Cephalopod Indicators for the MSFD

Final Report to Defra on Contract No ME5311

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Executive Summary

1. Cephalopods are short-lived marine invertebrates, characterized by a high metabolic rate, fast growth, and sensitivity to environmental change, which result in highly variable levels of abundance, and potentially high levels of certain heavy metals. They exhibit complex behaviour patterns and are important food web components (as both predators and prey) as well as significant fishery resources, especially in southern Europe but also in UK waters. In some respects they are the charismatic megafauna of the invertebrates.
2. Of around 30 cephalopod species in UK waters, three have significant commercial value as fishery target and bycatch species, namely common cuttlefish *Sepia officinalis* and two loliginid (longfin) squids, *Loligo forbesii* and *L. vulgaris*. Several other species are landed as bycatches, including two loliginid squids (*Alloteuthis subulata*, *A. media*), two cuttlefish species (*S. elegans, S. orbignyana*), two octopus species (*Eledone cirrhosa*, *Octopus vulgaris*) and three ommastrephid (shortfin) squids (*Todaropsis eblanae*, *Illex coindetii*, *Todarodes sagittatus*). In addition, several species of the family Sepiolidae are caught routinely during trawling surveys (e.g. *Sepiola atlantica*, *Rossia macrosoma*).
3. In the context of the Marine Strategy Framework Directive, for a species to be useful in assessment of the status of the marine environment it must be possible to: (1) define favourable status of the species, (2) devise indicators of how close the species is to favourable status, and (3) undertake monitoring to provide regular updates on indicator values. In practice, for cephalopods, all three criteria tend to be linked since existing monitoring data are needed to define indicators which can in turn be interpreted in terms of species status.
4. The present report aims to evaluate the viability of developing MSFD indicators based on cephalopods. As such it objectives are to (a) assemble and evaluate available data on cephalopod distribution, abundance and population parameters, (b) review knowledge on threats to cephalopods, (c) derive standardised abundance indices, (d) analyse patterns and trends in distribution, abundance and population parameters, (e) establish average (baseline) levels and quantify variability, (f) determine the degree to which variability is environmentally driven, (g) collect new data on age-size relationships to evaluate the utility of size-based indicators, (h) propose relevant indicators under descriptor 1, considering the extent to which variation is environmentally driven, (i) evaluate the monitoring required for the candidate indicators, (j) provide advice to Defra on the suitability of indicators based on cephalopods

5. Threats to cephalopod populations include fishing pressure, pollution, habitat disturbance and loss, underwater noise and climate change. Although cephalopod populations are generally thought of as being relatively resilient to high fishing pressure, fishing is probably the most important current threat. While total fishing pressure could be estimated based on current fishery monitoring, there is a need to quantify effort in fisheries which target cephalopods.
6. Landings of loliginid squid in Scotland, which are mainly bycatch, are thought to comprise mainly *Loligo forbesii* and have generally increased since 1985. We argue that they could provide an indicator of abundance so long as targeting of squid does not increase significantly (since they are sufficiently valuable to normally be landed if caught). A reference/baseline level which might indicate GES is however difficult to define due to high variability but a sustained decline would be cause for concern, suggesting a departure from GES, for example due to overexploitation. Over the whole series, the “effect” of the previous year’s landings was positive (i.e. high abundance supports high landings and leads to high landings in the following year), with no evidence of adverse effects of high landings. In addition, landings were positively correlated with indicators of sea temperature and productivity. Although CPUE could provide a better abundance index, there are no reliable fishing effort data available for Scotland since 1997.
7. Both *Loligo* species are routinely landed in English fisheries, but not distinguished from each other, which makes interpretation of trends difficult. However, as for *L. forbesii* in Scotland, a sustained fall in landings of loliginid squid or cuttlefish from English waters would be cause for concern. Landings of cephalopods caught in UK waters either fluctuate considerably between years (loliginid squid, cuttlefish) or are sporadic (ommastrephid squid, octopus). The relatively low commercial value of ommastrephids and octopods in the UK means that landings may not accurately reflect catches. Nevertheless, no evidence of long-term decline was apparent in any of the datasets examined.
8. Several Cefas trawl survey programmes collect data on cephalopods, including loliginids, cuttlefish, ommastrephids and octopus. Our analysis showed that signals of year to year abundance variation can be extracted, once spatial, seasonal and depth-related variation are taken into account. In some cases this interannual variation is demonstrably linked to environmental conditions (as exemplified by the NAO index) but further analysis is needed. In several ongoing survey programmes, “baseline” levels of cephalopod abundance could be defined based on relatively consistent catch rates over a period of a decade or more and the standardised survey abundance could thus be used as an indicator. Comparable survey data series are available from IFREMER.
9. Trawl surveys undertaken by MSS also provide data on cephalopods. We focused on loliginid squid, for which the longest time series is available, and showed that annual abundance is highly variable. Interannual variation was related to

environmental conditions and the previous year's landings (as also seen in the fishery data analysis) but the high proportion of unexplained variation in abundance makes it difficult to define baseline levels.

