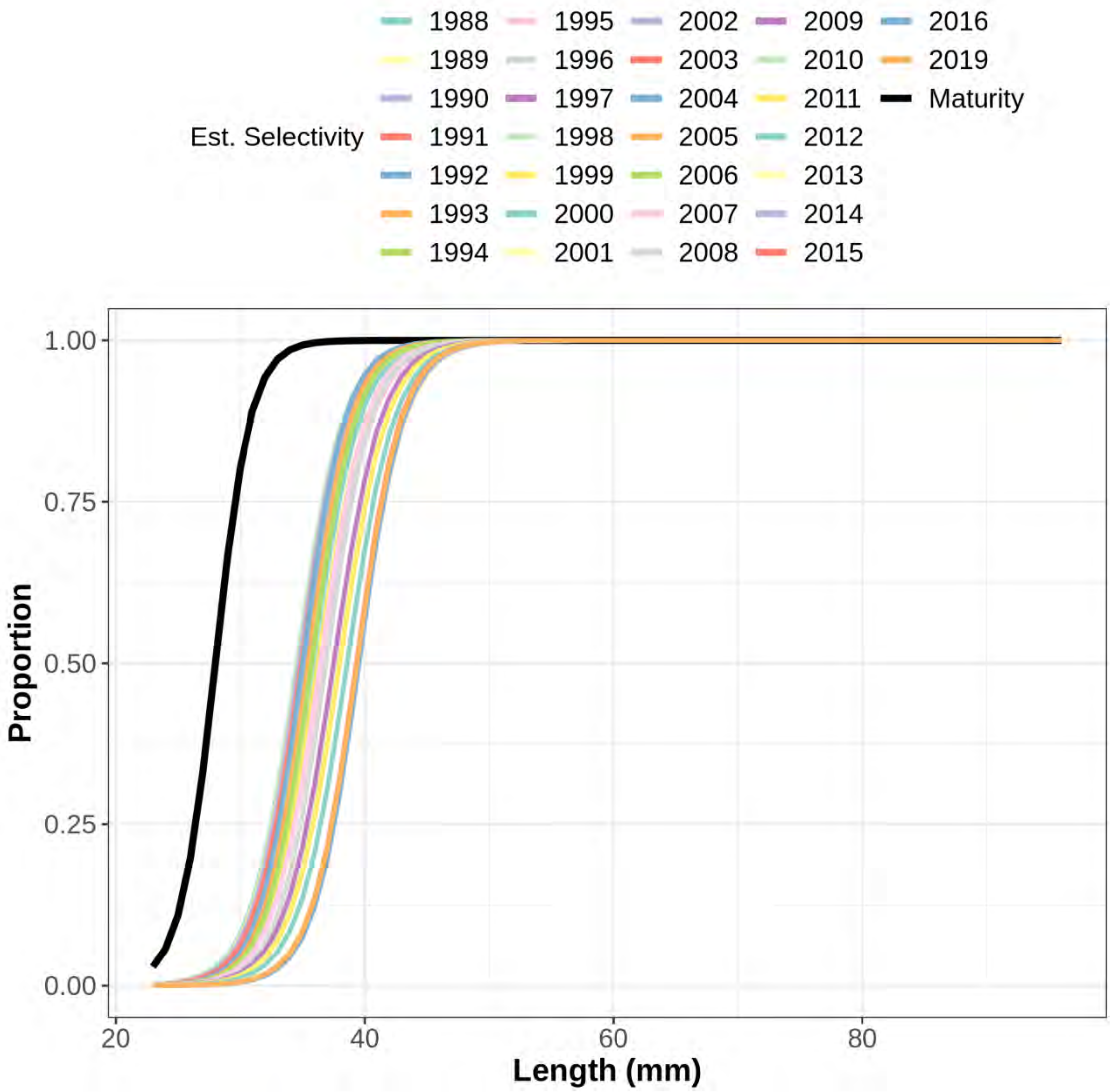
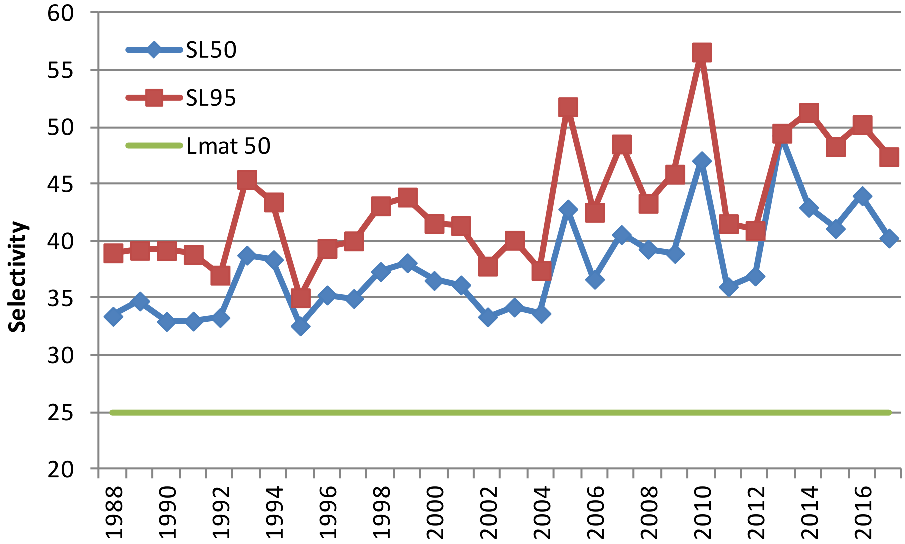
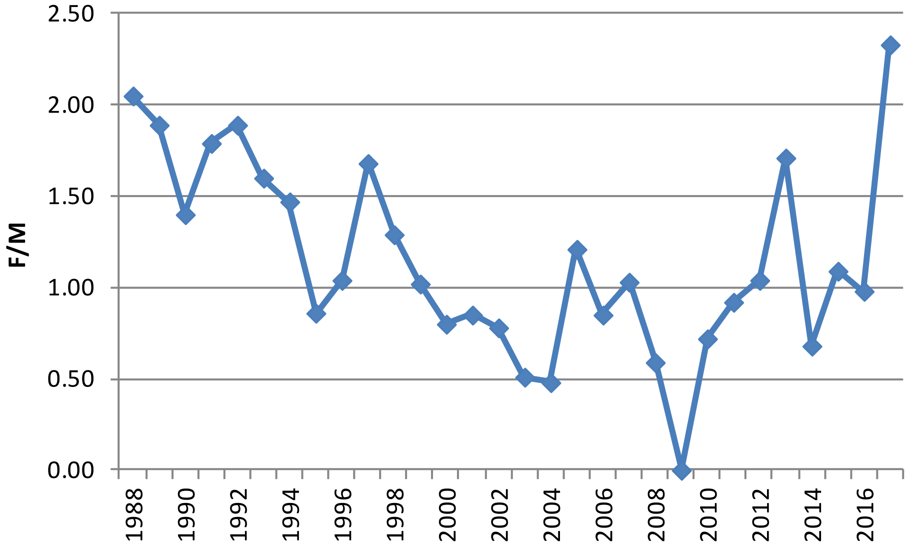


Figure 2.4.14. ***Nephrops*** **FU 31 females. Length at maturity ogive vs selection length ogive by year.**

Length at maturity for both, males and females, is below the L_c (Figures **2.4.13** and **2.4.14**).

Results


60
55
50
45
40
35
30
25
20
Selectivity
SL50
SL95
Lmat 50
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016


2.50
2.00
1.50
1.00
0.50
0.00
F/M
1988
1990
1992
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1998
2000
2002
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2006
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2016

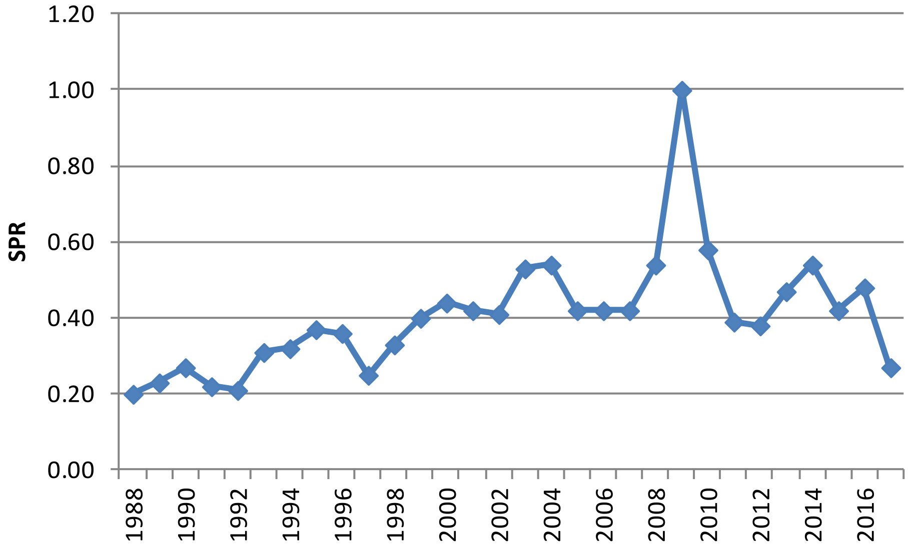


Figure 2.4.15. ***Nephrops*** **FU 31 males. Selectivity, F/M and SPR. In 2013 the model did not converge.**

Catch males sizes has been increasing along the time-series (Figure 2.4.15) and is higher than the size at maturity.

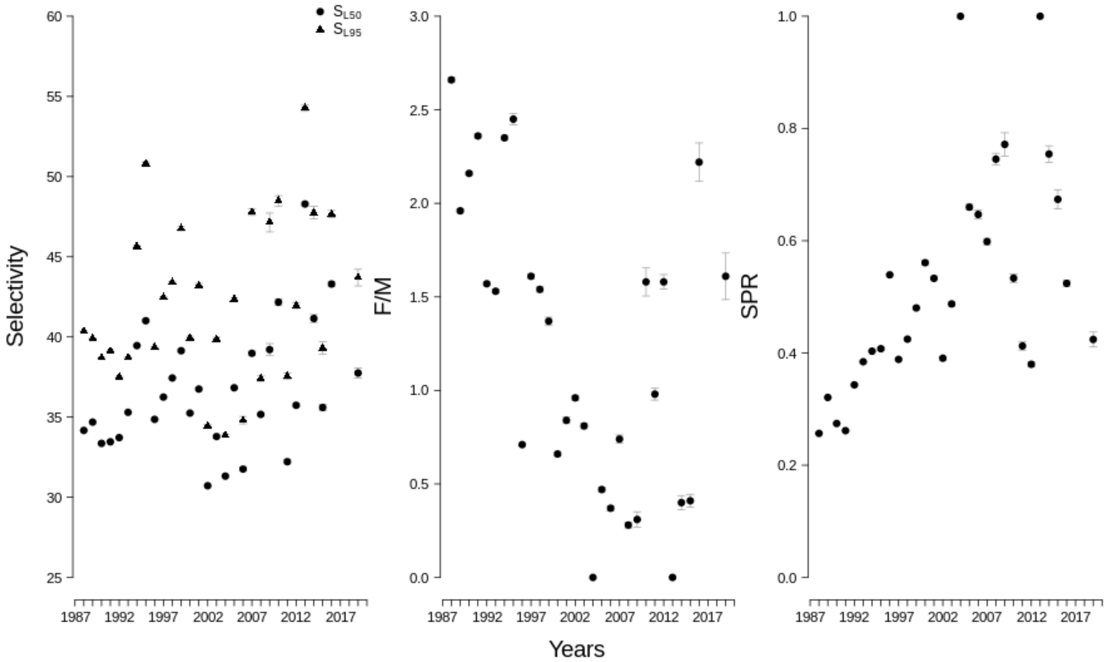


Figure 2.4.16. ***Nephrops*** **FU 31 females. Selectivity, F/M and SPR. In 2013 the model did not converge.**

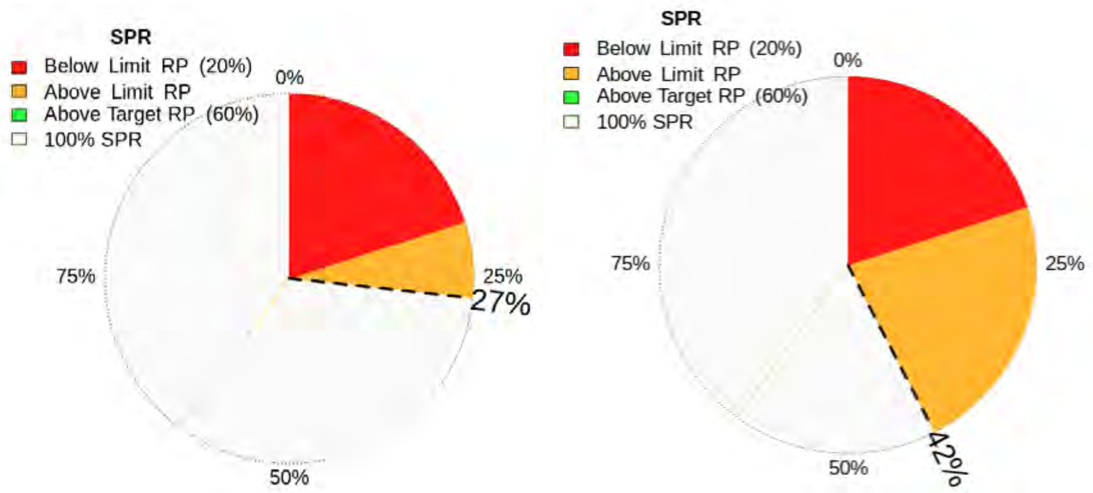


Figure 2.5.17. *Nephrops* FU 31. 2019 SPR. Males (left) and females (right).

According to this method, nowadays there would be the 27% of the spawning males and the 42% of the females of the original stock (Figure 2.4.17). The internationally accept SPR target for rebuilding a stock is 60%.

Issues about reference points estimation

SPR method it is not very suitable for FU 31 *Nephrops* because this FU is not in equilibrium and the recruitment was not constant along the time-series (see Figure 2.5.16 in section "Issues about reference points estimation in Mean Length-based estimators (Z)" section). Moreover, there is a high uncertainty about grown in *Nephrops*.

Conclusion

Present SPR in males and females are below of the target SPR of the stock.

Separable Cohort Analysis (SCA)

Method

Section 2.5 in ICES (2015) presents the method, data and information requirements, assumptions, outputs expected, method of operation, testing, caveats and software to which the reader is referred for further details.

Separable Cohort Analysis (SCA) is a statistical model which estimates recruitment, selectivity and fishing mortality by fitting to catch (and discards) by length and sex.

SCA works on the same general principles as Length Cohort Analysis (Jones, 1981) although LCA starts with the largest length classes and working backwards, whereas SCA estimates recruitment and works forwards. The main functional difference between the SCA and LCA is SCA's assumption of a parameterised selection pattern and the simultaneous fitting to male and female length distributions (assumption of equal recruitment).

SCA is not a dynamic assessment model, because it operates on length frequencies under the assumption of equilibrium (just as LCA does) and residuals from the model should be examined for evidence of gross departure from this assumption before any results are presented.

The method takes landings and discards (by length and sex) along with biological parameters for maturity and growth to estimate the recruitment and fishing pattern that has generated the observed length distributions. The model used to calculate reference points could assume sigmoid or domed selection, and estimates five parameters covering initial population size, two selection parameters and F for males and females (separately). Maturity and selectivity ogive parameters L25 and L50 are from the formula s=1/(1+(exp((L.50-LENGTH)/(L.50-L.25)))).

Critic assumptions

- Growth is continuous.
- Population is in equilibrium.
- Landings are taken throughout year.
- The change in availability with respect to length only affects females and is a function of size at first maturity.

In addition to these common assumptions, there are two other assumptions specific to the *Nephrops* application.

- Recruitment is equal between sexes.
- Recruitment occurs at smallest size in data on 1 January; selection functions for the fishery and follow a sigmoid or a dome curve.
- Survey represents an instantaneous snapshot in time.

Data & Parameters

Data used were 2019 catch length distributions by sex. Those data come from the Sentinel fishery carried out in July 2019.

Table 2.4.8. Input parameters.

Parameter	Males	Females
von Bertalanffy L∞ (mm)	86	63
von Bertalanffy k (yr-1)	0.15	0.1
Length weight a	0.00043	0.00043
Length weight b	3.16	3.16
Natural mortality M (yr-1)	0.3	0.2
L25 maturity (mm CL)	23.5	26.5
L50 maturity (mm CL)	25	28
UWTV	n.indiv	1
	Surv.time	0.5
	alpha	0.00001
	Tv.sel	16.5, 17
	f.range	0, 3, 0.005
	Discard.weight	1
Selection pattern	Sigmoid	
	Starting recruitment numbers	1.85
	LC25	39.1 mm CL
	LC50	1.076923077 (42 mm CL)
	F male	0.4
	F female	0.3

Results

Table 2.4.9. Results.

	Males	Females	Combined
$F_{0.1}$	0.04	0.04	0.04
$F_{35\%}$	0.04	0.13	0.13
F_{max}	0.11	0.22	0.14
$HR_{0.1}$ (%)	14	17	15
$HR_{35\%}$ (%)	12	32	30
HR_{max} (%)	26	41	31

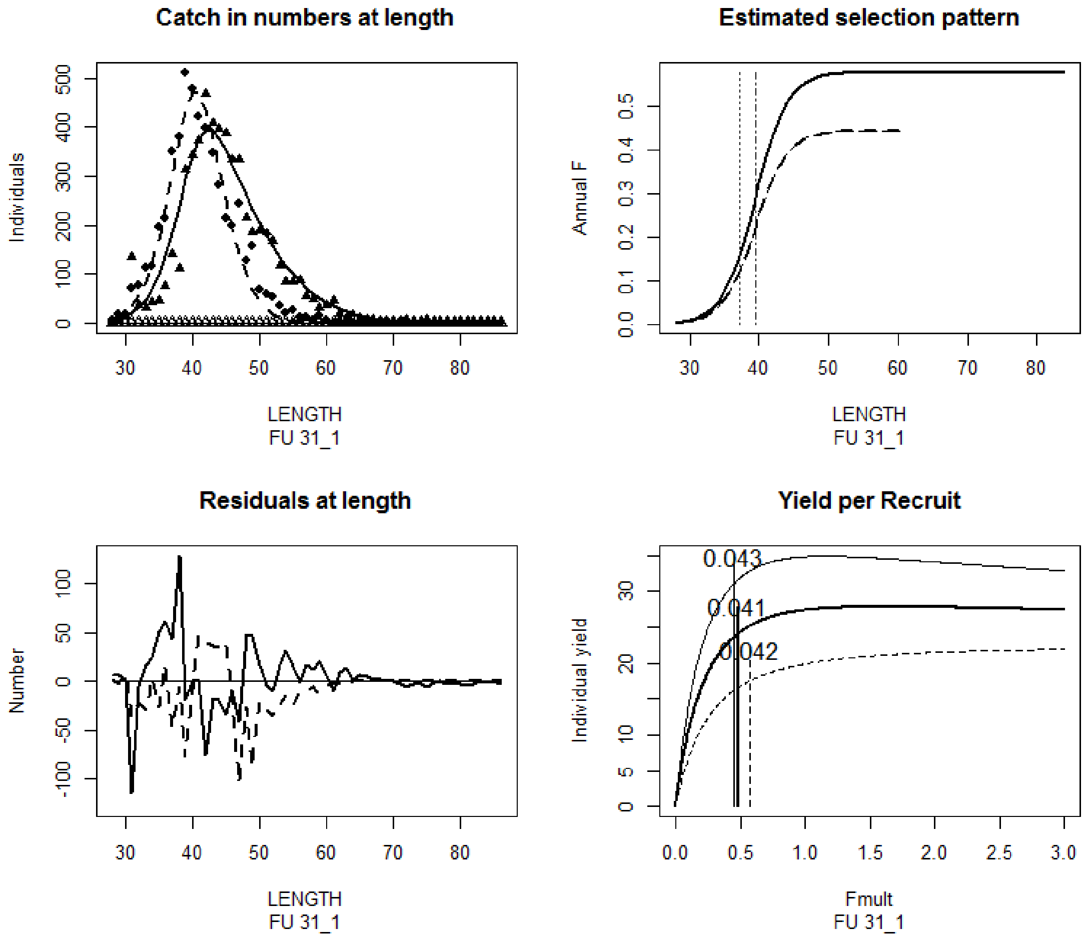


Figure 2.4.18. SCA for *Nephrops* in FU 31 in 2019. Triangles and solid lines are males, circles and are dashed lines are females and thick line are sexes combined. In Estimated selection pattern S_{25} is 37.2 mm CL and S_{50} 29.5 mm CL. Values in Yield per Recruit figure are $F_{0.1}$ values.