10. Analysis of the age-length relationship in *Loligo forbesii* based on new and historical age readings on statoliths of individuals collected during monthly market sampling in the 1990s and 2000s (N=749) revealed a surprisingly consistent relationship once the month of hatching (or capture) is taken into account, although unexplained variation is still high, especially in larger squid. A "large squid indicator" is less likely to be useful than an indicator based on the amount of very small animals in commercial catches (as seen in some years in the directed fishery). High catches of small squid would indicate fishing in recruitment areas, which could result in growth overfishing and have the potential to endanger the fished population.
11. It is expected that more detailed analyses, using expanded cephalopod fishery/survey datasets, will be undertaken in future and will clarify the proportion of variation in abundance attributable to environmental factors. Our preliminary results suggest that certain species (e.g. *Loligo forbesii*, *Sepia officinalis*) have potential as environmental indicators in UK waters, although further work is required in order to devise suitable targets and monitoring programmes.
12. Although we focus mainly on MSFD descriptor 1 (biodiversity) cephalopods also have the potential to provide indicators under descriptors 3 (fished species), 4 (food webs), 7 (oceanographic conditions), 8 (pollution), 9 (contaminants in seafood) and 11 (underwater noise). However, existing monitoring programmes provide suitable information only for descriptors 1 and 3. Of the remaining descriptors, high bioaccumulation of both heavy metals and organic pollutants by cephalopods would justify monitoring under descriptor 9 and, potentially, descriptor 8.
13. The review, analysis and synthesis reported here do not provide definitive answers to all the questions posed. However, we argue that the main commercial cephalopod categories could easily be brought into MSFD biodiversity monitoring, given that existing and ongoing trawl survey programmes provide valuable monitoring data, and that plausible indicators of abundance can be generated, allowing comparison with tentatively defined baseline levels and/or detection of sustained negative trends. Monitoring of size distributions in commercial catches could reveal effects of fishery exploitation, through use of a "small squid indicator" as well as more sophisticated assessment approaches. The main caveat with the existing survey and fishery data is the lack of routine identification to species level, potentially causing difficulties in interpreting observed trends.

1. Introduction: Cephalopods and the MSFD process

Around 30 species of cephalopods occur in UK and adjacent waters, a number of which are landed by fisheries, either as by-catch or target species and at least three (the cuttlefish *Sepia officinalis* and the squids *Loligo forbesii* and *L. vulgaris*) have significant economic value. Several other species are landed alongside the commercially important species, at least occasionally, reflecting their co-occurrence and the fact that cephalopod landings are rarely identified to species (for general reviews see Hastie *et al.*, 2009a; Pierce *et al.*, 2010).

Cephalopods are short-lived species characterised by high metabolic rates and rapid growth. As adults they may be benthic (octopus), demersal (cuttlefish and loliginid squids) or pelagic (ommastrephid squids), although many species have a pelagic paralarval stage and the distinction between demersal and pelagic squids is not clear cut. Cephalopods occur from coastal waters to the deep sea to, although few tolerate low salinity. Many species, including most squid and cuttlefish, undertake ontogenetic migrations and some squid also undertake daily vertical migrations. Cephalopods display complex behaviour patterns and octopuses in particular are believed to be amongst the most intelligent invertebrates. This is reflected in recent EU legislation regulating experiments on animals (EU Directive 2010/63/EU, Smith *et al.*, 2013; see also Moltschaniwskyj *et al.*, 2007).

Cephalopod populations have a high production to biomass ratio and display marked year-to-year fluctuations in distribution and abundance, as well as pronounced seasonal patterns reflecting the short (often annual) lifespan. They have important ecological roles as both predators and prey and, in some ecosystems, squid are keystone species (e.g. Gasalla *et al.*, 2010).

In addition, there is a range of evidence suggesting that cephalopods are sensitive to various anthropogenic and natural pressures. They are sensitive to environmental conditions, through effects on metabolism, growth, movements and trophic interactions, they are known to accumulate high levels of certain contaminants, notably cadmium (e.g. Bustamante *et al.*, 2002a,b), and there is evidence of mortality caused by intense underwater noise (specifically seismic surveys, Guerra *et al.* 2011; see section 3).

The Marine Strategy Framework Directive (MSFD) sets out a process by which EU Member States should achieve Good Environmental Status (GES) in their waters by 2020. It involves a series of staged actions: (1) Initial assessment of the current state of the marine environment in MS waters; (2) Definition of the characteristics that constitute Good Environmental Status (GES); (3) Development of objectives and indicators designed to show status in relation to GES; (4) A monitoring program to measure progress towards GES; (5) Design and implementation of a program of measures to achieve / maintain GES.

The MSFD defines 11 descriptors of GES (Box 1.1). In relation to these descriptors, cephalopods have potential to provide indicators under descriptors 1, 3, 4, 7, 8, 9 and 11, although existing monitoring programmes provide suitable information only for descriptors 1 and 3 (i.e. biodiversity and exploited species respectively) and evidence in relation to descriptors 4, 7, 8, 9 and 11 comes from specific research projects and associated publications (see section 3 below for further details).

Box 1.1: MSFD Descriptors

(1) **Biological diversity** is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.
(2) **Non-indigenous species** introduced by human activities are at levels that do not adversely alter the ecosystems.
(3) Populations of all **commercially exploited fish and shellfish** are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.
(4) All elements of the **marine food webs**, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.
(5) **Human-induced eutrophication** is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters.
(6) **Sea-floor integrity** is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.
(7) Permanent alteration of **hydrographical conditions** does not adversely affect marine ecosystems.
(8) **Concentrations of contaminants** are at levels not giving rise to pollution effects.
(9) **Contaminants in fish and other seafood** for human consumption do not exceed levels established by Community legislation or other relevant standards.
(10) Properties and quantities of marine litter do not cause harm to the coastal and marine environment.
(11) Introduction of **energy, including underwater noise**, is at levels that do not adversely affect the marine environment.

According to the implementation timetable (Figure 1.1), we are presently at the stage of design and implementation of monitoring programmes. In relation to cephalopods, which have not previously been subject to scrutiny in this context, there is therefore a need to rapidly progress through the previous stages to allow decisions to be made on their inclusion within monitoring programmes.

In undertaking this process for any marine taxon, some value judgement about the importance of the taxon is implied, either in relation to the taxon itself or its suitability as an indicator of the general state of the system. Clearly all marine taxa fulfil some role in marine ecosystems, and their ecological importance may be expressed in terms of energy flow, "keystoneness", or contribution to ecosystem goods and services. Species may also be viewed as "important" because they are threatened, sensitive to anthropogenic stressors, typical of a particular habitat or ecotype, or charismatic. Particular taxa may thus be selected as a basis for indicators for a variety of reasons. Good indicators should meet a number of criteria, including sensitivity to the pressure in question, specificity of the response, scientific support for its validity, and communicability to managers, stakeholders and the public (see Newson et al. 2009).