The full exploitation F estimate is around 0.4 for females and 0.6 for males.

2.4.3 Overview

Table 2.4.10. Overview of the methods used.

Necessities	Method: Mean length (Z)	LB Indicators	LB SPR	SCA	FU 31 situation
Assumptions					
Equilibrium	no		yes	yes	FU 31 no
Growth parameters (k, L_{inf}, L_0) known	yes	yes	yes		FU 31 yes, but general uncertainty in *Nephrops*
Constant Recruitment	yes		yes		FU 31 no
Knife >L_c	yes				
$L_{mat\ 50}$		yes	yes		FU 31 yes (from sampling), but with some uncertainty
$L_{mat\ 95}$			yes		FU 31 yes (from sampling), but with some uncertainty
Selectivity curve known			yes		FU 31 yes (from sampling)
Continuous growth				yes	yes
Data					
Max age	yes				FU 31 yes, but general uncertainty in *Nephrops*
M	yes	yes	no		FU 31 yes, but general uncertainty in *Nephrops*
M/K		yes	yes		FU 31 yes, but general uncertainty in *Nephrops*
Length weight parameters	yes				FU 31 yes (from sampling)
Results	One F by period; an unique $F_{0.1}$	Several parameters and indicators by year	Several indicators by year	Only last year available	

Issues and critical assumptions

There is a high uncertainty about the *Nephrops* life cycle parameters (k, L_{inf}, max age, M, t_0, a, b, males L_{mat}). The population structure of stocks with decades of high fishing pressure could have changed (e.g. decrease of individual maximum size). The estimation of the parameters (e.g. L_{inf}, k, a, b) with the present length distributions could fit models but not reflect the species original biological parameters.

If there is a contraction of a stock, the use of length-based methods without taking into account the whole scenario could overestimate the status of the stock. The different models used provide different estimates of the status of the stock. LBI Model seem to be very sensitive to changes in the inputs.

Several of the used methods assume:

1. Recruitment constant over time.
2. Population equilibrium.

conditions that FU 31 does not meet.

Roadmap for development

The improvement of the knowledge of *Nephrops* life cycle parameters. Explore more methods.

2.5 Data-limited approaches for FU28 and FU29

2.5.1 Stock and fisheries description

The Norway lobster (*Nephrops norvegicus*) is distributed along the continental slope off the southwest and south Portuguese coasts (FU 28 and FU29), at depths ranging from 200–800 m. Although FUs 28 and 29 are two different stocklets, landings records are not differentiated by FU and they are assessed together. This species and deep-water rose shrimp (*Parapenaeus longirostris*) are the main target species of a crustacean trawl fishery conducted in these FUs. They have a different but overlapping depth distribution. Rose shrimp occurs from 100–350 meters of depth whereas Norway lobster is distributed from 200–800 meters. The number of fishing trips directed to one species or to the other depends on the abundance of these species each year.

2.5.2 Data and life-history parameters

The available information for this stock comprises the following (ICES, 2019a):

- Length composition of the catches for the period 1984–2018. There are no discards on this fishery and then landings correspond to catches.
- Crustacean trawl survey index, 1997–2018 with some gaps.
- Standardized CPUE glm model, 1998–2018, using data from logbooks coupled with VMS records.
- Standardized effort, 1998–2018, derived from the CPUE standardization model.
- Life-history parameters:
  - Weight–Length relationship,
  - L_{50} for females (maturity ogive) and for males (breakpoint in segmented regression) (ICES, 2006),
  - Growth parameters (Figueiredo, 1989),
  - Natural mortality (assumed the same value of other NE Atlantic *Nephrops* stocks).

2.5.3 Stock assessment and advice

Before 2012, *Nephrops* FU 28–29 was assessed with XSA (eXtended Survival Analysis), using the length composition of the catches transformed in ages by slicing. This method has proved generally not to be appropriate for *Nephrops* stocks and abandoned. Since then, *Nephrops* FU 28–29 was considered within ICES category 3, i.e. a data-limited stock for which survey or other available indices provide reliable indications of trends in stock metrics, such as total mortality, recruitment, and biomass. The advice is based on the precautionary approach and the state of the stock and its exploitation are assessed relative to proxies for MSY reference points.

It has been assessed using the methods developed in WKLIFE-V (ICES, 2015) and first applied in WKProxy (ICES, 2016) to set the proxies for MSY reference points for several stocks. The methods used for this stock (based on the length composition of the catches and effort) include:

- Length-Based Indicators, LBI (Cope and Punt, 2009).
- Mean-length Z, G&H (Gedamke and Hoenig, 2006).
- Mean-length Z with effort, THoG (Then *et al.*, 2017).

The exploitation status is determined using the Mean Length Z with effort and comparing the F trends and values with the F_{MSY} proxy ($F_{0.1}$) obtained from the Y/R curve. M is an external input and assumed to be constant. There is no proxy for B_{MSY}, so it is not possible to evaluate the stock status condition. A qualitative evaluation of the stock status is based on the biomass index (standardized commercial CPUE) trend.

The advice is based on ICES rule for category 3 stocks, the HCR rule known as "2-over-3" rule, i.e. based on the ratio between the mean value of the biomass index for the two last years over the mean of the three preceding years, multiplied by the last advised catch:

$$C_{y+1} = C_{y-1}\left(\frac{\sum_{i=y-x}^{y-1} I_i/x}{\sum_{i=y-z}^{y-x-1} I_i/(z-x)}\right)$$

where y is the intermediate year (or assessment year), $x = 2$ and $z = 5$. Other factors are applied to this catch as the uncertainty cap (limiting the increase or decrease of the catch to ±20%) and a precautionary buffer (-20% when the stock status relative to candidate reference points for stock size or exploitation is unknown).

This rule, applied until 2019, was modified in WKLIFE VIII and WKLIFE IX based on simulation work, to include other factors related to MSY length-based proxies, $I_{trigger}$ (the lowest biomass index observed) and k and to include a stability clause (ICES, 2018, 2019c). This modified rule is proposed to be applied from 2021 onwards.

Based on these methods, the stock is considered not overfished with F below the F_{MSY} proxy ($F_{0.1}$), with an increasing trend in biomass in the last five years (ICES, 2019a, 2019b).

2.5.4 Further explorations

In WKNephrops 2019, further explorations of these and other length-based methods were performed and are summarized below. Some of the results are an update of the application of the same methods used in WKProxy (ICES, 2016) and in subsequent annual assessment expert meetings, while others constitute approaches not considered earlier for these stocks.

2.5.4.1 Length-based indicators (LBI)

Main indicators (ICES, 2015):

Indicator	Calculation	Reference point	Indicator ratio	Expected value	Property
Lmax5%	Mean length of largest 5%	Linf	Lmax5%/Linf	>0.8	Conservation (large individuals)
L95%	95th percentile		L95%/Linf		
Pmega	Proportion of individuals above Lopt+10%	0.3–0.4	Pmega	>0.3	
L25%	25th percentile of length distribution	Lmat	L25%/Lmat	>1	Conservation (immatures)
Lc	Length at first catch (length at 50% of mode)	Lmat	Lc/Lmat	>1	
Lmean	Mean length of individuals larger Lc	Lopt = 2/3 Linf	Lmean/Lopt	≈1	Optimal yield
Lmaxy	Length class with maximum biomass in catch	Lopt = 2/3 Linf	Lmaxy/Lopt	≈1	
Lmean	Mean length of individuals larger Lc	LF=M = (0.75Lc+0.25Linf)	Lmean/LF=M	≥1	MSY

Input data:

INPUT (in mm)	Males	Females
Length composition by sex	1984–2018	
Mean weight by length class and sex	1984–2018	
L_{inf}	70 mm	65 mm
L_{mat}	28.4 mm	26.6 mm

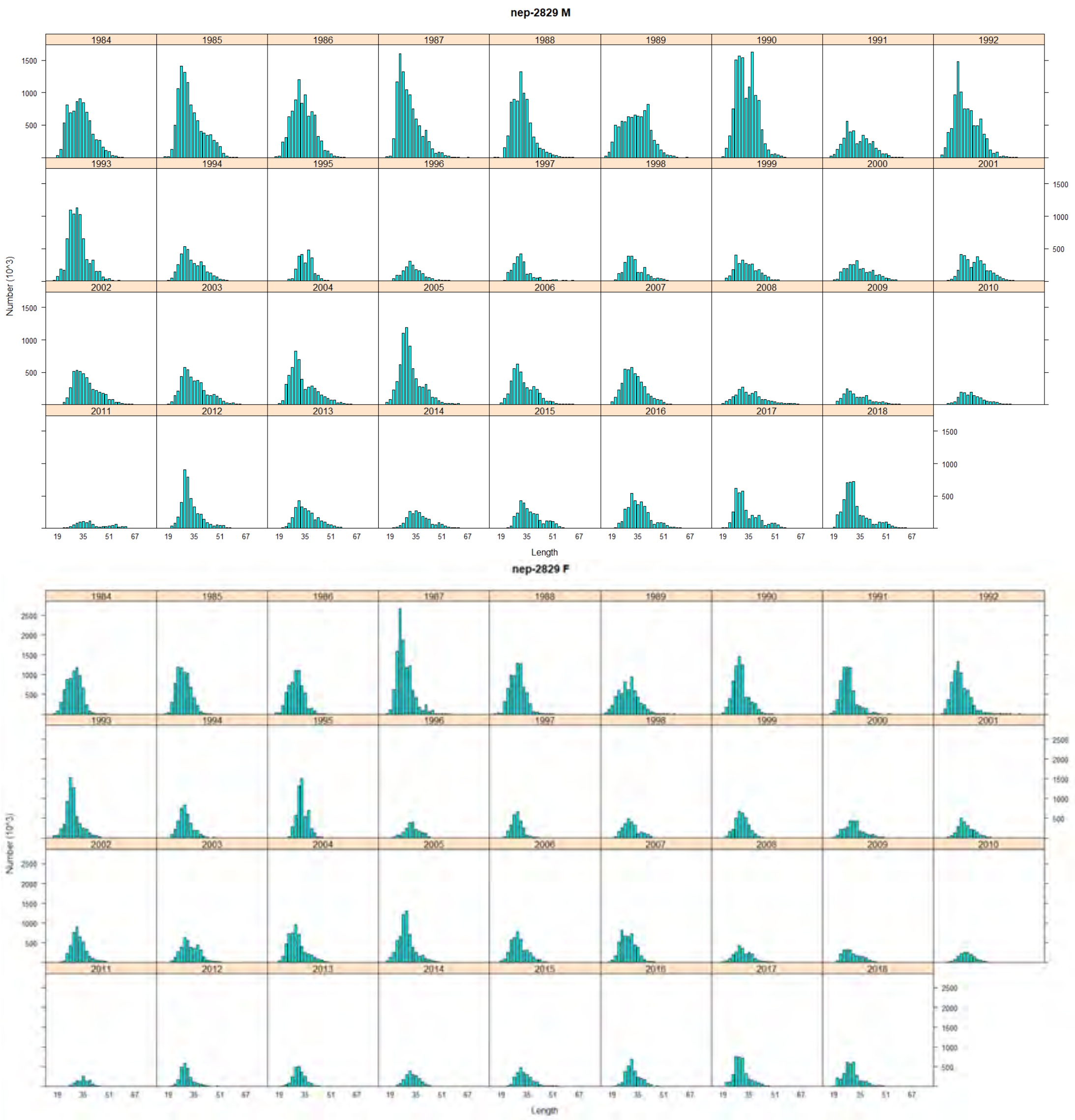


Figure 2.5.1. nep.fu.2829 – Length composition of *Nephrops* catches in FUs 28–29 by sex, for the period 1984–2018 (in 2 mm carapace length classes).

Results

Table 2.5.2 below shows the results of the indicator ratios for the last three years. Figure 2.5.2 shows the time-series for the indicators and ratios.

Table 2.5.2. *Nephrops* FUs 28–29 Length-based screening, traffic light indicators.

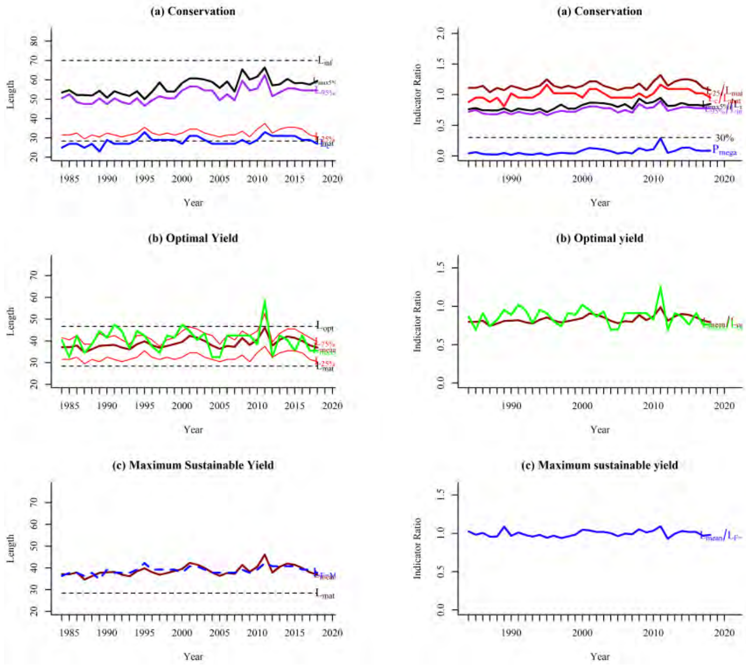
Sex	Year	Conservation				Optimizing Yield	MSY
		L_c/L_{mat}	$L_{25\%}/L_{mat}$	$L_{max5\%}/L_{inf}$	P_{mega}	L_{mean}/L_{opt}	$L_{mean}/L_{F=M}$
		>1	>1	>0.8	>30%	~1 (>0.9)	≥1
Males	2016	1.02	1.11	0.82	0.08	0.81	1.02
	2017	1.02	1.21	0.83	0.09	0.86	0.97
	2018	0.95	1.07	0.85	0.09	0.79	0.98
Females	2016	1.09	1.22	0.73	0.01	0.84	0.95
	2017	1.09	1.15	0.73	0.02	0.81	0.92
	2018	1.02	1.15	0.78	0.03	0.81	0.96

Looking at the L_c/L_{mat} and $L_{25\%}/L_{mat}$ ratios series for *Nephrops* in FUs 28–29 (Figure 2.5.2), there are no concerns regarding fishing on immature individuals.

Across the time-series, a lack of mega-spawners (P_{mega}) in the catches is observed. $L_{max5\%}/L_{inf}$ is relatively close to the lower limit of 0.8. This may indicate some truncation in length distribution in catches.

The mean length is stable across the time-series. The catch is close to the theoretical length of optimal yield. However, looking at Figure 2.5.2 the core distribution (between 25th and 75th percentile) is below the optimal length. The mean length is close to the MSY proxy of $L_{F=M}$.

Males



Females

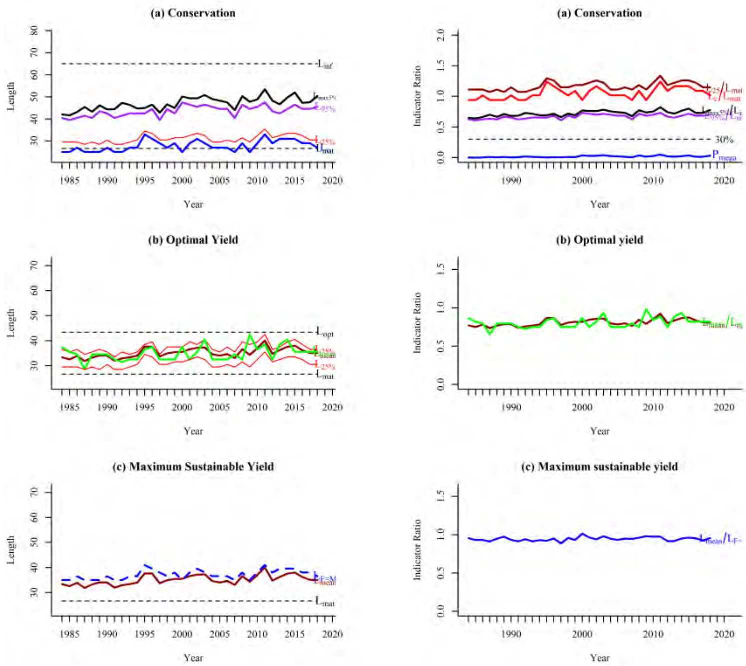


Figure 2.5.2. Length indicators and ratios for *Nephrops* in FU 28–29 (Males – upper panel, Females – lower panel; indicators – left panel, indicators ratios – right panel).

The overall perception from the length-based indicators analysis is that, in 2014 the stock was fished sustainably at levels close to optimum yield and with exploitation at MSY level.

Mean Length Z (Gedamke and Hoenig, 2006 and Then, 2017)

Input data:

- Length distribution time-series: Landings length composition by sex, 1984–2018. Discards considered negligible.
- Fishing effort: Standardized fishing effort time-series, 1998–2018.
- Parameters:

Parameter	Males	Females
Von Bertalanffy L_∞ (mm)	70	65
Von Bertalanffy k (yr^{-1})	0.2	0.065
Length–weight a	0.0028	0.0056
Length–weight b	3.2229	3.0288
Natural mortality M (yr^{-1})	0.3	0.2
Length-at-maturity (mm)	28.4	26.6

The mean length-based mortality estimator of Gedamke and Hoenig (2006) is a non-equilibrium extension of the Beverton and Holt (1957) mean length mortality estimator. Gedamke and Hoenig (2006) derived the transitional behaviour of the population mean length following a change in instantaneous total mortality (Z) and then generalized the derivation to include length changes due to multiple changes in total mortality. From a time-series of mean length data, total mortality rates are estimated in blocks of time as well as the years in which the mortality changed. The model uses a likelihood approach to obtain parameters that maximize goodness-of-fit to the mean length data. With an external estimate of the natural mortality rate (M), the fishing mortality rate (F) in the most recent time block of the time-series can be derived.