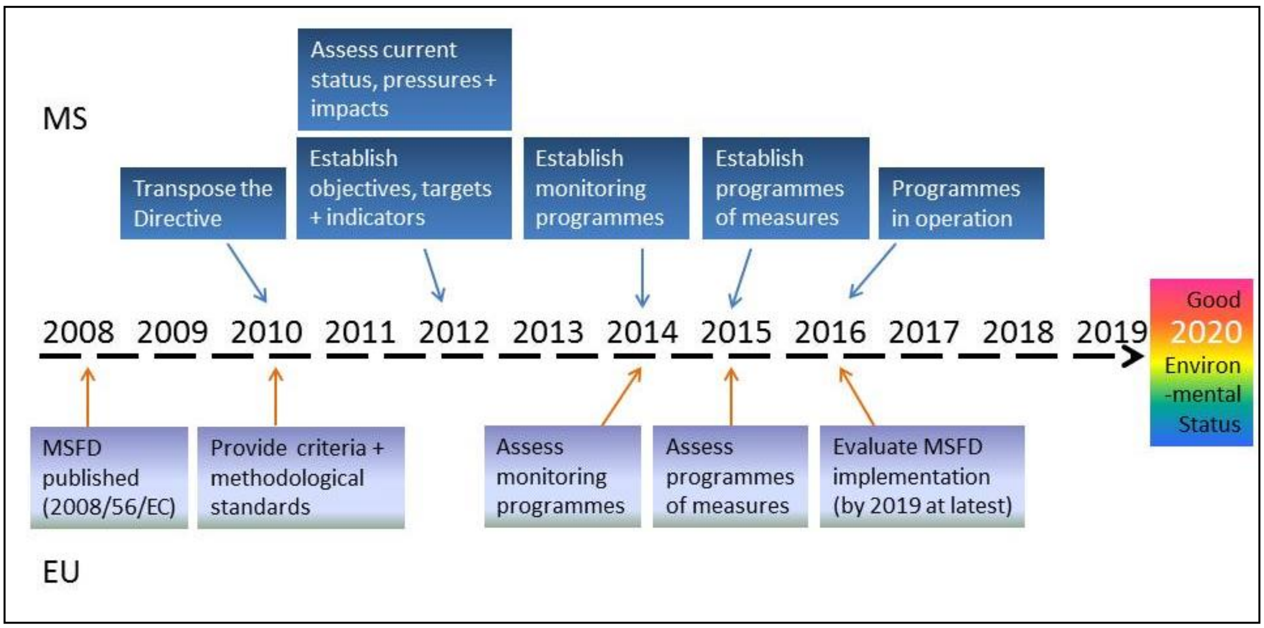


Figure 1.1. Implementation timetable for the MSFD Process (MS = Member States, EU + European Union) (adapted from Santos & Pierce, 2015).

The ecosystem characteristics defined under the MSFD include a series of functional groups (of marine organisms), two of which are Coastal/shelf pelagic cephalopods and Deep-sea pelagic cephalopods. Non-pelagic cephalopods are not included. In practice, little attention has been given to cephalopods. According to a report by the Joint Research Centre of the European Commission (Palialexis *et al.*, 2014), only one Member State has reported on the two cephalopod functional groups (as compared to 12 MS which have reported on demersal fish). An OSPAR Working Group on Fish, Cephalopods and Pelagic Habitats was unable to address the second two titular components due to lack of available expertise for the workshop on MSFD biodiversity descriptors (Löffler *et al.*, 2012). The Irish Marine Institute's (2014) public consultation document on MSFD monitoring makes frequent reference to “fish and cephalopods” but the content is almost devoted entirely to fish. It is stated that “cephalopod monitoring is covered under the Irish Groundfish Survey” but it seems doubtful that this would provide suitable data on pelagic cephalopods. Spain is currently considering monitoring for pelagic cephalopods in Canary Island waters.

In relation to the relevance of cephalopods (both pelagic and non-pelagic), we can point to their relatively high trophic importance, their value as current or potential fisheries resources and their relatively high public profile as perhaps the most charismatic of the marine invertebrates. In addition, as short-lived species, they can act as sentinels of environmental change, for example in relation to a range of anthropogenic stressors.

An essential part of the MSFD process is to identify baselines and reference points. In order to define these, we already need to have in mind what will be monitored and measured; in relation to biodiversity this will typically be abundance, range and the underlying demographic processes (e.g. mortality rate). This in turn implies that we can define the populations or management units which will be monitored and ultimately managed (while recognising that we can only manage human activities rather than the animals themselves).

The baseline is essentially the current status; examination of the recent or longer-term history of a species may also provide evidence of what constitutes the desired (target) status (an approximation to GES), while recognising that marine ecosystems are not in a pristine state and cannot realistically be returned to such a state. Analysis of historical data may also enable us to identify limit reference points, for example, the point at which status is so far removed from GES that management action becomes necessary.

For cephalopods, a key consideration is their environmental sensitivity, linked to their rapid growth and short life-cycles: abundance and distribution of many if not most species are expected to fluctuate widely from year to year. Thus, the baseline and reference points may not be fixed values, rather a description of the natural range of variability and its relationship with oceanographic and climatic variability. This then leads us to consider whether it is feasible to separate signals of impacts of anthropogenic stressors from the natural responses to climatic and other variability. For example, is it possible to disentangle fishery and environmental effects; can we distinguish signal from noise? Based on such analysis, the feasibility of defining GES objectives, reference points and indicators can be evaluated.

A second important consideration is the feasibility of implementing monitoring programmes. In principle, a case could be made for new monitoring programmes taking into account the need to balance the monitoring requirements for all MSFD indicators and the fact that any monitoring programme has to be realistically achievable given available resources. For these reasons, it is essential to evaluate whether existing and ongoing monitoring programmes (in this case probably mainly fishery monitoring) would provide sufficient information on the proposed indicators.