The model assumes (Gedamke and Hoenig, 2006) that:

- recruitment is constant over time,
- growth is deterministic, follows a von Bertalanffy growth equation and is time-invariant, and
- selectivity is knife-edge above the length of full selectivity (Lc) and is time-invariant.

The peak of the time-aggregated length–frequency histogram was at the 32.5 mm length bin for both males and females. Mean lengths above L_c were calculated. Although immature female *Nephrops* have different life history compared to mature animals, as L_c is above L_{mat}, immature females were not modelled.

Figure 3 shows the diagnostics output from the application of the method. Two Z periods were found either for males or for females, with different break years, 1997 for males and 1993 for females.

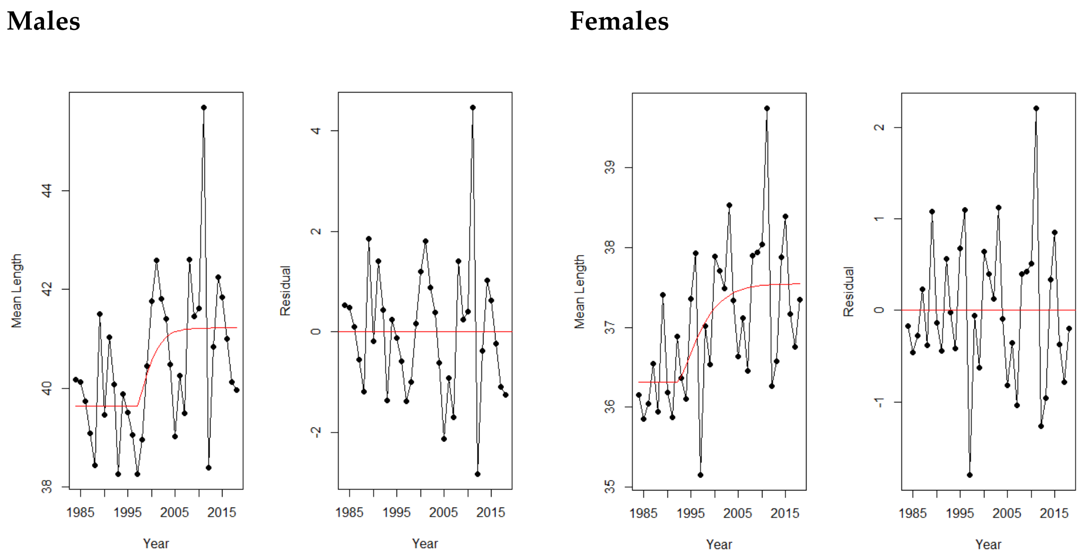


Figure 2.5.3. *Nephrops* in FUs 28–29. Observed and fitted mean lengths and residuals for males (left) and females (right).

Then *et al.* (2017) modified the Gedamke and Hoenig method (G&H), adding a time-series of effort, and estimate year-specific fishing and total mortality rates (*Fy*, *Zy*). The method, hereinafter referred as THoG, also estimates the catchability coefficient *q* and natural mortality *M* (or, if *M* is fixed, just *q* is estimated).

Reference points for fishing mortality rate were obtained using the Length-Based Yield per Recruit program. $F_{0.1}$, a proxy of F_{MSY}, was estimated to be 0.22 for males and 0.26 for females.

Figure 2.5.4 presents the time-series of *F* obtained with fixed *M* using the THoG method with effort data for the period 1998–2018, compared to $F_{0.1}$, for males and females.

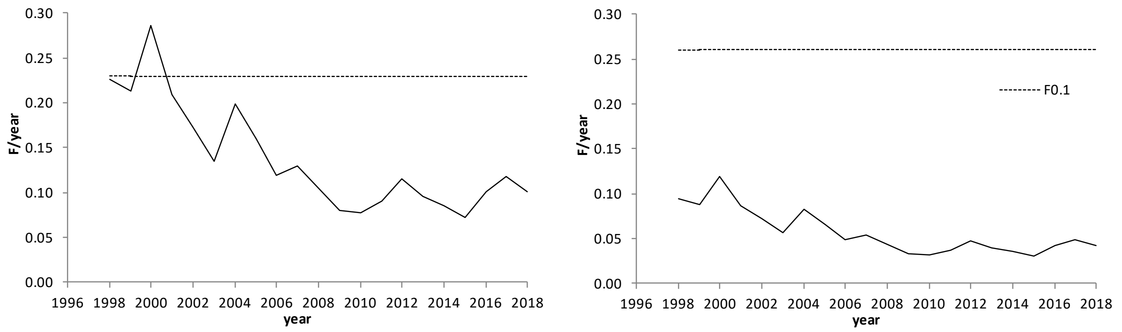


Figure 2.5.4. Time-series (1998–2018) of annual fishing mortality for males (left) and females (right), from THoG method. Horizontal dashed line represents the reference point $F_{0.1}$.

Table 2.5.3 summarizes the input and output of the Mean Length method using both methods.

Table 2.5.3. Summary of the input data and results from Gedamke & Hoenig and THoG methods.

		Males	Females
	Input:		
	LFD period	1984-2018	1984-2018
	Effort series	1998-2018	1998-2018
	Growth		
	Linf =	70	65
	K =	0.2	0.065
	t0 =	-0.15	-0.15
	W~L relationship		
	a =	0.00028	0.00056
	b =	3.2229	3.0288
	External M	0.3	0.2
Method	**Results**		
Gedamke & Hoenig	Z =	0.47	0.29
	F* =	0.17	0.09
THoG	q estimate =	0.004	0.001
	q estimate* =	0.025	0.010
	M estimate =	0.45	0.26
	F_{2018} estimate =	0.02	0.01
	F_{2018} estimate* =	0.10	0.04
Y/R	F_{MSY} proxy: $F_{0.1}$ =	0.22	0.26

* indicates estimates with external fixed M

Separable Cohort Analysis (SCA)

SCA R package (Bell, 2019), version 1.2.0, was used to estimate F reference points for *Nephrops* FU 28–29 and the fishing mortality for the last 3-year period (2016–2018).

The method has been used to estimate reference points for several *Nephrops* FUs with TV surveys and it is described in Annex 5 of WKNEPH 2009 report (ICES, 2009).

Input data:

- Landings and discards length composition by sex.
- Biological parameters: growth, maturity and natural mortality, discards survivability.
- Selectivity parameters.

The results and diagnostics of the model are shown in Figure 5 and the F values from the Y/R are presented in Table 2.5.4.

Table 2.5.4. SCA output. F reference points from Y/R curves.

	Males			Females		
	mult	F	HR	mult	F	HR
$F_{0.1}$	0.41	0.22	8.8%	0.76	0.20	14.6%
F_{MAX}	0.82	0.43	15.5%	3.24	0.85	35.0%
$F_{35\%SpR}$	0.34	0.18	7.5%	0.94	0.25	17.2%

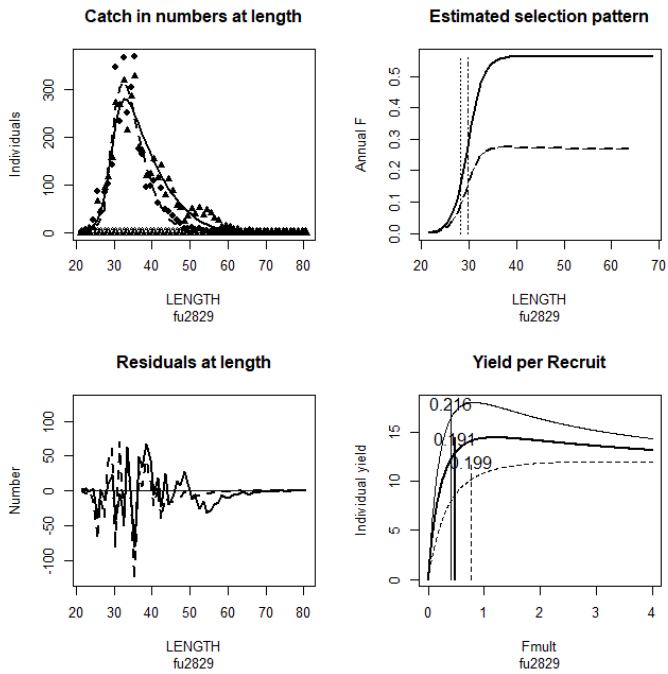


Figure 2.5.5. SCA Output and diagnostics for *Nephrops* FU 28–29.

Separable Length Cohort Analysis (SLCA)

F reference points were also estimated using a separable length cohort analysis (SLCA) with the package nepref, version 0.2.2 (Dobby, 2019), which uses the same input as SCA.

The estimation uses a separable length cohort analysis with a length dependent logistic ogive for fishing mortality which is estimated by fitting to the observed dead catch at length data (total landings and dead discards) making an assumption about the discard survival. The estimated parameters are then used in a per-recruit analysis.

Table 2.5.5 and Figure 2.5.6 summarize the results from the Y/R analysis for *Nephrops* FU 28–29.

Table 2.5.5. SLCA output. F reference points from Y/R curves.

	Males			Females		
	mult	F	HR	mult	F	HR
$F_{0.1}$	0.24	0.22	7.6%	0.43	0.20	11.7%
F_{MAX}	0.49	0.45	12.7%	3.25	1.48	30.9%
$F_{35\%SpR}$	0.29	0.27	8.8%	0.69	0.31	15.7%

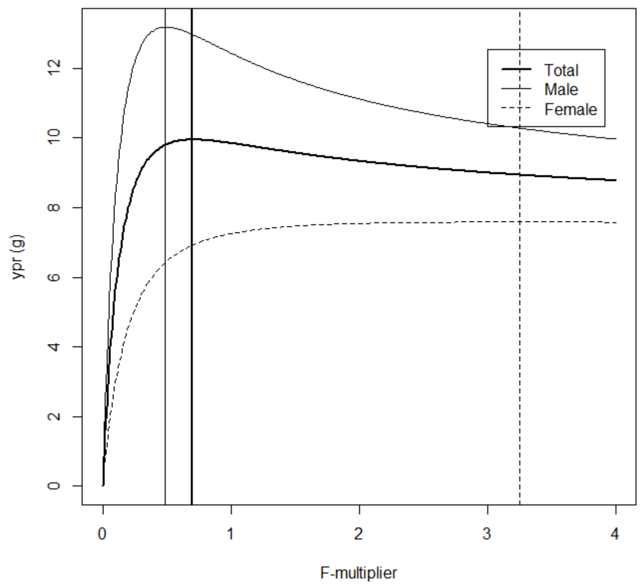


Figure 2.5.6. SLCA: Y/R curves for *Nephrops* FU 28–29, male and female.

Stochastic Surplus Production model in Continuous Time (SPiCT)

The Stochastic Surplus Production model in Continuous-Time (SPiCT) (Pedersen and Berg, 2017) was used for *Nephrops* FU 28–29, males and females combined. SPiCT is formulated as a state–space model and incorporates dynamics related both to the fisheries (F) and to the biomass (B) in the form of Pella and Tomlinson (1969), which are related to the observed data (catches and CPUE).

$$\frac{dB_t}{dt} = \frac{r}{n-1} B_t \left(1 - \left[\frac{B_t}{K}\right]^{n-1}\right) - F_t B_t$$

Where:

- B_t is the exploitable stock biomass,
- F_t is the fishing mortality,
- r is intrinsic growth rate,
- K is the carrying capacity, and
- n is the parameter determining the shape of the production curve.

Several runs were performed using as input the total catches for the period 1984–2018, and

- two biomass indices: standardized commercial CPUE (1998–2018) and survey biomass index (1997–2018);
- standardized commercial CPUE only (1998–2018);
- survey biomass index only (1997–2018);
- and standardized effort only (1998–2018).

The prior for n was set as 2, corresponding to the Schaeffer model. Uncertainty was added to the catches prior to 1993 and to the survey index in years 2010 and 2014, which were extreme values. All the parameters are estimated by the model. Table 2.5.6 summarizes the results of the four runs.

Table 2.5.6. Summary of SPiCT results.

	Biomass indices			
	surv+cpue	surv	cpue	effort
K	2787	3274	2539	2019
r	0.68	0.58	0.64	0.83
q1 (CPUE)	0.00240		0.00291	
q2 (survey)	0.00163	0.00151		
qf (effort)				0.000004
B_{2018}	2586	2733	2152	1686
B_{2018}/K	1.91	1.94	1.69	1.66
F_{2018}	0.11	0.10	0.13	0.16
F_{2018}/F_{MSY}	0.39	0.35	0.48	0.44
F_{MSY}	0.28	0.31	0.27	0.37
MSY	375	406	344	376

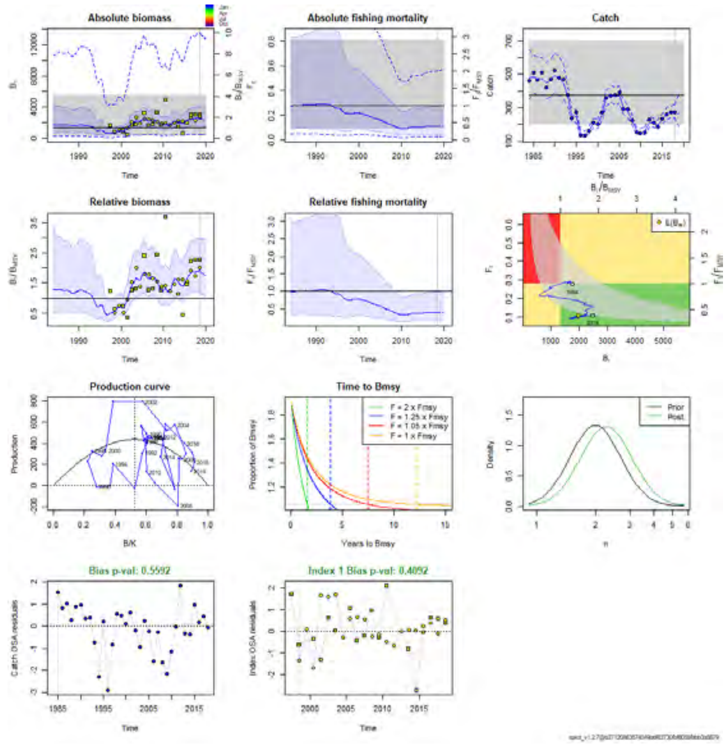


Figure 2.5.7. SPiCT output plots from the model with standardized CPUE and survey index together. Estimates (biomass, fishing mortality, catch, production) are shown using blue lines, 95% CIs of absolute quantities in dashed blue lines, 95% CIs of relative biomass and fishing mortality in shaded blue regions, estimates of reference points (BMSY, FMSY, MSY) represented by black lines and 95% CIs of reference points are shown using grey shaded regions. The two biomass indices used are shown in different colours.

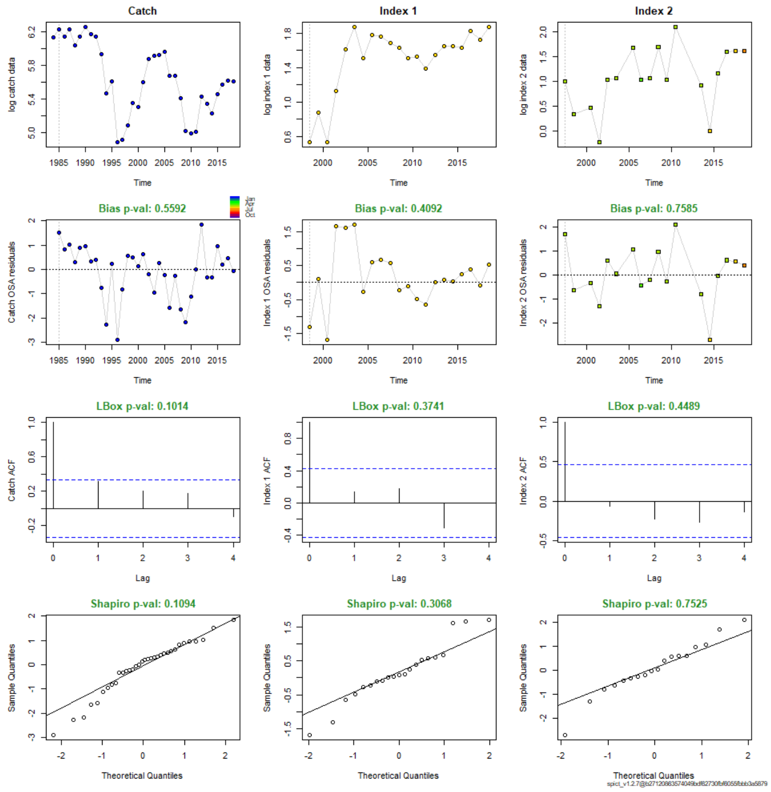


Figure 2.5.8. SPiCT output plots from the model with standardized CPUE and survey index together. Diagnostic plots.

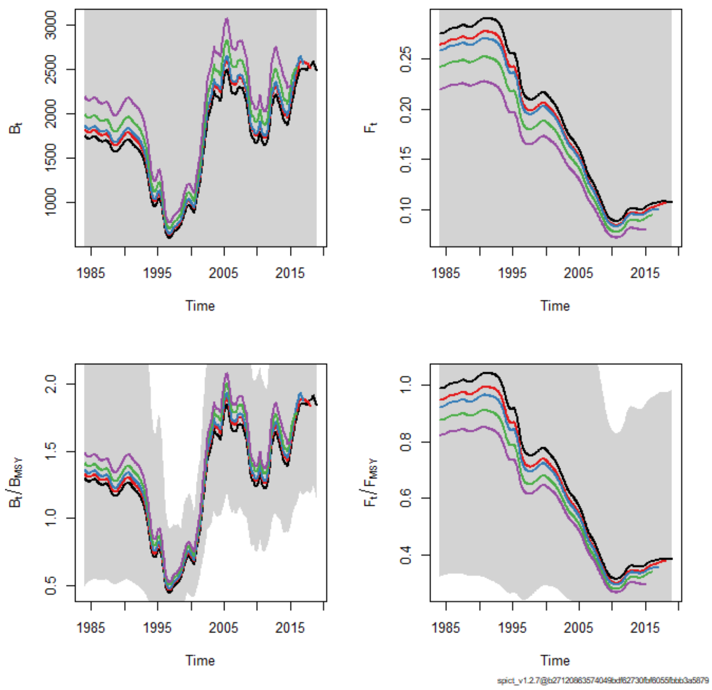


Figure 2.5.9. SPiCT output plots from the model with standardized CPUE and survey index together. Retrospective pattern.

The best model was the one where both biomass indices, the standardized CPUE and the survey index, were jointly used (Figures 2.5.7–2.5.9). No significant bias was observed in the OSA (one-step-ahead) residuals. Both QQ-plot and the Shapiro test show normality in the residuals. Some retrospective pattern is observed, suggesting some past underestimation of fishing mortality and overestimation of biomass. However, each peel of the retro is within the 95% confidence intervals of the assessment which are very wide.

Length-based Stock Potential Ratio (LBSPR)

In general, the Stock Potential Ratio is defined as the ratio of the total reproductive production at equilibrium for a given level of fishing mortality divided by the reproductive production in the unfished state, and represents the expected equilibrium SPR if a stock was held indefinitely at the given fishing mortality and recruitment was constant. It is a direct function of instantaneous fishing mortality (F), the selectivity of the fishery, and the maturity schedule for the species. The Length-based Spawning Potential Ratio method uses maximum likelihood methods to find the values of relative fishing mortality (F/M) and selectivity-at-length that minimize the difference between the observed and the expected length composition of the catch, and calculates the resulting SPR (Hordyk *et al*., 2015).

Like any assessment method, the LBSPR model relies on a number of simplifying assumptions. In particular, the LBSPR models are equilibrium based, and assume that the length composition data are representative of the exploited population at steady state.

The LBSPR method has been developed for data-limited fisheries, data requested are:

- A representative sample of the size structure of the catch.
- An understanding of the life history of the species.

The LBSPR method does not require knowledge of the natural mortality rate, but instead uses the ratio of natural mortality and the von Bertalanffy growth coefficient, M/K, which is believed to vary less across stocks and species than M (Prince *et al*., 2015).

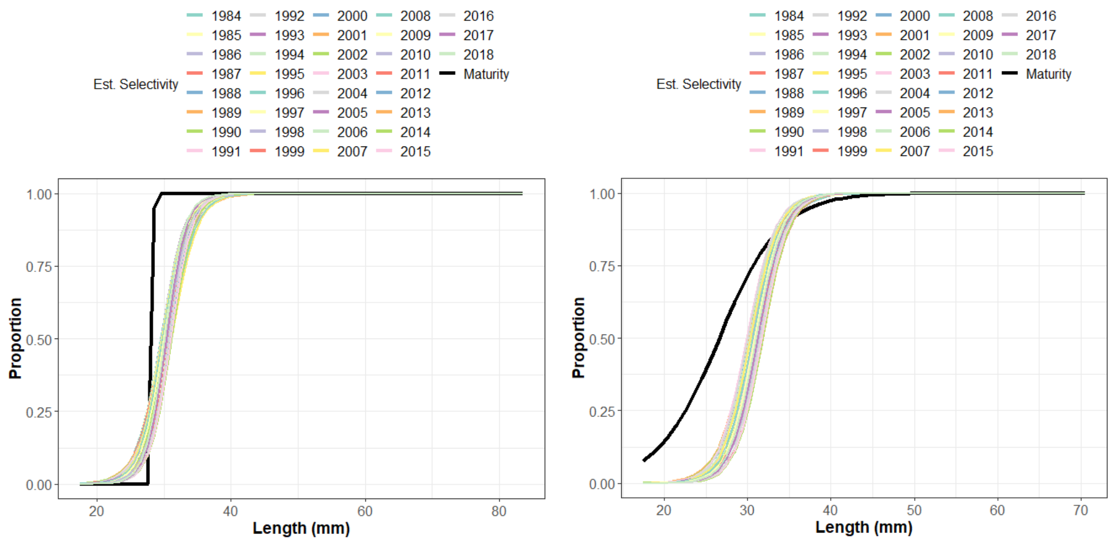


Figure 2.5.10. *Nephrops* FU 28–29. Selectivity and maturity ogives for males (left) and females (right).

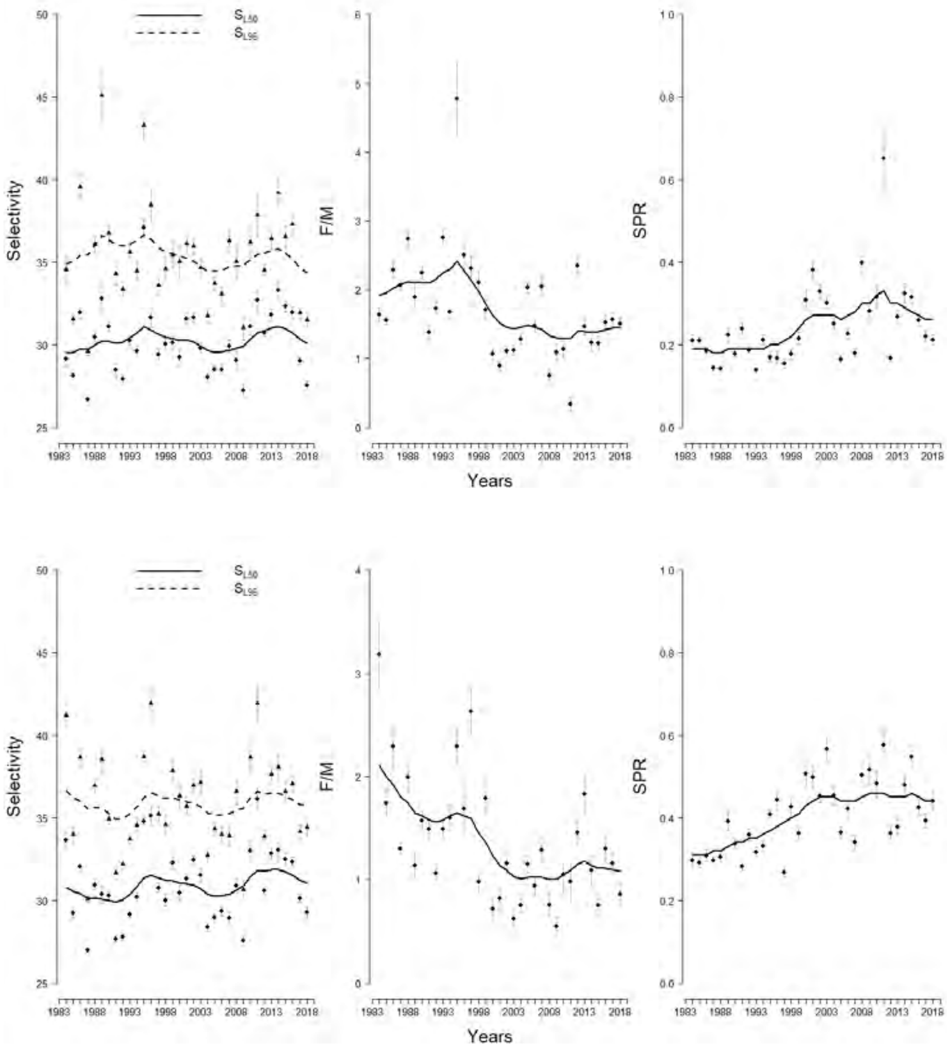


Figure 2.5.11. *Nephrops* FU 28–29. LB-SPR outputs: Selectivity, F/M and Spawning Potential Ratio for males (upper panel) and females (lower panel) with 95% confidence intervals and a smoother.

A SPR in the range of 35%–40% are usually considered a population at MSY level although this is a quite variable parameter. A population with SPR below 0.1–0.15 are considered collapsed. The lowest values of F/M and the highest SPR for males and females were obtained after the year 2000 with the Spawning Potential Ratio between 26% and 33% for males and ≥43% for females.

2.5.5 Summary

From Length-Based Indicators (LBI), we conclude that stock is being sustainably fished at levels close to optimum yield and with exploitation at MSY level.

Reference points were determined from the Y/R curves for males and females. F_{MAX} is not well defined and $F_{0.1}$ was set as a proxy of F_{MSY} for this stock. The estimation of Y/R reference points is integrated in the functions built for the Mean Length Z and in the packages SCA and SLCA.

Both approaches of Mean Length Z and SPiCT indicate that the stock is being fished at a level below MSY and the F trends are the same. However, SCA and SLCA indicate the opposite, i.e. the stock is being exploited at a level higher than $F_{0.1}$.

The LB-SPR method indicates that the Spawning Potential Ratio of this stock increased in the last two decades and it is above 40% for females and below 30% for males.

2.6 Data-limited approaches for FU30

2.6.1 Stock summary

Nephrops in FU 30 is exploited mainly by a unique Spanish bottom otter trawl métier (OTB_MCD≥55_0_0) and in a small proportion by the Portuguese fleet. It is considered a multi-specific fishery targeting to a variety of crustaceans, cephalopods and demersal fish (Rose shrimp, *Nephrops*, Tiger shrimp, Spottail shrimp, Octopus, squids, cuttefish, hake, mullets, sparids, wedge sole, sole, Horse-mackerel…) using a mesh size of 55 mm. Discard is negligible.

This stock is currently classified by ICES as category 3, in spite of a lot of information is available. FU30 was benchmarked in 2016 and the UWTV survey based approach was proposed to generate catch options (ICES, 2016). UWTV survey was considered appropriated for providing scientific advice on the abundance of this stock. However, MSY reference points could not be derived so ICES cannot assess the stock and exploitation status relative to MSY reference points. On the other hand, PA reference points are also not available.

2.6.2 Data

Table 1 summarizes the main input for the application of different methods to derived indicators of the status of this stock or reference points.

Settings and initial parameters used in the Separable Cohort Analysis is detailed in the Table 2.6.2. The SCA R package (Bell, 2019), version 1.2.0, was used for this purpose. Full code and input files are available at WKNephrops 2019 SharePoint.

Table 2.6.1. *Nephrops* FU30 (Gulf of Cadiz). Life-history data, length composition and effort series period used, as well as, abundance from UWTV surveys used as input in the models.

PARAMETERS	MALES	IMMATURE FEMALES	MATURE FEMALES
Growth-K	0.2	0.2	0.065
Growth-L_∞ (mm)	70	70	65
Natural Mortality	0.3	0.3	0.2
Length–Weight-a	0.000845		0.001873
Length–Weight-b	2.953452		2.726119
Size at first maturity CL_{50}(mm)	28.4		26.5
CL_{25}(mm)	25.3		22.5
Length frequency distribution	2009–2018	2009–2018	
Direct *Nephrops* effort series*	2009–2018	2009–2018	
TV abundance (millions individuals)	2015= 298 2016= 233 2017= 371	2018= 329 2019= 113	

***Fishing trips with at least 10% *Nephrops* in catches.**

Table 2.6.2. *Nephrops* FU30 (Gulf of Cadiz). Settings and initial parameters used in the Ewen's SCA R package.

Length frequency distribution (three year average)	**2016–2018**
TV abundance (millions individuals) (three year average/last survey)	2016–2018 / 2019
Discard survival	0%
Surv.time	0.5
TV.sel	16.5–17
Alpha (low weight / off weight)	0.0001/ 0
f.range	seq(0, 3, 0.005)
discard.weight	c(1)
initial.parameters (Sigmoid Selection)	c(1.85,26,1.12,0.4,0.30)
initial.parameters (Domed Selection)	c(1.85,26,1.12,0.4,0.30,1.15,1.15,0.5)

2.6.3 Methods

Different models have been applied during WKNephrops. Some of them are methods developed for data-limited stocks as Length Based Indicators (LBI) or Mean Length-Z. In addition, the Separable Cohort Analysis (SCA-Ewen's model), used for calculating MSY reference points for category 1 *Nephrops* stocks, was also explored.

Figure 2.6.1 shows the length compositions by sex for the 2009 to 2018 period, which are inputs for LBI and Mean Length Z methods.

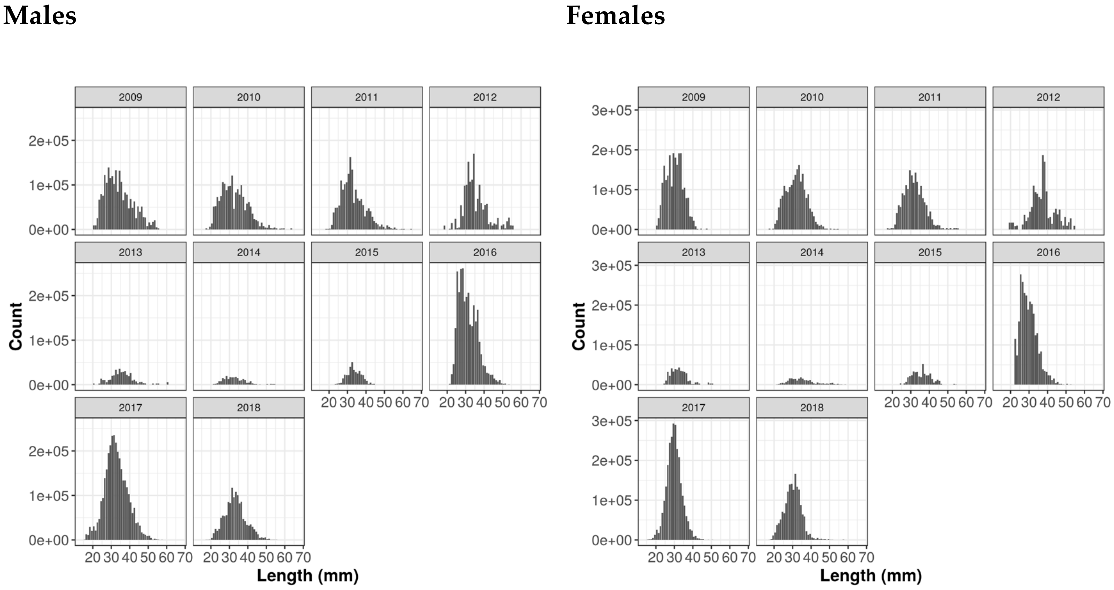


Figure 2.6.1. *Nephrops* FU30 (Gulf of Cadiz). Length distributions of catches in males and females from 2009 to 2018. Discards are considered negligible.

2.6.4 Results

Length B Indicators (LBI)

Results are presented below in a traffic light system, according to conservation/sustainability, yield optimization and MSY considerations.

Sex	Year	Conservation				Optimizing Yield	MSY
		L_c / L_{mat} >1	$L_{25\%}$ / L_{mat} >1	$L_{max5\%}$ / L_{inf} >0.8	P_{mega} >0.3	L_{mean} / L_{opt} ≈ 1 (>0.90)	L_{mean} / $L_{F=M}$ ≥1
Males	2016	0.88	0.95	0.64	0	0.68	0.87
	2017	0.95	1.02	0.66	0	0.73	0.90
	2018	0.95	1.02	0.66	0	0.74	0.91
Females	2016	0.94	1.02	0.64	0.10	0.95	0.99
	2017	1.02	1.02	0.60	0.07	0.97	0.96
	2018	1.02	1.02	0.62	0.09	0.99	0.98

Male L_c is below L_{mat} across the entire time-series. However, $L_{25\%}$ is above L_{mat} in two last years. In the case of females, L_c and $L_{25\%}$ are at or slightly above L_{mat}. The exploitation on immatures makes the stock vulnerable to overexploitation.

In the recent years, as well as across the time-series, a lack of mega-spawners (P_{mega}) in the catches can be observed. $L_{max5\%}/L_{inf}$ is relatively close to the lower limit of 0.8. This may indicate some truncation in length distribution in catches.

In the three last years, the females catch is close to the theoretical length of optimal yield (L_{opt}) but not in the case of the males. The mean length is close to the MSY proxy of LF=M, mainly in females.

In conclusion, the overall perception from the LBI analysis is that in 2018, the stock was not exploited sustainably for both sexes (at levels close to optimum yield only for females) and the exploitation was slightly above MSY proxy. Nevertheless, according to the conservation criteria, the fishery was also taking small individuals, below L_{mat}.

Mean Length-Z

The peak of the length frequency distributions, or the assumed L_c for males and females was at the value of 31 mm and 32 mm of CL, respectively (Figure 2). Figures 3 and 4 show the output plots from the Gedamke-Hoenig and THoG models.

The Gedamke-Hoening model produced a single estimate of Z for both sexes. The THoG model was highly sensitive to starting values of M, mainly in males, producing very high M estimates and negatives *q* estimates, that were not consistent with what is currently believe about this FU. Therefore, M was fixed at 0.3 for males and 0.2 for females in this model.

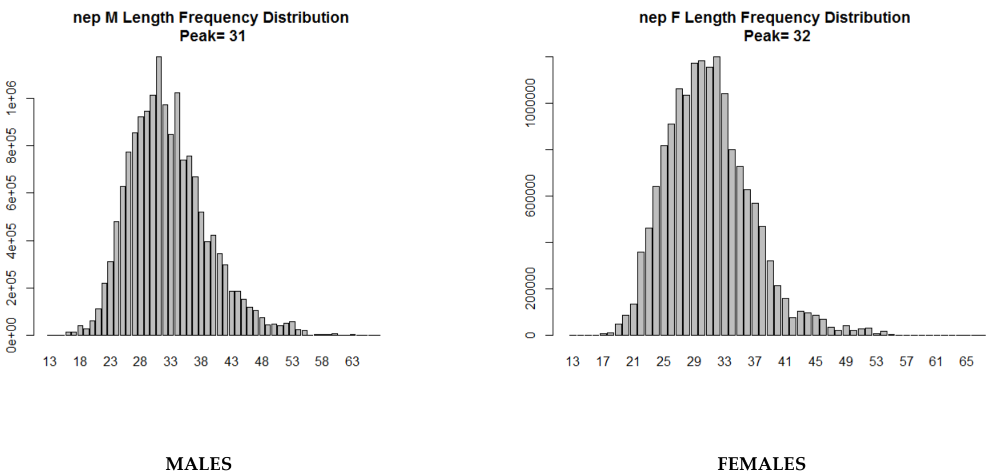


Figure 2.6.2. *Nephrops* FU30 (Gulf of Cadiz). Length frequency distribution aggregated over all years (2009–2018) for both sexes.

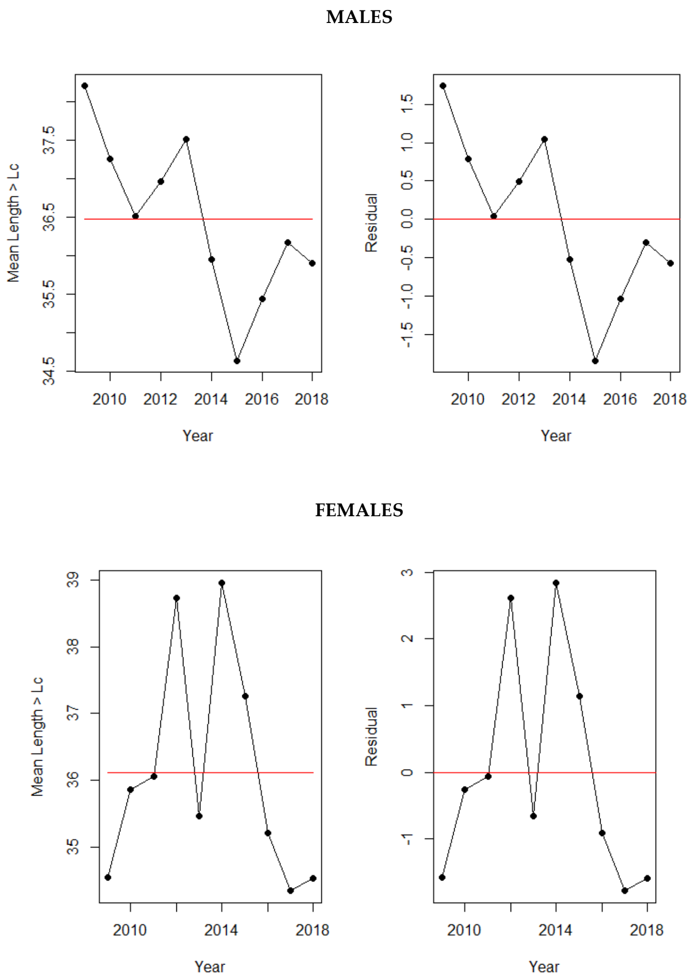


Figure 2.6.3. *Nephrops* FU30 (Gulf of Cadiz). Observed and fitted mean lengths for males and females from Gedamke and Hoening model.