The objectives of the present project were to:

(1) Assemble and evaluate literature and data sources for biological features of cephalopod species occurring in UK waters, covering distribution, abundance, demography, contaminant burdens, and ecological role in marine communities, and including information on commercial and non-commercial species, and on eggs and life stages, where available; To evaluate scope and consistency of recording and taxonomic resolution, taking into account differences in catching power of different vessels and gears; To inform the selection of species and area covered by further analysis;

(2) Review knowledge on threats and possible threats to cephalopod populations in UK and adjacent regional waters including, but not restricted to, fishing, habitat loss, pollution, underwater noise, and climate change;

(3) Review literature and analyse data on biological features of cephalopods to, where feasible:
    a. develop standardized abundance indices based on survey and/or fishery data;
    b. identify patterns and trends in abundance, distribution, demographic and ecological parameters; identify preferred habitats;
    c. describe variability and environmental sensitivity of parameters investigated under (a) above; identify baselines and quantify natural variability around baseline levels;
    d. make a preliminary selection of possible indicators of species or community status;

(4) Support the development of demographic indicators for squid by obtaining new age data from stored samples, permitting derivation of age-size relationships, analysis of variability in size-at-age and, hence, evaluation of the utility of size-based indicators;

(5) Develop appropriate candidate quantitative or qualitative indicators for cephalopod distribution range and abundance, taking into account uncertainty about baselines, and potential difficulties in separating environmentally-driven variation from that due to anthropogenic impacts;

(6) Develop appropriate candidate quantitative or qualitative indicators for cephalopod demography, contaminant levels, and ecological / community indicators. As in (5) above, this will take into account uncertainty about baselines, and potential difficulties in separating environmentally-driven variation from that due to

anthropogenic impacts, and considering the additional constraint that while relevant data exist in project databases they are not necessarily currently routinely collected;

(7) Synthesise results to provide an evaluation of all candidate indicators, including full documentation and, where monitoring is currently inadequate, propose fit-for-purpose monitoring programmes;

(8) Report on the current status of cephalopod stocks in UK waters, in the context of long-term sustainability of the corresponding fisheries.

(9) Determine if suitable indicators, based on unambiguous signals, can be devised, and discuss the feasibility of initiating relevant targets and monitoring programmes.

(10) Provide advice to Defra in the context of MSFD milestones, specifically:

   a. A preliminary report on possible indicators (in advance of full evaluation) at the end of August 2013, for submission to ministers ahead of the public consultation exercise;
   b. An interim report in March 2014 to inform the Defra policy team in their preparation of responses to the public consultation.

2. Assembly of data and literature

The focus has been on assembly and analysis of datasets relevant to MSFD Descriptor 1 (biodiversity), specifically datasets relevant to understanding cephalopods abundance, distributional range and population dynamics, thus covering criteria 1, 2 and 3 at the species level. We thus assume that the habitat and ecosystem levels of descriptor 1 are adequately addressed elsewhere and we do not specifically consider them in relation to cephalopods. The habitats and ecosystems in which cephalopods live are essentially those also occupied by other marine biota, although it may be noted that many cephalopods are to some extent reliant on seabed habitats, e.g. for attachment of eggs (all benthic and demersal species), building dens (octopus) and burrowing (sepiolids). In addition, given evidence of high "keystoneness" in some loliginid squids e.g. Gasalla *et al.*, 2010), we recommend that cephalopods are included in ecosystem models.

A considerable amount of historical information is available on cephalopod distribution and abundance. Many cephalopod species are recorded during fish abundance surveys in UK waters, and large project datasets are available for a few cephalopod species, namely the veined squid (*Loligo forbesii*), the common cuttlefish (*Sepia officinalis*) and the lesser octopus (*Eledone cirrhosa*). Smaller datasets are also available for other species and groups (e.g., ommastrephid squid). Depending on the source and the geographical area, identification may be to species, genus or family level.

Written and e-mailed requests for relevant information on cephalopods in UK waters were sent out to a number of UK and European institutes (Table 2.1). Most responses were favourable, and contacts provided cephalopod data of interest to the current project. However, finally, not all datasets were provided in time to complete the present report. We were nevertheless able to assemble sufficient data to complete the project.

Three main types of cephalopod data were reviewed and analysed:
(a) fishery data (landings, CPUE (if available))
(b) research vessel (RV) trawl survey data (abundance, biomass)
(c) databases of biological information (size, age, growth, maturation, phenology)

The main sources of fishery and survey data are Cefas (England & Wales), Marine Scotland, Marine Institute (Ireland) and IFREMER (France). Substantial amounts of historical data were acquired for three species in particular, in UK waters: squid (Loliginidae, including *Loligo forbesii*), curled octopus (*Eledone cirrhosa*) and cuttlefish (*Sepia officinalis*). We have copies of the FAO cephalopod landings data (as part of Fishstat J, 2013 edition) and the continuous plankton recorder (CPR) database (SAHFOS).

The fishery and survey datasets received were screened in order to focus on the most useful potential long-term indicators of the condition of cephalopod stocks in UK waters; this process was initiated before all the datasets arrived. We also carried out a preliminary analysis of long-term plankton records of cephalopod larvae from the continuous plankton recorder (CPR) database (SAHFOS). However, since cephalopods were not identified to species we did not explore this further.

In relation to biological data, we hold probably the largest available database on *Loligo forbesii* as well as some data on other UK cephalopod species. A historical archive of statoliths of *L. forbesii* has been mined to generate new data on age and growth patterns.

In relation to other MSFD descriptors, we have summarised relevant literature and datasets available for cephalopods. The fishery and survey data can potentially yield descriptors for fished cephalopods in relation to Descriptor 3 but here we report only on existing work on this topic rather than attempting new analysis. Work relevant to descriptors 3, 4, 7 9 and 11 is covered in section 3. The remainder of the report is devoted to descriptor 1.

Table 2.1. Cephalopods as indicators for MSFD: Available data on distribution and abundance.

		DATA					
	GEOGRAPHIC	TYPE	RESOLUTION				
SPECIES	**AREA**	**Fishery/ Research**	**TEMPORAL**	**SPATIAL**	**PERIOD**	**SOURCE**	**STATUS**
Squid [*L. forbesii*]	NE Atlantic, N Sea	Scottish landings **F**	Monthly	ICES rectangle	1985 – 2012	Scottish Govt.	Acquired
Squid [*L. forbesii*]	NE Atlantic, N Sea	UK landings **F**	Monthly	ICES rectangle	2000 – 2012	Scottish Govt.	Acquired
Octopus [*E. cirrhosa*]	NE Atlantic, N Sea	Scottish landings **F**	Monthly	ICES rectangle	1985 – 2012	Scottish Govt.	Acquired
Octopus [*E. cirrhosa*]	NE Atlantic, N Sea	UK landings **F**	Monthly	ICES rectangle	2000 – 2012	Scottish Govt.	Acquired
Cuttlefish [ND]	NE Atlantic, N Sea	Scottish landings **F**	Monthly	ICES rectangle	1985 – 2012	Scottish Govt.	Acquired
Cuttlefish [ND]	NE Atlantic, N Sea	UK landings **F**	Monthly	ICES rectangle	2000 – 2012	Scottish Govt.	Acquired
Squid [*L. forbesii*]	NE Atlantic, N Sea	RV survey IBTS **R**	Quarterly	ICES rectangle	1998-2012	Marine Scotland	Acquired
Octopus [*E. cirrhosa*]	NE Atlantic, N Sea	RV survey IBTS **R**	Quarterly	ICES rectangle	2008-2012	Marine Scotland	Acquired
Cuttlefish	NE Atlantic, N Sea	RV survey IBTS **R**	Quarterly	ICES rectangle	2008-2012	Marine Scotland	Acquired
Squid [*Loligo* spp.]	NE Atlantic, N Sea	UK landings **F**	Monthly	ICES rectangle		DEFRA/CEFAS	
Octopus [*E. cirrhosa*]	NE Atlantic, N Sea	UK landings **F**	Monthly	ICES rectangle		DEFRA/CEFAS	
Cuttlefish [*S. officinalis*]	NE Atlantic, N Sea	UK landings **F**	Monthly	ICES rectangle		DEFRA/CEFAS	
Squid [*L. vulgaris*]	NE Atlantic, N Sea	RV survey IBTS **R**	Quarterly	ICES rectangle	1982-2012	CEFAS	Acquired
Octopus [*E. cirrhosa*]	NE Atlantic, N Sea	RV survey IBTS **R**	Quarterly	ICES rectangle	1988-2012	CEFAS	Acquired
Cuttlefish [*S. officinalis*]	NE Atlantic, N Sea	RV survey IBTS **R**	Quarterly	ICES rectangle	1989-2012	CEFAS	Acquired
Squid [*Loligo* spp]	English Channel	RV survey CFGS **R**	Annual	English Channel	1990 – 2012	IFREMER	Acquired
Cuttlefish [*S. officinalis*]	English Channel	RV survey CFGS **R**	Annual	English Channel	1990 – 2012	IFREMER	Acquired
Squid [*Loligo* spp.]	E Channel, east	RV survey CFGS **R**	Annual	English Channel	1988 – 2011	IFREMER	Acquired
Cuttlefish [*S. officinalis*]	E Channel, east	RV survey CFGS **R**	Annual	English Channel	1988 – 2011	IFREMER	Acquired
Squid [*L. forbesii*]	E Channel, N Sea	French landings **F**	Monthly	ICES rectangle		IFREMER	
Octopus [ND]	E Channel, N Sea	French landings **F**	Monthly	ICES rectangle		IFREMER	
Cuttlefish [*S. officinalis*]	E Channel, N Sea	French landings **F**	Monthly	ICES rectangle		IFREMER	
Squid [*L. forbesii*]	NE Atlantic	Irish landings **F**	Annual	NE Atlantic	1995 – 2012	Mar. Inst. [Eire]	Acquired
Squid [ommastrephids]	NE Atlantic	Irish landings **F**	Annual	NE Atlantic	1995 – 2012	Mar. Inst. [Eire]	Acquired
Octopus [*E. cirrhosa*]	NE Atlantic	Irish landings **F**	Annual	NE Atlantic	1995 – 2012	Mar. Inst. [Eire]	Acquired
Cuttlefish [ND]	NE Atlantic	Irish landings **F**	Annual	NE Atlantic	2003 – 2012	Mar. Inst. [Eire]	Acquired
Squid [*L. forbesii*]	Irish Sea	RV survey **R**	Annual	N/A		Bangor Univ.	
Octopus [*E. cirrhosa*]	Irish Sea	RV survey **R**	Annual	N/A		Bangor Univ.	
Squid [*L. forbesii*]	English Channel	RV survey **R**	Annual	N/A		MBA Plymouth	
Squid [*L. forbesii*]	NE Atlantic, I Sea	RV survey **R**	Annual	ICES rectangle		DARDNI	
Octopus [*E. cirrhosa*]	NE Atlantic, I Sea	RV survey **R**	Annual	ICES rectangle		DARDNI	
Cuttlefish [*S. officinalis*]	NE Atlantic, I Sea	RV survey **R**	Annual	ICES rectangle		DARDNI	
Squid [*L. forbesii*]	North Sea	RV survey IBTS **R**	Annual	ICES rectangle		GEOMAR	
Squid [*A. subulata*]	North Sea	RV survey IBTS **R**	Annual	ICES rectangle		GEOMAR	

3. Literature review: environmental relationships, trophic interactions and threats

3.1. Overview

More than 30 species of cephalopod have been recorded in UK and adjacent waters (Hastie *et al*., 2009a), of which three (*Sepia officinalis*, *Loligo forbesii*, *L. vulgaris*) are currently of significant economic importance as fishery resources in UK waters, while at least six others are of minor importance and/or are commercially exploited elsewhere in their ranges (*Eledone cirrhosa*, *Octopus vulgaris, Illex coindetii, Todarodes sagittatus, Todaropsis eblanae*, *Alloteuthis subulata*).