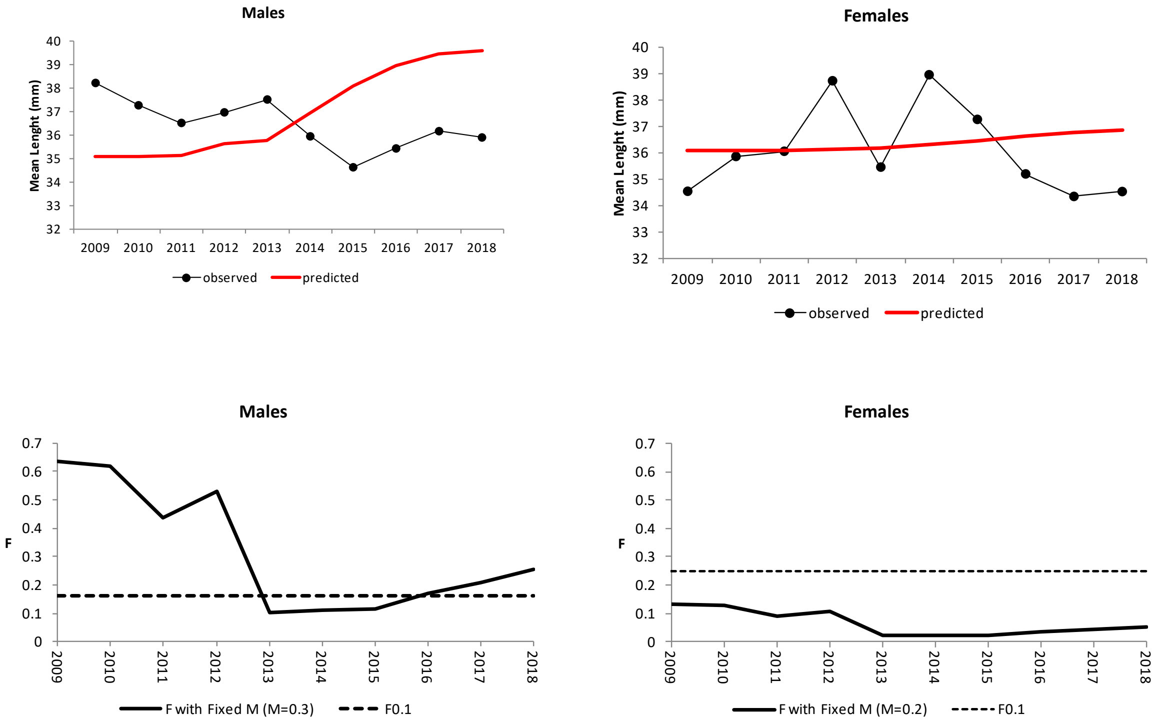


Figure 2.6.4. *Nephrops* FU30 (Gulf of Cadiz). Results of fitting the THOG model for males (left) and females (right). The observed and predicted mean lengths are shown on the upper panel and estimated fishing mortalities from THoG model with fixed natural mortality for males (M=0.3) and females (M=0.2) on the lower panel.

Results are summarized in the follow table:

MODEL	PARAMETER	MALES	FEMALES
Gedamke-Hoening	Z (yr-1) estimated	0.75	0.36
	F (yr-1) (derived from Z estimate and external M)	0.45	0.16
THoG (Using external M)	M fixed to	0.3	0.2
	F2018 estimated	0.25	0.05
Y/R (Using external M)	F_{MSY} proxy ($F_{0.1}$)	0.16	0.25

Gedamke-Hoening and THoG models results indicate that both sexes seem are exploited in a different way. It is inferred that overfishing is occurring on males in almost the whole of the time-series but not on females. Overfishing is not occurring on males during 2013–2015 periods, when fishery was limited by the sanction applied in 2012 and as consequence the effort was reduced.

Separable Cohort Analysis

Different explorations were carried out considering the number of individuals of the population from UWTV survey as the average of the 2016–2018 periods (311 millions of burrows), as well as, the abundance obtained in 2019 (113 millions of burrows) (see Table 1 for abundance by year). A sigmoid and domed selection pattern was explored for each case.

Results show better fit when a sigmoid selection pattern and data from 2019 UWTV survey was used. However, there is a considerable difference between the population estimates from the model and the abundance obtained from UWTV survey. Thus, the ratio between the abundance predicted by SCA and the abundance observed from TV survey was 0.10 when only is considerate the 2019 data. As a result, harvest rates derived from SCA were very high, leading to much larger recommended catches than experienced historically because of the larger population estimate from the UWTV survey. Results for SCA using the abundance obtained in 2019 are shown in Figure 5 and Table 3. Model was not good fitted when the 2016–2018 abundance average from UWTV survey was used. Additionally, the differences between the abundance estimate by the model and the abundance average from TV survey input was higher than when the 2019 data were used.

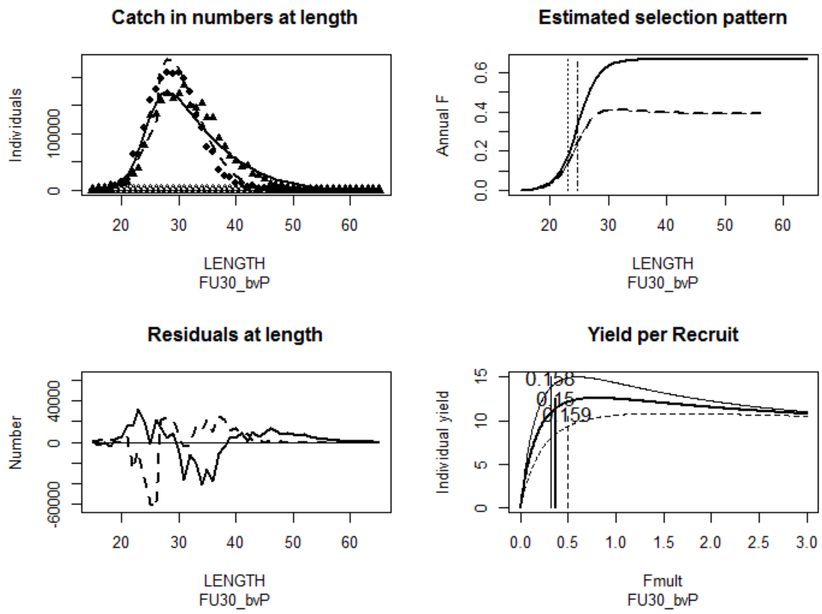


Figure 2.6.5. *Nephrops* FU30 (Gulf of Cadiz). SCA results for the 2016–2018 average length distribution and 2019 UWTV survey abundance.

An additional run was carried out without fit the UWTV survey. Results are showed in Figure 2.6.6 and Table 2.6.3. Harvest rates resulting also were very high and similar results were obtained with or without the 2019 UWTV survey.

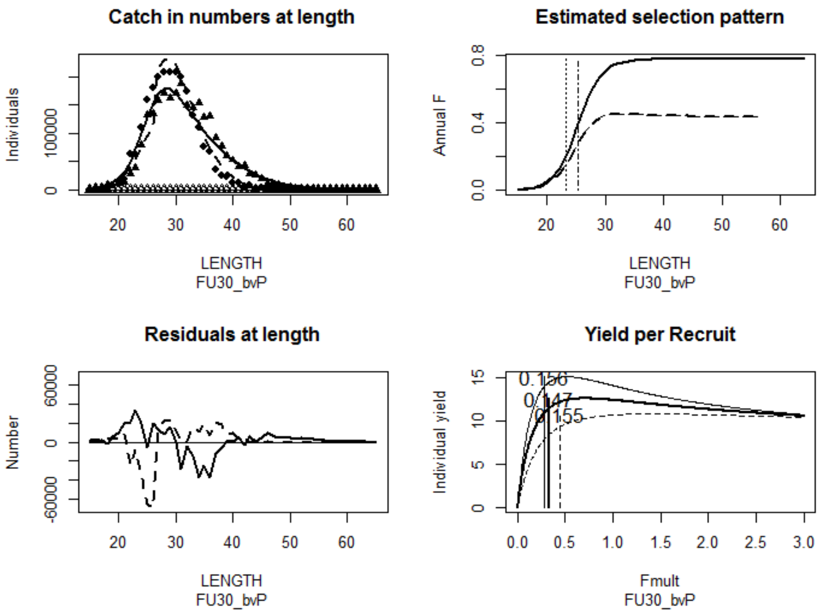


Figure 2.6.6. *Nephrops* FU30 (Gulf of Cadiz). SCA results for the 2016–2018 average length distribution and do not taking account the abundance from UWTV survey.

Table 2.6.3. *Nephrops* FU30 (Gulf of Cadiz). Outputs of SCA for the 2016-2018 average length distribution and 2019 UWTV survey abundance.

	2019 UWTV Survey			Without UWTV Survey		
	F mult	F	HR	F mult	F	HR
F0.1 (T)	0.37	0.15	0.2	0.33	0.15	0.20
F0.1 (M)	0.32	0.16	0.18	0.28	0.16	0.18
F0.1 (F)	0.50	0.16	0.27	0.45	0.16	0.26
Fmax (T)	0.80	0.32	0.39	0.71	0.32	0.38
Fmax (M)	0.60	0.29	0.31	0.52	0.29	0.3
Fmax (F)	1.55	0.49	0.64	1.42	0.49	0.63
F35spr (T)	0.55	0.19	0.25	0.42	0.19	0.25
F35spr (M)	7.50	0.09	0.11	0.16	0.09	0.11
F35spr (F)	48.06	0.17	0.29	0.50	0.17	0.29

2.6.5 Issues and critical assumptions

Two methods to derive the status of exploitation for data-limited stocks were used during WKNephrops (LBI and Mean Length – Z). These methods are based on the length frequency distributions of the catches (landings in the case of FU 30). In spite of the size distributions for this stock are available since 2001, some inconsistencies were found in the past for the 2001–2005 period since the sampling of landings was not stratified by commercial categories (Silva *et al.*, 2016). Up to 2008, length frequency distribution sampling was targeted to the species and it was carried out in port. Since 2009 concurrent sampling by métier is carried out onboard vessels (Castro *et al.*, 2016). Therefore, the time–series from 2009 to 2018 was considered for these analyses. However, some noise was observed in samples size in 2012–2015 periods. Since 2016, sampling was reinforced and length distributions were improved.

On the other hand, there is uncertainty in the values of natural mortality and in the growth parameters for *Nephrops* stocks. Regarding to natural mortality, there are indications that it may be higher for some *Nephrops* stocks than previously assumed (ICES, 2016). In relation to the growth parameters, it is very difficult to estimate them using the traditional age methods, in crustacean in general and in *Nephrops* in particular. Von Bertalanffy parameters for a FU specific have been usually estimated long time ago, and they are often used for other FUs. For this stock, the FU29 (South Portugal) growth parameters were used.

SCA and SLCA models are traditionally used to derive the MSY reference points for *Nephrops* stocks with UWTV survey and classified by ICES as category 1. SCA was used for FU 30. Part of the SCA model output is an estimate of the absolute stock abundance. This method gives FU 30 stock estimates far below those of the UWTV survey. Factors as the uncertainty of the natural mortality and growth parameters can affect the shape of the catch-at-length distribution and can produce different magnitudes of stock abundance. On the other hand, the abundance from UWTV input value in the model for FU 30 seems be very sensitive since when the UWTV survey input was lower the model was better fitted. Some explorations runs were carried out using SLCA but the HRs resulting were also very high.

2.6.6 Actions for this meeting

In conclusion, MSY reference point could not be derived properly in this WKNephrops. It is necessary to explore other methods in order to obtain specific FU 30 MSY reference points and upgrade this stock to *Nephrops* category 1.

3 Comparison between UWTV HR and fishing mortality estimates from LCAs

3.1 Introduction

Estimates of F_{MSY} for *Nephrops* stocks are derived as per-recruit proxies based on either $F_{0.1}$, $F_{35\%}$ or F_{max}, the choice being dependent on the perceived stock productivity and apparent vulnerability to overfishing. (ICES, 2014). To address the particular biological characteristics of *Nephrops* stocks, bespoke per-recruit models have been developed which use (as input), fishery parameters derived from a separable length cohort analysis (SLCA) modified from Jones (1979). The analysis is typically based on three year average catch length frequency data and sex specific biological parameters (ICES, 2018). Although the SLCA is usually only used to derive parameters for the per-recruit analysis it does also provide estimates of current fishing mortality and stock abundance. Despite the usual caveats associated with equilibrium assumptions, one would likely expect these estimates of fishing mortality and stock abundance to be reasonably in line with those derived using the survey data. However, during WKNEP (ICES, 2017), this was found not to be the case. Using the usual approach to estimate F_{MSY} harvest rate reference points for FU 23–24 and FU30 would have resulted in a very significant increase in advised catches when applied to survey estimates of abundance (despite being stocks which had recently been considered overexploited). This was identified as being due to a large discrepancy between the stock size as estimated by the SLCA compared to the survey, with the survey estimate being an order of magnitude greater. Additionally , the low estimates of SLCA abundance were coupled with very high estimates of fishing mortality which also seemed counter intuitive, given the fisheries had been very small in the recent past.

This ToR was therefore proposed to explore whether the estimates of fishing mortality from the SLCA (which derives a measure of exploitation based on catch length frequency data) were generally in line with estimates of the harvest ratio calculated from the catch numbers and survey abundance estimates for FUs with longer time-series of data.

3.2 Method

Estimates of F in relation to F_{MSY} were derived and compared from two approaches:

1. The annual harvest ratio (dead catch numbers/survey abundance) as presented on the ICES advice sheets was calculated relative to the F_{MSY} (F_{MSY} fixed over the whole time period).
2. SLCA was carried out using 3-year average catch-at-length data (rolling three year average over the time-series of data available). The estimated F-multiplier (scaling factor on the length-dependent fishery selectivity ogive) from the SLCA was calculated in comparison to the F-multiplier associated with the relevant F_{MSY} reference point derived from the per-recruit analysis (again, with F_{MSY} fixed over the time period).

In both cases the F_{MSY} was defined as the average of the most recent five estimates (i.e. derived from per-recruit analysis of the five most recent SLCA parameter estimates) for ease of computation. Hence the standardised survey harvest rate presented here may not be quite the same as standardising those values in the advice sheet using the published F_{MSY} value as there are typically small changes in F_{MSY} over time.

3.3 Results

By and large the values of F relative to F_{MSY} appear quite comparable between the two approaches (Figure 3.1), and smoothing the values derived using the survey data may improve the consistency further by reducing the interannual variations observed in this method (The LCA is already smoothed to some degree through the use of a 3-year average catch length frequency). Stock status (i.e. F above or below F_{MSY}) is often the same between approaches and the two approaches also show similar temporal trends for FU11 and FU12. Prior to 2006, there is believed to have been some underreporting of landings which would result in bias in the harvest rate (an under-estimate) as estimated from catch numbers and survey (red line). This could potentially explain the large discrepancy between the two approaches in FU13 during 2000 to 2006 where the length composition data (LCA) suggest the stock to be more highly exploited than the catch/survey derived harvest rate. (Also apparent to a lesser degree in FUs 11 and 12).

The FUs where the biggest differences arise are FU7 and to a lesser degree FU9. In FU7, the harvest rate, as derived from the catch numbers and survey abundance, suggests the stock to have been relatively lightly exploited with F> F_{MSY} only in four years during the late 2000s. In contrast, the results of the LCA suggest that the stock has generally been exploited above F although both approaches suggest a decline in exploitation to around 2015/2016. In contrast, in FU9, the LCA suggests the stock to have been mostly fished below F_{MSY} in recent years while the survey estimate of harvest ratios has been fluctuating around F_{MSY} (and mostly above in the past).

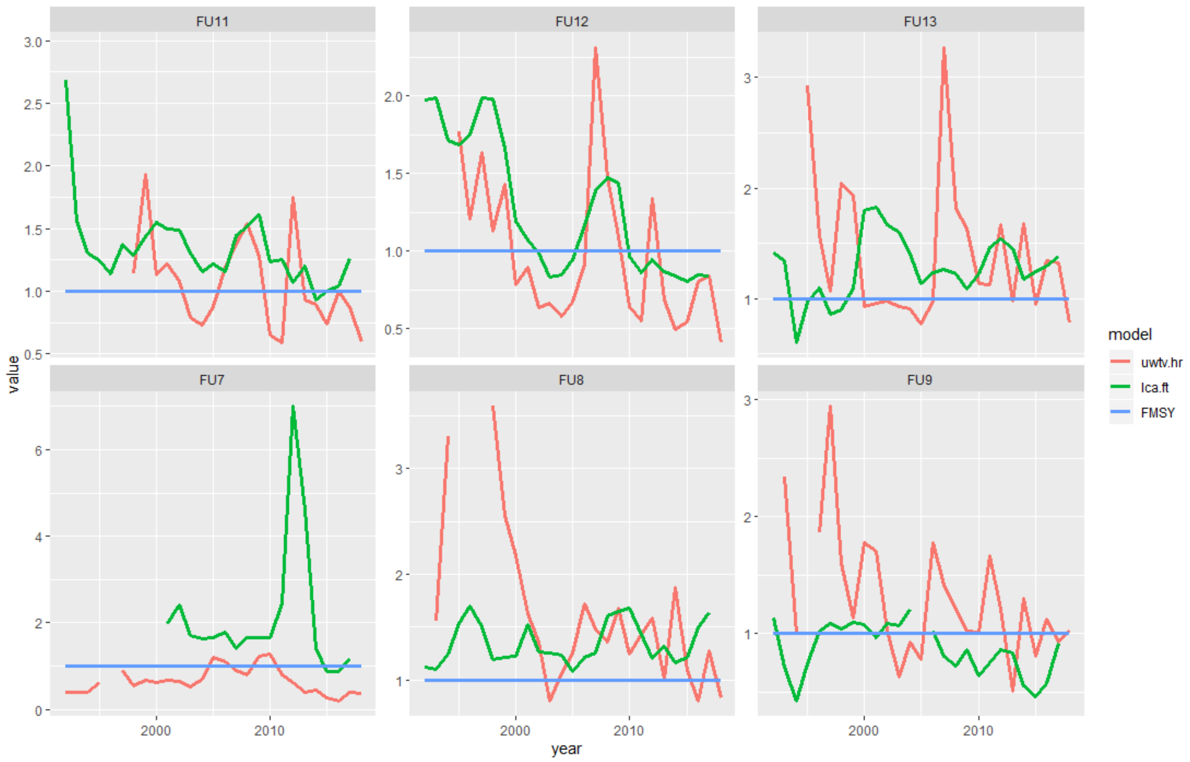


Figure 3.1. Comparison of fishing pressure relative to F_{MSY} as estimated using catch numbers and survey abundance (red) and SLCA (green). SLCA values are plotted against the mid-year of the year range used in the analysis. F_{MSY} is defined as recent 5-year average of F_{MSY} estimates.