A considerable amount of historical information is available for several of the exploited species of economic importance and detailed reviews are available for most cephalopods occurring in continental shelf waters around the UK, covering basic life cycle biology and ecology, as well as more detailed explorations of population dynamics, environmental relationships and fishery exploitation (e.g. Pierce & Guerra, 1994; Pierce *et al*., 2008a, 2010; Hastie *et al*., 2009a; Rosa *et al.*, 2013a,b; Jereb *et al.*, In Press; Rodhouse *et al.*, 2014).

Recent literature on cephalopod distribution, abundance and population dynamics, including environmental relationships, has been searched extensively and recent publications (e.g. González *et al*., 2010; Oesterwind *et al*., 2010; Lourenco *et al*., 2012; Bloor *et al*., 2013a, b; Smith *et al.*, 2013; MacLeod *et al.*, 2014; Moreno *et al.*, 2014; Sonderblohm *et al.*, In Press) have been reviewed, and new information incorporated alongside the material from previous reviews.

Until very recently there have been several important gaps in knowledge of European cephalopods. One of these concerns the distribution and abundance of the early life stages. Cephalopod hatchlings and paralarvae have proved to be difficult to sample effectively and are difficult to identify. The Continuous Plankton Recorder includes records of the class Cephalopoda (Figure 3.1; see also the ZIMNES website http://192.171.193.133/detail.php?sp=Cephalopoda; Hastie *et al.*, 2015). However, not only are these samples not identified to species, it is not certain that all are cephalopods (Richardson *et al.*, 2006).

A second knowledge gap concerns growth rates in the field, due to slow progress in the application of age determination methods. Especially in short-lived and fast growing animals like cephalopods, uncertainty about the age of animals sampled generates significant doubts about the life history of these animals (e.g. Boyle *et al.*, 1995). Before age determination using daily growth ring on statoliths, it was thought (based on the presence of several “cohorts” in length-frequency data) that many squid species lived for several years.

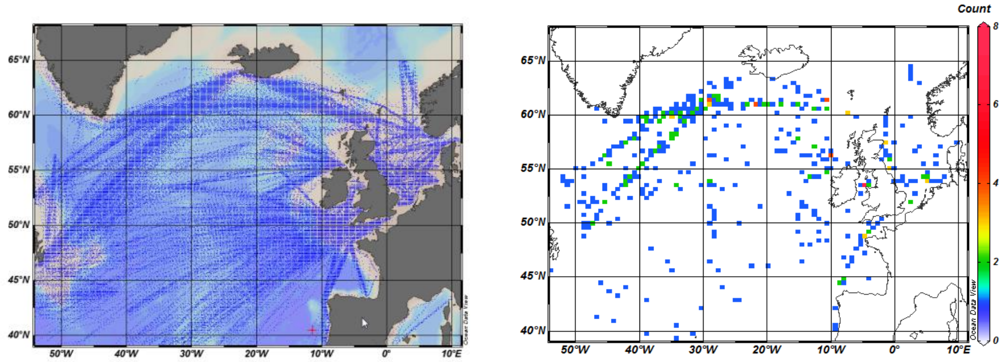


Figure 3.1. (Left) Locations of the CPR samples for Jan-Dec 1960-2010. (Right) Total count of samples corresponding to cephalopod larvae for the same months/years.

3.2. Environmental relationships

Sensitivity to environmental conditions, including hydrographic/oceanographic conditions potentially makes cephalopods relevant to descriptor 7. However, relevant changes in hydrographic conditions can be monitored directly and/or through monitoring changes in other marine taxa (e.g. jellyfish, Condon *et al.*, 2013); the need for a cephalopod-based indicator is doubtful. Nevertheless, understanding environmental relationships is essential in relation to the use of cephalopod-based indicators under descriptors 1 and 3.

A particular challenge is to isolate environmental, fishery and stock size effects on population dynamics. Many studies have analysed cephalopod-environment relationships (e.g. Pierce *et al.*, 1994a, 1998, 2005, 2008a; Waluda & Pierce, 1998; Bellido *et al.*, 2001; Denis *et al.*, 2002; Sobrino *et al.*, 2002; Pierce & Boyle, 2003; Wang *et al.*, 2003; Zuur & Pierce, 2004; Chen *et al.*, 2006; Otero *et al.*, 2008, 2009; Viana *et al.*, 2009) but, while there is agreement that environmental factors play a major role in determining distribution and abundance and on the general nature of the causal relationships (Pierce *et al.*, 2008a), the forms of empirical relationships vary between studies and detailed understanding of the underlying mechanisms remains limited. This reflects both the high plasticity of cephalopod life cycles and the relatively short time-series that have been available to previous studies.

Some basic principles can be established in relation to when and how environmental variation may affect individual growth and survival, and population distribution and dynamics. Many species have pelagic paralarvae which are subject to passive transport as well as being vulnerable to predation by planktivores. Even in those species with benthic early life stages, the initial post-hatching phase is probably the period of highest vulnerability to predation. Many species show ontogenetic migrations which may take advantage of ocean currents (as documented in several squid of the family Ommastrephidae in different parts of the world). Metabolic rate and growth rate are sensitive to ambient temperature and the plasticity of growth and maturation patterns is such that both the timing of reproduction and the final adult size vary substantially, with environmental conditions experienced around the hatching period being especially important (e.g. Pecl *et al.*, 2004; Moreno *et al.*, 2012). Outcomes may be counterintuitive, with slower growing individuals reaching a larger adult size.

Environmental effects may be expressed through changes in life-cycle phenology. This can be seen in the variable timing of migration, which may be linked to sea temperatures as reported for *Loligo forbesii* in the English Channel (Sims *et al.*, 2001); see also Pierce *et al.* (2005).

The rapid growth of cephalopods is supported by feeding: as voracious predators, cephalopods depend on the distribution and abundance of their prey. Changes in temperature will affect ecosystem function; based on a trophic model, Nye *et al.* (2013) predicted that a 3^{o}C rise in temperature would lead to a 50% increase in squid biomass off the Northeast USA. Temperature-induced distribution shifts also have implications for cephalopod fishery management (Link *et al.*, 2010).