3.4 Discussion

These differences were discussed at the workshop with specific reference to FU7. There is little reason to suspect the survey abundance estimates to be biased (overestimation of abundance would result in underestimation of harvest ratio) given that of all *Nephrops* FUs, this is one of the most straightforward in terms of analysing survey video footage with large, clear burrows at low density and few other burrowing fauna. FU7 is a large FU with much of the *Nephrops* taken in a mixed fishery for *Nephrops* and finfish, with the distribution of effort associated with demersal fish abundance (in addition to *Nephrops*). It has been noticeable in the past that effort (fishing location derived from VMS data; ICES, 2019) has often been concentrated in the south rather than being dispersed more evenly across the large area of *Nephrops* habitat, some of which has very low *Nephrops* density. Given that dynamic pool assumptions are particularly unlikely to hold for sedentary species such as *Nephrops*, this fishery behaviour likely results in spatial heterogeneity in exploitation rate and length composition. Hence there is potential for the catch length composition data from the area of the fishery to indicate a stock which is more heavily exploited than the whole *Nephrops* FU (on average).

In FU9, the difference between F status is in the opposite direction to FU7, although to a lesser degree. It suggests that either the survey is underestimating the stock abundance or the catch length composition data suggest that the stock is less exploited. A potential explanation for the former could be that there is additional *Nephrops* habitat outside the currently surveyed area although this seems unlikely in an area where the sediment is believed to be pretty well mapped. This FU has relatively good catch sampling levels with a sampling scheme that ought to provide data which are representative of the fishery as a whole, and therefore bias in the length composition data is not thought to be a factor. Further data exploration, in terms of vessel activity in relation to the current stock boundaries, and the characteristics of sampled vessels compared to the fishery as a whole may shed further light on this issue in relation to this FU. Misspecification of biological parameters in the SLCA could also contribute to these differences, both in this FU and others.

4 Evaluating Separable Cohort Analysis (SCA)

4.1 Introduction

This section describes the evaluation of a fisheries stock assessment model that implements a length-based separable cohort analysis (SCA) to estimate biological reference points (BRPs) for crustaceans and other marine species for which reliable age data are not available. For the analysis presented here, life-history parameters determining growth, maturity, and natural mortality are chosen to be representative of Norwegian lobster (*Nephrops norvegicus*). In addition to these fixed parameters, the behaviour of the model is tested for different non-stationary scenarios involving systematic long-term changes in reproductive success and fishing intensity. By necessity, these tests are based on artificially generated population and catch numbers-at-length distributions.

4.2 Artificial Length Distributions

Artificial distributions of population and catch numbers-at-length are aggregated from an ensemble of cohort simulations (Figure 4.1). To be able to control long-term population dynamics, reproductive success (or "recruitment") and fishing intensity are prescribed on a common timeline for all cohorts. As it is assumed that there are no density effects on reproduction and mortality, the individual cohort simulations are independent of each other.

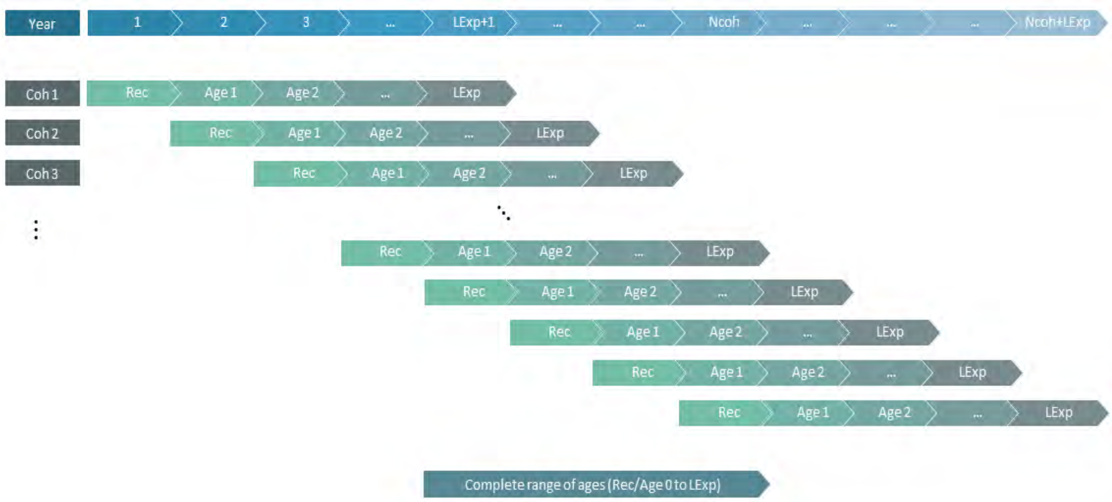


Figure 4.1. Association of different cohort simulations to the common timeline. Each of the Ncoh cohorts is simulated from recruitment (age 0) to the specified maximum life expectancy (LExp).

The duration of each cohort simulation (or "maximum life expectancy") is set to 20 years, which is long enough that, for the chosen natural mortality values, 98.2% of the female, and 99.8% of the male starting population have died out by the end.

Maximum life expectancy determines the length of the spin-up period, i.e. that period with an incomplete age distribution of the overall simulated population (Figure 4.2). For the analysis discussed here, with an ensemble of 50 simulated cohorts, the valid data period with a complete age distribution (from recruitment at age 0 to the maximum life expectancy) is 30 years.

For each simulated cohort, recruitment is specified as a starting population with lengths normally distributed around 12 mm, with a standard distribution of 1 mm. During the spin-up period, and for the first cohort of the valid data period, the maximum of the starting population length distribution is set at 50 million. Depending on the scenario, the maximum is then either kept constant throughout the simulated period, or changes (up or down) by a certain percentage each year. Alternatively, changes in annual recruitment can be specified to oscillate regularly throughout the simulated period.

For males, effects of maturity are not taken into account. For females, maturity as a function of length is parameterised through a logistic function,

$$\mu(L) = \left(1 + \exp\left(\frac{L_{50}-L}{L_{50}-L_{27}}\right)\right)^{-1},$$

with $\mu(L_{27}) \approx 0.27$ and $\mu(L_{50}) = 0.50$. For the results shown below, the quantile lengths are chosen as $L_{27} = 27.2$ mm and $L_{50} = 30.5$ mm.

Growth – or the increase in size, L, over a given time interval, Δt – is described by the von Bertalanffy equation,

$$L(t + \Delta t) = L_\infty - \left(L_\infty - L(t)\right)\exp(-K\Delta t)\ ,$$

where K is a measure of growth rate, and L_∞ is the asymptotic size for $\Delta t \to \infty$. The von Bertalanffy growth parameters for males are kept constant at $K_m = 0.16$ and $L_{\infty,m} = 66$ mm. However, for females, growth parameters are assumed to depend on maturity (and therefore length) through.

$$K_f(\mu) = \mu\, K_1 + (1 - \mu)\, K_0\ ,$$

where $K_0 = K_m = 0.16$ and $K_1 = 0.06$, and

$$L_{\infty,f}(\mu) = \mu\, L_{\infty,1} + (1 - \mu)\, L_{\infty,0}\ ,$$

where $L_{\infty,0} = L_{\infty,m} = 66$ mm and $L_{\infty,1} = 58$ mm.

Similarly, while the annual natural mortality rate for males, M_m, is kept constant at 0.3, for females, it is assumed to depend on maturity through

$$M_f(\mu) = \mu\, M_1 + (1 - \mu)\, M_0\ ,$$

where $M_0 = M_m = 0.3$ and $M_1 = 0.2$.

The annual rate of fishing mortality, F, is kept constant during the spin-up period. Subsequently, depending on the scenario, it either remains fixed at the same value, or linearly increases or decreases for the remaining simulated period.

Gear selectivity is parameterised through a logistic function,

$$\mathrm{S}(L) = \left(1 + \exp\left(\frac{SL_{50}-L}{SL_{50}-SL_{27}}\right)\right)^{-1} - \sigma\left(1 + \exp\left(\frac{DL_{50}-L}{DL_{50}-DL_{27}}\right)\right)^{-1},$$

with quantile lengths $SL_{27} = 20.60$ mm and $SL_{50} = 22.27$ mm. A potential decrease in selectivity for large sizes is controlled through the second term, with depensation rate σ set to either zero or 0.5, and with $DL_{27} = 35.0$ mm and $DL_{50} = 37.0$ mm.

The probability of being landed is also parameterised through a logistic function,

$$P_l(L) = \left(1 + \exp\left(\frac{PL_{50}-L}{PL_{50}-PL_{27}}\right)\right)^{-1},$$

with quantile lengths $PL_{27} = 25.47$ mm and $PL_{50} = 27.64$ mm.

Depending on the scenario, the quantile lengths of gear selectivity and the probability of being landed are either kept constant throughout the simulated period, or are simultaneously increased by 2 or 5 mm halfway through the valid data period.

Discard mortality, M_d, is assumed to be 0.5 for females and males.

The probability of unnatural death combines the probability of being landed with discard mortality,

$$P_d = P_l + M_d(1 - P_l) \ .$$

The total mortality rate from natural causes and fishing activity (including discarding), during time interval Δt, is then given by

$$D_{f,\mathrm{m}} = 1 - \exp\left(-\left(M_{f,m} + F\,S\,P_d\right)\Delta t\right) \ .$$

In addition to the fixed model parameters, each simulated scenario is determined by the specified long-term trends of recruitment and fishing mortality, as well as by the different parameterisations of gear selectivity and probability of being landed. All scenarios are simulated a hundred times, each run with different annual fishing mortality rates that are randomly selected from a normal distribution, with a standard distribution of either 10% or 20% of the specified central value.

The evolution of the cohort length distribution is simulated with a monthly time-step in an iterative process, whereby total mortality is calculated at the beginning of each time-step, followed by the monthly growth of the survivor population. Annual catch numbers-at-length are aggregated at monthly intervals, while population numbers-at-length are saved at annual intervals.

The aggregated population numbers-at-length during the valid data period show the coexistence of distinct cohorts more clearly than would be expected from real data, due to the constant growth rates and the regular "sampling" interval (Figure 4.3).

Determined by the balance between decreasing population numbers and increasing individual weights with age, the population biomass of each cohort is highest between 1 to 2 years after the start of the simulation, depending on the fishing mortality rate (Figure 4.3).

The simulated yield strongly depends not only on the long-term evolution of fishing mortality, but also on recruitment (Figure 4.4). With constant recruitment and low fishing mortality during the spin-up period, the population size, and therefore yield, initially increases. However, for the chosen life-history parameters, even an annual decline in recruitment of only 2% depresses an increase in yield, despite a doubling of fishing mortality.

Catch numbers-at-length, population biomass-at-age, and yield over the lifetime of a cohort are higher for males than for females, due to the faster growth rate and larger asymptotic size.

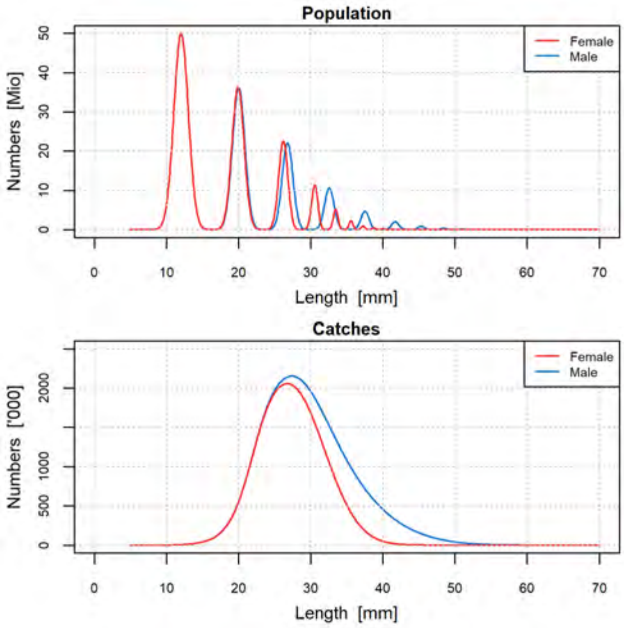


Figure 4.2. Population and catch numbers-at-length, averaged across the valid data period, with constant annual recruitment and fixed asymptotic fishing mortality of 0.5.

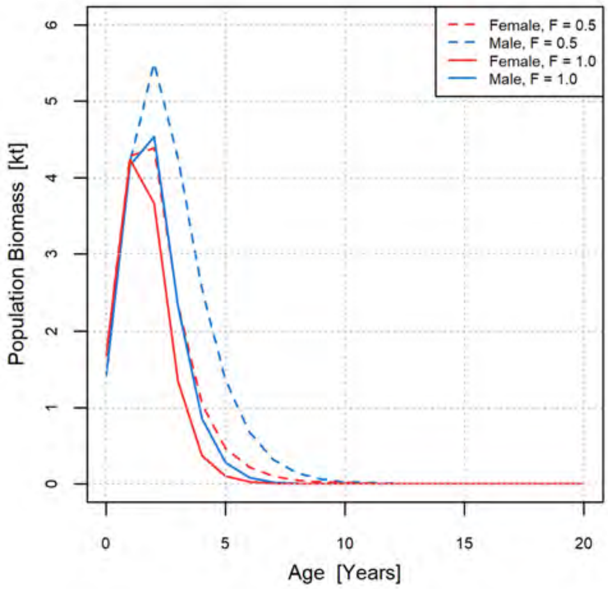


Figure 4.3. Population biomass-at-age, averaged across all cohorts, with constant annual recruitment and different but fixed asymptotic fishing mortality rates.

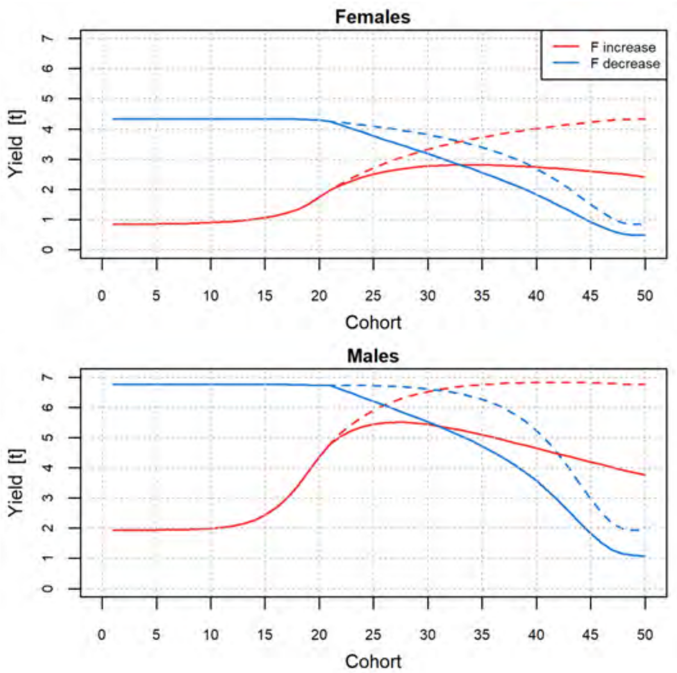


Figure 4.4. Yield for each simulated cohort, with constant recruitment (dashed lines) or a 2% annual decrease in recruitment (solid lines), and either an increase in asymptotic fishing mortality from 0.05 to 1.00 (red lines), or a decrease from 1.00 to 0.05 (blue lines). Cohorts 1 to 20 are "born" during the spin-up period.

5 Length-Cohort Analysis for Crustaceans using the R/TMB Programming Language

5.1 Introduction

One of the most important tasks of fisheries science is the estimation of population sizes of commercially exploited marine species. Currently, the main tools for obtaining absolute abundance estimates are sonar for pelagic finfish, and cameras for the benthic habitat. Both observation techniques have their limitations. Acoustic surveys, which have been conducted since the 1930s (Hodgson & Fridriksson, 1955), rely on simultaneous trawling for calibration, species identification, and age/length sampling. Underwater television (UWTV) surveys have been conducted increasingly more frequently over the past 20 years, especially for *Nephrops* (Leocádio, *et al*., 2018), but detection of animals or burrows in video footage is difficult and to some degree subjective.

Therefore, stock assessments of many marine species still have to rely primarily on methodologies that estimate the size of the living population based on commercial catch data, i.e. the number of animals removed by the fishing industry within a given timeframe, and deploying a certain combined effort. One common approach in fisheries science is a cohort analysis (e.g. Lassen and Medley, 2001). This is a special case of an ecological population model (Figure 5.1), whereby the evolution of the demographic structure of a closed population (i.e. one without migration) is simulated as the net effect of reproduction and mortality. The goal is to estimate population numbers at different ages that support the reported landings and discards. The fundamental problem is that only information concerning fisheries-related mortality is available. Practically unknown is natural mortality, which is affected by environmental conditions, diseases and parasites, inter- and intra-species competition for food and shelter, and predation.

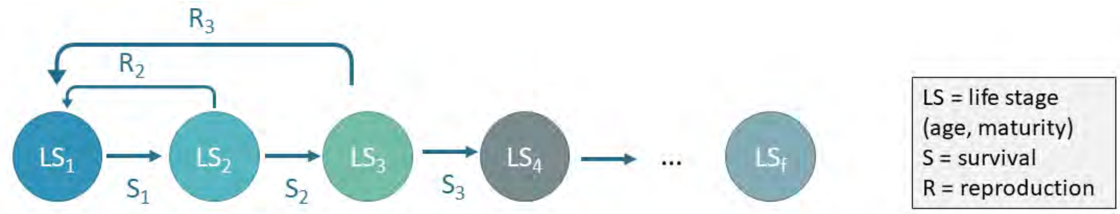


Figure 5.1. Schematic representation of a stage-structured population model in an isolated environment.

For crustaceans, compared with finfish and some other shellfish species, the development of a dynamic population model is further complicated by a limited ability to accurately age individuals. This makes it necessary to use size as a proxy measure for age and maturity. The progression of time is then introduced through a growth equation. The determination of growth parameters only requires the ageing of a representative sample of individuals of a given species, ideally for each distinct population, as growth rates may vary with environmental conditions, such as temperature.

Here, the development of a length-cohort analysis (LCA) for crustaceans is introduced. Section 7.2 describes the basic functional relationships of size-structured population dynamics. The intrinsic nonlinear nature of these parameterised relationships prevents an effective use of linear regression analysis for the determination of optimum model parameter values. Maximum likelihood estimation is therefore introduced in Section 5.3, as a more general approach. This requires a numerical technique to determine the optimised set of parameters, which is introduced in Section 5.4. A specific implementation of the model for Norwegian lobster (*Nephrops norvegicus*) is then described in Section 5.5.

5.2 Population dynamics

In its most basic form, an LCA simulates the evolution of a population size distribution as the combined effect of reproduction, mortality, and growth (Figure 5.2).