Those species which lay their eggs on the seabed substrate (octopus, cuttlefish, and loliginid squid) depend on the availability of suitable structures to attach the eggs as well as a good oxygen supply, adequate temperature and high salinity. Most cephalopods are intolerant of both low salinity and hence egg production can be adversely affected by high rainfall leading to high freshwater input into coastal waters.

Finally, most cephalopod species have short life cycles and non-overlapping generations so abundance is not buffered against variable recruitment success. Environmentally induced variation in spawning success and recruitment is therefore expected to have a stronger and more immediate effect on cephalopod abundance than would be the case in longer-lived species.

Thus, a range of direct and indirect environmental effects on distribution and abundance, at different temporal and spatial scales, can be hypothesised. Temperature is certainly important, as are large-scale climatic phenomena that affect current patterns, e.g. the North Atlantic Oscillation, which affects the strength of the North Atlantic current and hence the strength of inflow of warm Atlantic waters into the North Sea. Meso-scale oceanographic features can signal productivity hotspots exploited by predators such as squid.

Statistical modelling, notably time series methods such as dynamic factor analysis will potentially allow separation of climate, fishery and stock effects on abundance patterns (see Zuur & Pierce, 2004; Sonderblohm *et al.*, In Press).

3.3. Trophic relationships

Cephalopods are significant components of marine food webs, as both prey and predators (see Croxall & Prince, 1996; Klages, 1996; Pierce & Santos, 1996; Rodhouse & Nigmatullin, 1996; Smale, 1996; Santos *et al.*, 2001a; Hastie *et al.*, 2009a; Jereb *et al.*, In Press). At a global scale, Clarke (1987, 1996) estimated that sperm whales alone could be consuming almost two orders of magnitude more cephalopods than were then taken by world fisheries. Where cephalopods have been included in ecosystem models, they appear to be an important, even keystone, species (Gasalla *et al.*, 2010; Wangvoralak, 2011).

In the context of MSFD trophic indicators (descriptor 4), while cephalopods feature in the diet of a wide range of marine predators, including fish, seabirds, seals and cetaceans, their abundance is most likely to be important for teuthophagous cetaceans such as Risso's dolphin (*Grampus griseus*), long-finned pilot whale (*Globicephalus melas*) and sperm whales (*Physeter macrocephalus*). In addition, various, mainly oceanic, small cetaceans feed on both fish and cephalopods and could be impacted by changes in cephalopod abundance. Recording cephalopod remains in stomach contents can be incorporated into ongoing monitoring of cetacean diets, as has been the case for many years within the Scottish component of the UK Strandings Investigation project (see Santos *et al.*, 1999, 2001b,c,d, 2002, 2004, 2006, 2008, 2014; Canning *et al.*, 2008; MacLeod *et al.*, 2014).

3.4. Threats to cephalopods in UK waters

The main potential anthropogenic threats to cephalopod populations in UK waters include fishing pressure, heavy metal bioaccumulation (including metals from natural sources), various direct and indirect impacts of offshore development, including underwater noise, and climate change. These threats have been reviewed in a number of Strategic Environmental Assessment reports (Pierce *et al*., 2002; Hastie *et al*., 2006; Sacau *et al*., 2005; Stowasser *et al*., 2004) and were reviewed more recently in Hastie *et al.* (2009a). In addition, recent work has highlighted the potential risks to cephalopods associated with underwater noise (André *et al*., 2011; Guerra *et al.,* 2012).

The threats investigated or reviewed in the above-mentioned studies are still considered to be important at present. Individual cephalopod species may be more or less vulnerable to particular threats, due to a number of factors including: level of exploitation, life cycle characteristics (e.g. spawning behaviour), habitat preferences and geographic distribution. Those species/groups considered to be most vulnerable are listed in Table 3.1. We emphasize that there are still significant gaps in knowledge on the topic of threats to cephalopods, and much of what has been inferred, although based on some factual data, is rather speculative. A list of current threats, based on those provided in Hastie *et al.* (2009a) is provided here.

3.4.1. Fishing pressure

There are problems for the assessment and management of cephalopod stocks, associated with their biology, life histories and lack of knowledge for many species. The short life cycle offers little opportunity to adjust fishing effort on individual cohorts, and renders cephalopods vulnerable to overfishing (Bravo de Laguna, 1989), although it also contributes to their apparent resilience. In UK waters, growth overfishing may already be affecting *Loligo forbesii* catches (Pierce & Guerra, 1994), for example due to targeting of new recruits using small mesh nets. Recruitment overfishing may have more serious consequences at the population level although, strictly speaking, stock-recruitment relationships have not been established so this remains speculative. The non-overlapping generations and lack of a buffer of older animals mean that if a cohort is fished out prior to spawning, the species may become locally extinct. However, factors such as the existence of many microcohorts (the life cycles of which are out of phase) and a wide distribution, mean that cephalopod stocks may also be able to recover quickly from over-exploitation (Caddy, 1983).

Stock assessment exercises have been carried out on loliginid squid stocks (Royer *et al.*, 2002) in *Loligo forbesii* (Challier *et al.*, 2005) and in the common cuttlefish *Sepia officinalis* (Royer *et al.*, 2006; Gras *et al.*, In Press). These assessments were based on a range of tools including depletion methods, VPA on a monthly time scale, and a two stage biomass model. In squid, depletion methods and VPA gave similar results for recruitment and abundance trends and VPA enabled Thomson and Bell projections for exploitation diagnostics. Results showed that, for the period 1993 – 1996, both species of *Loligo* were overexploited except when abundance as low (as in 1996 in *Loligo forbesii*) when the resource was just "fully exploited", apparently because fishing pressure shifted to other resources. This concerns "growth overexploitation" since it describes the consequences of fishing pressure on newly recruited specimens. In *L. forbesii* (Challier *et al.*, 2005), updated assessments showed no evidence of recruitment overfishing and, furthermore, indicated that recruitment was more related to environmental parameters than to adult abundance (i.e. there was no clear stock-recruitment relationship.