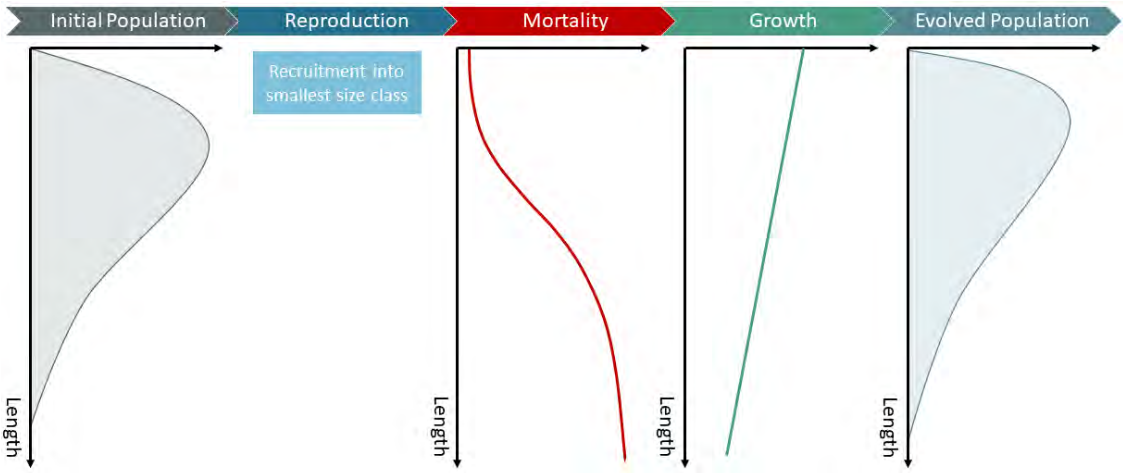


Figure 5.2. Sequence of transformations of the initial population size distribution during each time-step of a length-cohort analysis.

Reproduction is measured by the number of animals being recruited into the smallest size class each year, which is an indication not only of the reproductive potential of the parent generation, but also of the rate of survival of offspring, before they become available to the fishery.

The ratio of survivors during a period of time, Δt, relative to the initial population, is conventionally modelled by an exponential decay,

$$S(L, Y, \Delta t) = \exp(-Z(L, Y)\Delta t) \,,$$

where the total mortality exponent, Z, is the sum of the exponents related to natural and fishing mortality, and generally varies between size classes, L, and years, Y. Often in LCAs, natural mortality is kept constant, while fishing mortality (and therefore total mortality) is defined to increase with size, typically according to a logistic function (see Section 5.5.3 for details). This underestimates the high natural mortality of juveniles, which is taken into account in the definition of recruitment.

Growth – or the increase in size, L, over a given time interval, Δt – is typically described by the von Bertalanffy equation,

$$L(t + \Delta t) = L_\infty - \big(L_\infty - L(t)\big)\exp(-K\Delta t) \,,$$

where K is a positive constant, and L_∞ is the asymptotic size for $\Delta t \to \infty$. The rate of growth for a given time interval,

$$\frac{\partial L(t+\Delta t)}{\partial \Delta t} = K\big(L_\infty - L(t)\big)\exp(-K\Delta t) = K\big(L_\infty - L(t + \Delta t)\big),$$

is size-dependent and linearly decreases as $L(t + \Delta t)$ approaches L_∞.

Crucially, cohort analyses – whether length- or age-based – only simulate changes in population numbers, rather than absolute abundances. They can therefore be used to estimate long-term trends in population sizes. To obtain absolute values for numbers-at-length, ideally total abundances in each year are provided, most likely from UWTV surveys. Alternatively, if only commercial catch data are available, estimates of total abundance can be derived for different assumed harvest rates.

5.3 Maximum likelihood estimation

The equations of population dynamics introduced in the previous section are only crude approximations of reality. They do not capture a wide range of factors that influence the marine ecosystem, such as environmental impacts on reproductive success, biological differences between individuals in growth rate and health, or variations in food availability and predation pressure due to changes in the abundances of other species.

The main challenge, therefore, in any heavily parameterised ecological model is to adequately express the inherent uncertainties stemming from high natural variability. As predictions of a set of deterministic equations are uniquely specified by the model parameters and the initial conditions, uncertainties are represented by error terms, whose minimisation provides criteria for model parameter selection. The functional form of these error terms is usually given by a suitable probability distribution.

For experiments aimed at establishing abundances or occurrences, there are two well-established discrete probability distributions. For a fixed number of counts, n, with binary (true/false) outcomes, the number, k, of "true" outcomes, with associated probability p, follows a binomial distribution,

$$\frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}.$$

In market sampling, for example, this can be used to predict the number of berried brown crabs in a box with a known number of females. By contrast, for an indefinite number of counts conducted within specified intervals of time and space, the number of hits, k, with a long-term expected (or mean) value λ, follows a Poisson distribution,

$$\frac{\lambda^k e^{-\lambda}}{k!}.$$

This is applicable, for example, to the analysis of UWTV survey data, where camera tows are conducted to cover a specified area of the seabed, with a fixed aperture and height above ground, and a fixed speed and duration.

However, actual counting is only feasible with sufficiently small samples, collected over confined areas and periods of time. Without these restrictions, it is necessary to rely on asymptotic statistics, where both the binomial and Poisson distribution tend towards a normal distribution for large sample sizes ($n \to \infty$), or a large number of expected hits ($\lambda \to \infty$), respectively (e.g. van der Vaart, 2000). For sampling from a large population, it is therefore safe to assume that the observed values, y, are normally distributed around the actual value, $\bar{y}$, with standard deviation, σ,

$$P(y, \bar{y}, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(y-\bar{y})^2}{2\sigma^2}\right).$$

In the maximum likelihood approach to ecological population modelling, simulations using different sets of parameter values are interpreted as large samples from the modelled population. With N different observables, y_i, associated actual values, $\bar{y}_i$, and standard deviations, σ_i, their joint probability is proportional to:

$$\Lambda = \prod_{i=1}^{N} \exp\left(\frac{-(y_i-\bar{y}_i)^2}{2\sigma_i^2}\right) = \exp(-E),$$

where

$$E = \sum_{i=1}^{N} \frac{(y_i - \bar{y}_i)^2}{2\sigma_i^2} = -\log(\Lambda)$$

is proportional to the mean square error of the standardised variables $y_i\ \sigma_i^{-1}$. The joint probability is a measure of the likelihood that a set of simulated values represents the actual values. The necessary criterion for the maximum likelihood estimate is that the gradient of the likelihood function with respect to all model parameters, p_j, vanishes,

$$\frac{\partial\Lambda}{\partial p_j} = -\exp(-E)\frac{\partial E}{\partial p_j} = 0, \quad \forall p_j.$$

As derivatives of sums are easier to calculate than those of a product, for practical reasons, the minimisation of the error term, rather than the maximisation of likelihood, is the preferred approach. Therefore, in maximum likelihood estimation, it is the negative log-likelihood that is defined as the objective function to be minimised.

From linear regression analysis, it is well established that for any parameterisation that is linear in all parameters,

$$y(x) = \sum_j p_j\, f_j(x),$$

with arbitrary functions, f_j, of the independent variable, x, the zero-gradient condition for the mean square error can be solved analytically. Under more general conditions, however, the minimisation of the error term, requires numerical techniques.

5.4 The template model builder

The simultaneous optimisation of potentially tens or even hundreds of model parameters, under the criterion of minimising the negative log-likelihood function, requires a stable and efficient numerical routine that is capable of accurately calculating gradients of complex surfaces in multidimensional spaces.

One such routine is the Template Model Builder (TMB), developed at the Danish National Institute of Aquatic Resources (DTU Aqua), with continuous improvements since 2009 (Kristensen, Nielsen, Berg, Skaug, & Bell, 2016). It is an open-source software package, built from individual C++ templates, and follows a similar approach to that of the Automatic Differentiation Model Builder (ADMB; Fournier *et al.*, 2012). It uses the well-established algorithmic differentiation C++ package `cppAD`. The calculation of the objective function is broken down into a sequence of simple algebraic operations (sums, products, and exponents), as well as some basic differentiable transcendental functions (such as logarithms or trigonometric functions). Differentiation is then performed symbolically via the chain rule.

The easy integration of TMB into scripts written in the R programming language (R Core Team, 2019) has made it a popular choice for a wide range of ecological applications. In a combined R/TMB modelling framework, the sequence of processes begins in R, then calls the TMB routine, and finally returns to R (Figure 5.3). The initial data preparation is performed in R. The observational data against which the model is to be optimised, as well as the initial values of all model parameters, are transferred to TMB, which calculates the objective function and its gradient. These results are then transferred back to R, for use in a minimisation routine, such as `nlminb`. This determines the optimised set of model parameters through iteration from the initial conditions, following the maximum gradient of the objective function.

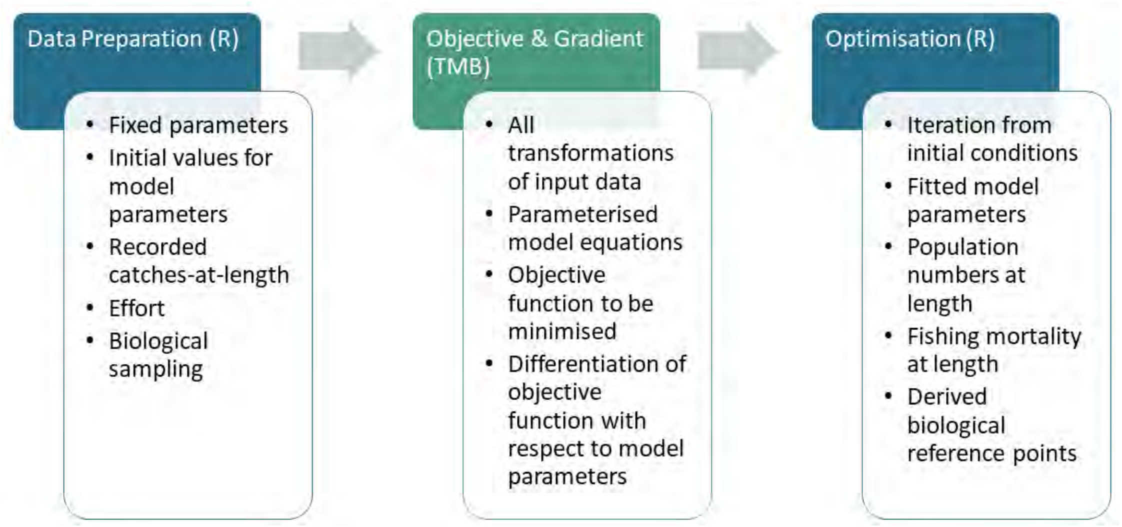


Figure 5.3. Sequence of processes in an R/TMB modelling framework for a fisheries stock assessment.

5.5 The Model

The crustacean model presented here implements a standard LCA, based on the equations introduced in Section 5.2. It is therefore applicable to the assessment of all marine species for which commercial catch numbers-at-length (rather than numbers-at-age) are available, as long as the length-dependent growth rate of the species, and biological parameters estimating maturity and natural mortality, are sufficiently well known.

5.5.1 Input data

The initial information that is used to run the model is:

- Catch, survey, and sampling data:
  - Commercial catch numbers, or landings and discards, at length (required),
  - Total abundance (optional),
  - Total annual effort (optional),
  - Proportion of egg-carrying (“berried”) females (optional),
  - Proportion of soft-shelled animals (optional).
- Fixed parameters:
  - Harvest rate (in the absence of total abundance data),
  - Maturity: parameterised either as a logistic function with specified quantile lengths (L_{27}, L_{50}), or with a threshold length (L_{mat}),
  - von Bertalanffy growth (K, L_∞), either fixed or maturity/size dependent,
  - Annual natural mortality rate (M), either fixed or maturity/size dependent,
  - Discard mortality (M_d).

In the case of a logistic parameterisation, maturity is given by

$$\mu(L) = \left(1 + \exp\left(\frac{L_{50}-L}{L_{50}-L_{27}}\right)\right)^{-1},$$

with $\mu(L_{27}) \approx 0.27$ and $\mu(L_{50}) = 0.50$. As an option, maturity can then be used to calculate vulnerability to being caught, either through a logistic or a quadratic function.

5.5.2 Model parameters

The model parameters to be optimised are:

- Selectivity; fitted either as a logistic (two parameters) or quadratic (three parameters) function in length;
- Vulnerability (optional); fitted either as a logistic or quadratic function in maturity;
- Probability of being landed (if total catch data are used); fitted as a logistic function in length;
- Asymptotic fishing mortality; fitted either as individual values for each year, or as a linear trend over the simulation period (with fitted beginning and end values);
- Recruitment; fitted either as individual values for each year, or as a linear trend over the simulation period;
- First-year population numbers; fitted individually for each length class;
- Standard deviations around reported or observed values of simulated catch numbers-at-length and total abundance.

The number of model parameters primarily depends on the number of initial conditions required for the population matrix (Figure 7.4). This depends on the simulation period and the number of length classes. Additionally, it depends on whether recruitment and asymptotic fishing mortality are defined as linear trends or through individual annual values.

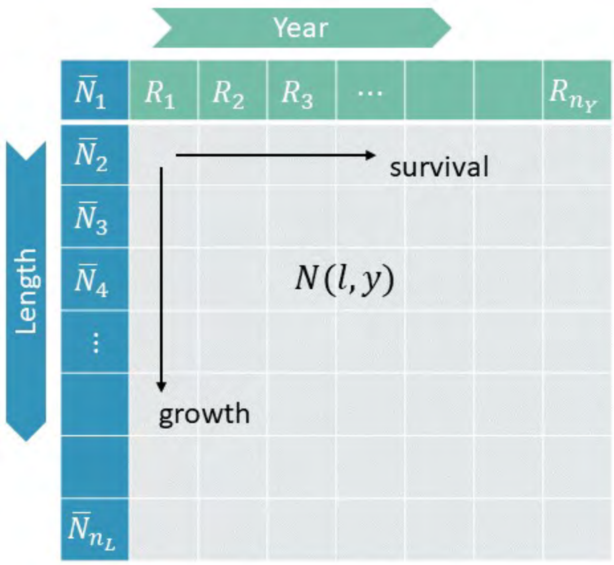


Figure 5.4. Schematic representation of the population matrix with initial conditions.

5.5.3 Mortality

As described in Section 5.2, the second step of the LCA, following the inclusion of annual recruitment into the smallest size class, is the application of total (natural plus fishing) mortality across the entire population.

Natural mortality is specified either as a fixed constant for all sizes and years, or as being maturity dependent. In the latter case, natural mortality is usually defined to be smallest for mature females.

Fishing mortality is composed of different components,

$$F(l, y) = F_a(y)\, \Theta(l)\, \Phi(l, y)\, F_l(l, y),$$

where selectivity, $\Theta(l)$, depends on length (typically through a logistic function), and asymptotic fishing mortality, $F_a(y)$, specifies the maximum of the selectivity function for each year. If specified, vulnerability, $\Phi(l,y)$, explicitly depends on maturity, which itself may depend on length and year.

If total catch (rather than landings and discards) data are used, the component $F_l(l,y)$ represents the probability of being landed, together with discard mortality,

$$F_l(l,y) = \gamma_l(l,y) + M_d\big(1 - \gamma_l(l,y)\big).$$

For the probability of being landed,

$$\gamma_l(l,y) = p_l(l)\big(1 - \beta(l,y) - \sigma(l,y)\big),$$

the main component has a logistic dependence on length,

$$p_l(l) = (1 + \exp(-aL - b))^{-1}.$$

If appropriate for a given species, the proportion of berried females, β, or the proportion of soft-shelled animals, σ, can be included to reduce the probability of being landed. Discard mortality, M_d, is applied to those animals that are not being landed (with probability $1 - \gamma_l$).

If landings, L, and discards, D, data are used, the total fishery-related mortality, or effective catch, is calculated as

$$C = L + M_d\, D.$$

In that case, $F_l(l,y)$ is omitted in the fishing mortality term.

5.5.4 Growth

After mortality has been taken into account, the next step of an LCA is the growth of the survivor population. This is expressed in the model by multiplication of the length distribution column vector, $\vec{N}_L = (N_1, N_2, \ldots)^{\mathrm{T}}$, with the growth transition probability matrix, G,

$$\vec{N}_L(t + \Delta t) = \mathrm{G}\, \vec{N}_L(t).$$

Growth transition probabilities between different length classes L_i, with population numbers N_i, are calculated from the von Bertalanffy equation (Section 5.2). If length classes are wider than the length measurement interval, the length distribution of population numbers within length classes is taken into account (Figure 5.5). As this transformation represents pure growth (conservation of animals, without mortality or migration), all columns of G sum to one. As there can be no shrinking, all entries of the transition matrix above the diagonal are equal to zero. As there can be no growth out of the plus group, the entry for the largest size class is always one. If length classes are equal to the measurement intervals, all entries of the transition matrix are either zero or one. However, experience has shown that this leads to unstable model simulations.

Generally, the best results are obtained, if the time-step of the model, in combination with the width of length classes and the growth parameters, is chosen such that the central diagonal of the growth matrix, as well as the next higher length classes, contain no zeros, e.g.

$$G = \begin{pmatrix} 0.6 & 0 & \vdots & \vdots & \vdots \\ 0.4 & 0.7 & 0 & \vdots & \vdots \\ 0 & 0.3 & 0.8 & 0 & \vdots \\ \vdots & 0 & 0.2 & 0.9 & 0 \\ \vdots & \vdots & 0 & 0.1 & 1 \end{pmatrix}.$$

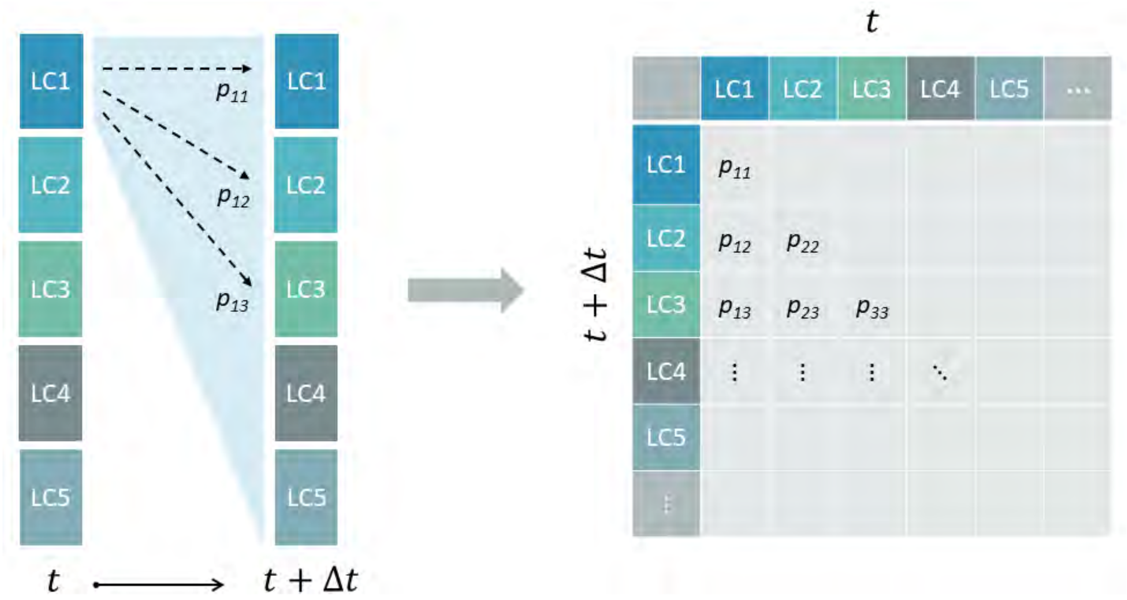


Figure 5.5. Transition probability matrix for growth between different length classes.

5.5.5 Case study–*Nephrops* in FU 8 (Firth of Forth)

The available input data are commercial landings and discards at length for the period 1998–2018, with length measured to the nearest odd millimetre. No sampling data are available for the proportion of berried females and soft-shelled animals. However, total abundance estimates for the study period are provided by UWTV surveys.

The annual natural mortality rate is fixed at 0.3 for males, and decreases from 0.3 to 0.2 for females, depending on maturity, where the length-at-maturity is set at 26 mm. Discard mortality is fixed at 0.75 for both sexes.

The growth rate, K, is fixed at 0.163 for males, and decreases from 0.163 to 0.065 for females, depending on maturity. The asymptotic length, L_∞, is fixed at 66 mm for males, and decreases from 66 to 58 mm for females.

The smallest detectable length from UWTV footage is set at 17 mm. This is used to determine the lowest size class for the calculation of total abundances from model simulations.

Selectivity is fitted as a logistic function in length, and vulnerability is omitted (i.e. set to one).

Annual recruitment and asymptotic fishing mortality are fitted as individual values for each year of the simulation period.

For the results shown below, the full range of sizes is divided into five length classes, with 10 mm widths for females, and 11 mm widths for males, except for the highest and lowest length classes, which are open towards the tails of the distribution.

The weights of different terms in the negative log-likelihood function can easily be modified. For the results shown below, they are chosen such that the catch numbers-at-length are weighted at 45%, total abundance at 45%, and year-to-year changes in asymptotic fishing mortality at 10%.

Simulated recruitment for both sexes is similar, but fluctuates greatly from year to year, without any persistent trend over the study period (Figure 5.6). Asymptotic fishing mortality is also similar between the sexes and shows an overall decline over the study period.

With higher reported and simulated catches-at-length for males (Figure 5.7), the simulated male population numbers-at-length are also higher than those of females (Figure 5.8).

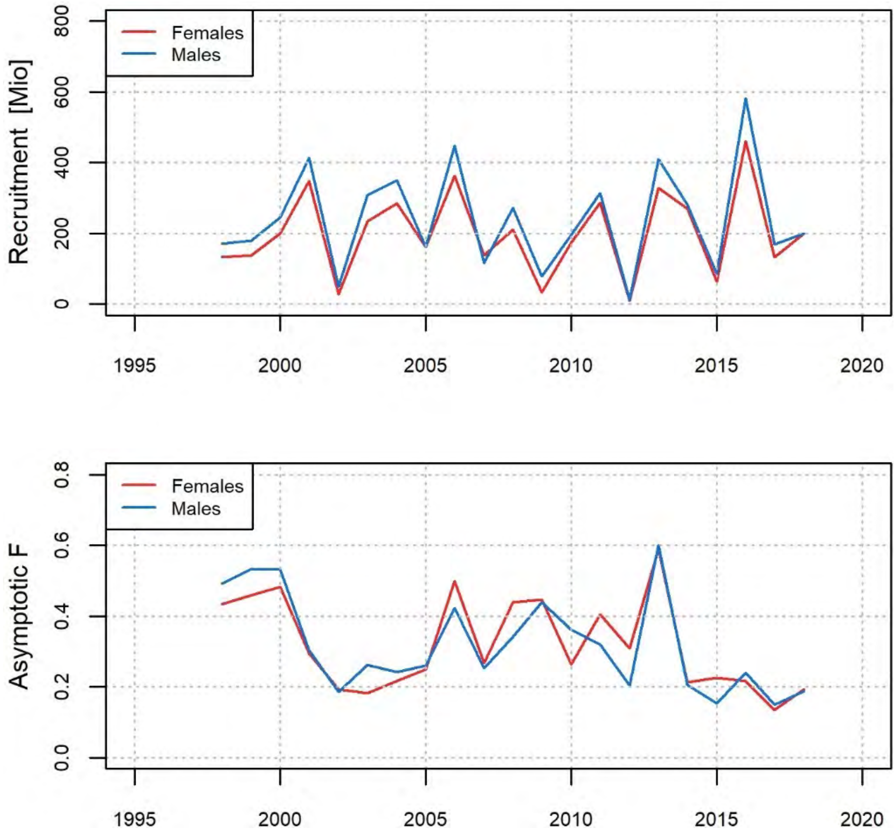


Figure 5.6. Simulated annual recruitment and asymptotic fishing mortality by sex of *Nephrops* in FU 8.

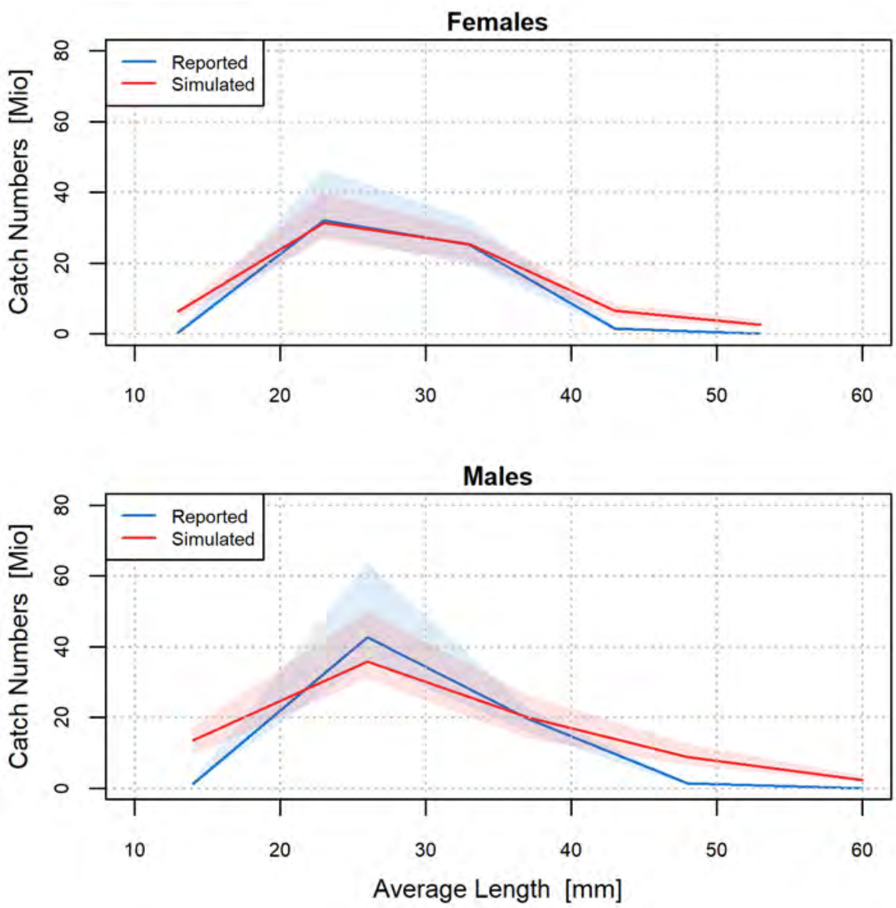


Figure 5.7. Reported and simulated catch numbers-at-length by sex of *Nephrops* in FU 8. The solid lines represent the median for all years of the 1998–2018 study period, and the shading represents the 25th to 75th quantile range.

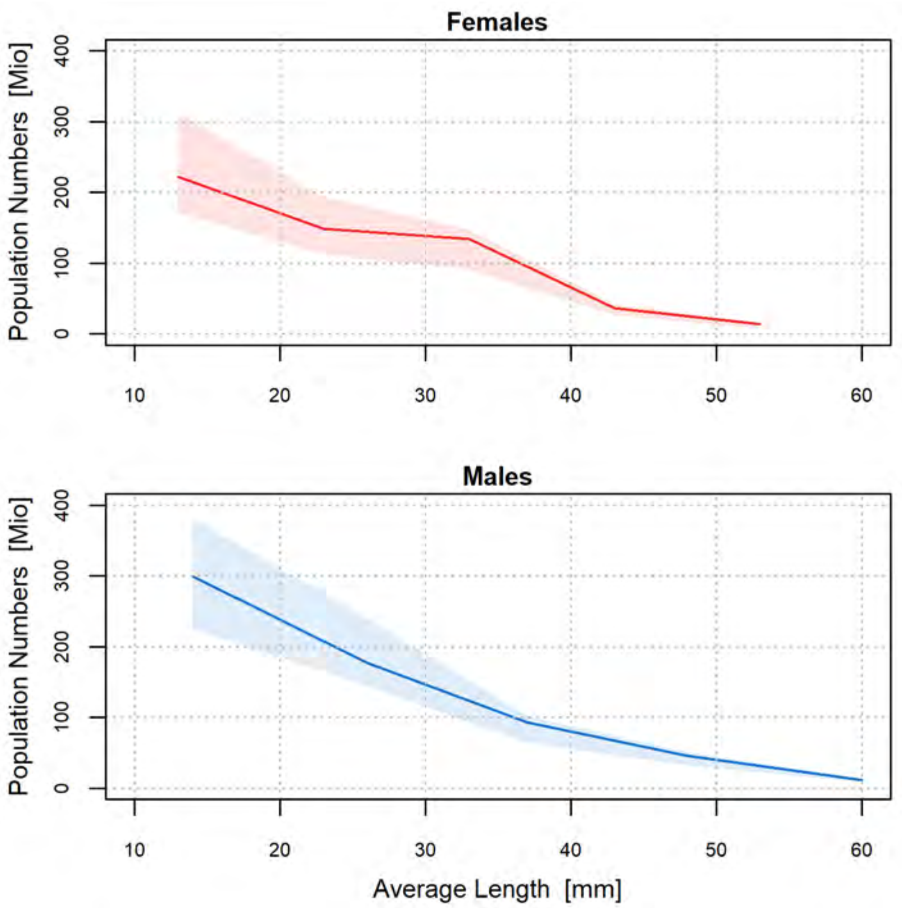


Figure 5.8. Simulated population numbers-at-length by sex of *Nephrops* in FU 8. The solid lines represent the median for all years of the 1998–2018 study period, and the shading represents the 25th to 75th quantile range.

6 Reviewer's comments

At the time of the meeting of the expert group, much of the work identified in the terms of reference was still in progress, and a consensus view on how reference points might be updated had yet to be reached. Consequently, this review discusses some of the main issues that arose during the meeting and suggests possible further lines of research rather than offering a critique of work undertaken.

It is clear from an overview of the stocks assessed by ICES that there is a wide difference in the amount and quality of data available. Thus there is unlikely to be a single approach to the identification of reference points. Where a comprehensive range of data is available, it may be possible to use conventional length based MSY models, but for a number of stocks data-poor methods that are more reliant on life-history traits will need to be used.

6.1 Data-rich stocks

For the stocks that are more data-rich, the available data comprise landings, discards, length compositions from the catch and underwater TV surveys (UWTV). Generally the UWTV surveys are used to track population abundance, while exploitation status is based on quasi-equilibrium length cohort analysis, developed from the Jones method. These models, referred to as separable cohort analysis (SCA), assume an equilibrium state in the length composition for a recent period of years, and use externally derived growth parameters and natural mortality to reconstruct the stock. The models allow for the estimation of fishery selectivity and can be calibrated using the UWTV survey if desired.

One of the main issues that has arisen from the use of SCA, is that the abundance estimates differ substantially from the UWTV surveys. This difference can be as much as an order of magnitude, and is largely an issue of scaling rather than estimation error. Since SCA is used for exploitation status and UWTV for abundance, this inevitably leads to problems of translation between scales. Currently there does not appear to be a sound explanation of why the two approaches differ so markedly. Typically it is the UWTV estimate that exceeds the SCA value. Such differences are not unusual in fishery-independent surveys and arise, for example, in acoustic surveys, egg and larval surveys and swept-area trawl surveys. Scaling issues for the UWTV surveys are likely to relate to the expansion factors such as, burrow occupancy, area swept and habitat area, while in SCA it will relate to assumptions about natural mortality, selectivity and growth parameters.

These scaling effects are well known in the working group but have not yet been resolved. However, it would be desirable to try to base advice on a single measurement scale and a simple "fix" would be to allow survey catchability, q, to be estimated within an integrated model. This in effect assumes that the UWTV survey is on a relative scale, and is treated as an index of abundance rather than absolute abundance. Such an approach does, of course, simply hide the issue but may provide a pragmatic work around until the difference in scale is better understood. Treating the UWTV survey as an index does assume that population change seen by the survey is reflected in the length frequency data. If not, then the two data sources are simply inconsistent and cannot be used in an integrated model. Work carried out at the meeting on some FUs using the SCA approach in a semi-dynamic way, suggested that the population signal in the survey was reflected in the catch data and offers some reassurance that an integrated modelling approach may be appropriate.

In the past some *Nephrops* stocks were assessed by first using cohort slicing to create pseudo-age composition data that were then input to XSA. This approach has very obvious limitations in its assumptions about the conversion of length to age, and has been abandoned. It may be possible to obtain a satisfactory assessment using length only methods that do not attempt to convert from length to age. During the meeting such a model was in development where animals grow using a standard model, but with dispersion around the mean length. A number of models of this type are already available and include, Stock Synthesis (Methot and Wetzel, 2013), CASAL (Bull *et al*., 2012), LIME (Rudd and Thorson, 2017) and Gadget (Begley, 2005). Many are reviewed by Punt *et al*. (2013) in relation to crustaceans. A crucial element for the success of such models is the correct modelling of growth and is particularity challenging for *Nephrops*, given the step-wise increments in growth associated with moulting since not only is moulting frequency variable but differs between the sexes. If in addition, growth in time varying, a length-based model that assumes invariant growth may simply fail. Despite these challenges, there is clearly value in researching such methods to see if these complexities can be adequately overcome with simplifying assumptions. An alternative approach that requires less information on growth is the so-called DeLury method and discussed by Mesnil (2003). Here the length composition is binned into two or three stages, corresponding to recruits, juveniles and adults. Such methods may be useful where the length frequency sample is sparse and larger unequal bins can nevertheless be reasonably well populated.

As the length-based model used during the meeting was still in development it was not fully documented, and it is not possible to provide a review here. One element of the model that deserves some thought, is the appropriate objective function. It appeared that the observation errors were assumed to be lognormal, an assumption commonly made in ICES assessment models. However, many practitioners argue that a more natural assumption for compositional data such as length or age, is multinomial. The latter forms the basis of Stock Synthesis for example. While there is some merit in the multinomial, the problem that arises is the estimation of the effective sample size for the data, which can lead to serious incorrect weighting of the data. The LIME model referenced above uses a Dirichlet-Multinomial model to try to overcome this problem and may be worth investigating.

6.2 Data-limited stocks

For stocks that have limited length frequency data and little or no UWTV surveys, the working group is considering a range of methods that rely more heavily on life-history theory in the absence of data on stock abundance. These include length-based indicators, methods based on spawning potential ratio (SPR) and surplus production models such as SPiCT (Pedersen and Berg, 2016). These are established methods, and it is appropriate to investigate their utility for *Nephrops*. As much of the analysis was being performed at the meeting, it was not possible to draw any general conclusions. In one stock investigated, a variety of such data-limited methods gave different estimates of stock status, which at face value indicates that reference points are model-sensitive, which means that choosing one approach may not be sufficiently robust for management purposes. It was important and useful to see such differences as model uncertainty is typically under-estimated in ICES assessments.

6.3 Discards

Discard survival was discussed and investigated during the meeting. This is an issue of importance to the industry, as it affects the way the fisheries are managed. It appeared that reference points were relatively insensitive to the discard survival, rate but unexpected results emerged depending on the type of reference point calculated. Discard survival will affect the shape of the yield per recruit curve and may influence the estimated of F_{MSY} and $F_{0.1}$ differently.

For fisheries where discards account for a very low percentage of the catch, discard survival is not likely to be important.

6.4 Conclusions

There is still much work to do in relation to the assessment and derivation of reference points on *Nephrops* stocks. The move toward dynamic length-based models is desirable and may help address the reference point issue. Noting that a new length-based model is in development, it is important that this is done by building on existing models, and making use of the best elements of these. Work is being done to develop a Gadget model, and this is a potentially useful additional tool.

Where data-limited methods are being examined, there may be value in testing these on data-rich stocks to gain an understanding of their performance where stock status is better understood, so that the choice of method to apply is well informed.

I thought that valuable work was being done to address the issues listed in the ToRs, and that a co-ordinated work plan setting out a systematic approach to the development, testing and application of the methods might be beneficial in the medium term. This, of course will be heavily dependent on the expert resources available within the contributing institutes.

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Annex 2: Meeting agenda

Workshop on Methodologies for *Nephrops* Reference Points (WKNephrops)

IPMA, Lisbon, 25th November–29th November 2019

Draft Agenda

Monday 25 November 2019		
16:00–18:00	Arrival at IPMA • Meet-and-greet • Informal discussion	Anyone already arrived

Tuesday 26 November 2019		
09:30–10:00	Meeting preliminaries: • Welcome and introductions • Overview of Terms of Reference • Agree Agenda • Housekeeping	All Cristina Silva
10:00–11:00	Current state of reference points: • Review of ICES Reference Points • Stock-by-stock reviews	 Mike Bell Stock assessment leaders
11:00–11:20	Coffee-break	
11:20–13:00	Overview of current and potential methods and software implementations (ToRs1, 3 & 4): • Existing length-based approaches • Dynamic models • Approaches for data limited stocks • Life-history models	 Ewen Bell / Helen Dobby Isabel González Herraiz Mike Bell
13:00–14:00	Lunch	
14:00–16:00	Overview of critical inputs and their sources (ToRs 1, 3 & 4): • Natural mortality • Growth • Discard survival (N.B. WGBIE recommendation on French stocks) • Maturity	All
16:00–16:20	Coffee-break	
16:20–17:30	Planning and allocation of tasks	All
17:30–18:00	Peer reviewer comments and discussion	Robin Cook

Wednesday 27 November 2019		
09:00–09:30	Planning of day's activities	Plenary
09:00–11:00	Work time (ToRs 2, 3 & 4)	
	• Application of methods for estimating reference points to stock data	Sub-groups and individuals
11:00–11:20	Coffee-break	
11:20–12:45	Work time (continued)	
12:45–13:00	Report on progress	Plenary
13:00–14:00	Lunch	
14:00–16:00	Work time (continued)	
16:00–16:20	Coffee-break	
16:20–17:30	Review of progress and additional activity planning	Plenary
17:30–18:00	Peer reviewer comments and discussion	Robin Cook

Thursday 28 November 2019		
09:00–09:30	Planning of day's activities	Plenary
09:00–11:00	Work time (ToRs 2, 3 & 4)	
	• Application of methods for estimating reference points to stock data	Sub-groups and individuals
11:00–11:20	Coffee-break	
11:20–13:00	Presentation of results for ToRs 2-4, wrap-up discussion	Plenary
13:00–14:00	Lunch	
14:00–16:00	Harvest control rule and transition from PA to MSY advice (ToR 5)	
16:00–16:20	Coffee-break	
16:20–17:30	Workshop recommendations and future planning	Plenary
17:30–18:00	Peer reviewer comments and discussion	Robin Cook

Friday 28 November 2019		
09:00–11:00	Wrap-up discussions for remaining participants	Plenary
11:00	End of Meeting	