In cuttlefish, Thomson and Bell projections and exploitation diagnostics indicated clear evidence of over-fishing in 1995, 1997 and 1998 and a slight under-exploitation in 2000 (Challier *et al.*, 2006). Use of a two-stage biomass model (Gras *et al.*, In

Press) provided exploitation rates (ratio of catch over biomass) which were rather high (between 30-40%) but which did not show any significant trend. In addition, high exploitation could very well be followed by a strong cohort, suggesting a low inertia in the cuttlefish population. Diagnostics could be biased by uncertainty about natural mortality but, nevertheless, there seems to be little scope for increased exploitation.

3.4.2. Heavy metal contamination

Heavy metals, including arsenic, barium, cadmium, chromium, copper, iron, mercury, nickel, lead and zinc; reach the marine environment via rivers and certain marine operations, such as the exploitation of offshore resources and disposal of dredged materials. Most may ultimately be of natural origin but transferred to the water column by human activity. Metallic contaminants are incorporated into cephalopods and other marine predators via the food chain (e.g. Bustamante *et al*., 1998, 2002a, b; Seixas & Pierce, 2005a, b; Seixas *et al.*, 2005a, b).

High levels of mercury and cadmium have been reported in certain cephalopod species in the north-east Atlantic. Cephalopods are known to rapidly accumulate cadmium, copper, mercury and zinc in the digestive gland (hepatopancreas) and other tissues (Bustamante *et al*., 1998; Stowasser *et al*., 2005; Pierce *et al*., 2008b). This clearly poses a risk to consumers, including humans, and some studies have shown levels in individual cephalopods that exceeded safe limits for human consumption (e.g. lead in octopus, Seixas & Pierce, 2005a). Thus there is a rationale to consider monitoring cephalopods under descriptor 9. The effects on cephalopods themselves are less clear; some recent studies suggest some level of resistance while others show damaging effects. It is questionable to what extent these effects can be seen as anthropogenic, but insofar as human activity mobilises toxic elements and transfers them to the water column, these findings are relevant under descriptor 8.

Culture experiments at different stages of the life cycle of common cuttlefish *Sepia officinalis* using zinc and cadmium tracers with seawater, sediments, and food as uptake pathways suggested that food is the main route for bioaccumulation, and that the digestive gland plays a major role in storage and (presumed) detoxification (Bustamante *et al.*, 2002a, b). Juvenile physiology of cuttlefish can be disturbed by heavy metals (e.g. silver, cadmium, copper), negatively affecting embryo growth and hatchling survival (Le Bihan *et al.*, 2004; Lacoue-Labarthe *et al.*, 2010). Ecotoxicological studies using isolated cuttlefish digestive gland cells show that some heavy metals (copper, zinc, and silver) disrupt enzymatic systems (Le Bihan et al., 2004).

3.4.3. Organic pollutants

Offshore hydrocarbon production is a major environmental issue in European waters (Pierce *et al*., 2002; Stowasser *et al*., 2004; Sacau *et al*., 2005). The main risks of oil pollution are from accidental spills, bunkering operations, fishing vessel casualties/ accidents and tanker source spillages. Discharges of certain wastes associated with oil and gas production are regulated. As in the case of heavy metals, uptake of contaminants by cephalopods may be more of an issue for consumers than the animals themselves. However, more research in this area is required.

Cephalopods are known to accumulate persistent organic pollutants such as pesticides and PCBs, again potentially putting consumers at risk. Danis *et al.* (2005) exposed cuttlefish to PCBs in seawater, sediment and food, demonstrating that PCBs are incorporated to high levels in their tissues and propose that cuttlefish might be useful bio-indicators of ambient water PCB contamination.

There is experimental evidence that pharmaceutical residues (specifically fluoxetine) can negatively affect early growth of cuttlefish (Di Poi *et al.*, 2013). There are also reports of malformed common cuttlefish thought to be due to the teratogenic effects of the antifouling compound tributyltin (TBT) (Schipp & Boletzky, 1998).

3.4.4. Radionuclides

Radioactive material discharged by the nuclear industry may also have a contaminating effect on marine biota. In UK waters, concentrations of radionuclides have been influenced by discharges from European nuclear reprocessing plants (Livingston & Povinec, 2000). Radionuclide levels have been reported in a small number of squid species (egg. *Gonatus fabricii*, *Loligo vulgaris*) (Heldal *et al*., 2002a, b; Heyraud et al., 1994). However, little is known about how these accumulate in the food chain and how cephalopods are affected.

3.4.5. Habitat damage and disturbance

Another potentially serious impact on cephalopod species in UK waters would be the physical damage to or disturbance of spawning grounds due to localised displacement of bottom sediments. Benthic spawning species, such as *Loligo forbesii*, *Sepia officinalis* and *Eledone cirrhosa*, may be particularly vulnerable to physical disturbance in certain areas (Stowasser *et al*., 2005). Drilling activities, dredging operations (gravel extractions) and extensive fisheries could impact the spawning ground of *L. forbesii*. Overall, cephalopod diversity is unlikely to be significantly affected since measureable physical disturbances of the seabed are typically localised. However, fishing itself may have the most damaging effects on spawning habitat. Aside from the well-documented habitat damage caused by trawling gear, squid and cuttlefish are known to attach their eggs to fixed fishing gear, including gill nets and creels, and indeed also cuttlefish traps; the mortality caused to eggs by lifting the gear may be very substantial in certain areas and there is a need for further research on this.

3.4.6. Underwater noise

As in the case of many marine animals, squid may show startle responses to marine noise, potentially resulting in displacement from preferred areas (Fewtrell & McCauley 2012). However, more serious effects are also documented. In NW Spain, strandings of giant squid have been associated with seismic surveys and the tissue damage described is consistent with the likely effect of exposure to loud noises (Guerra *et al.* 2011). Experimental studies on several cephalopod species have shown that such damage (e.g. to the hearing and balance system, i.e. the statocysts) is not only plausible but is likely to be fatal in exposed animals (Andre *et al 2*011; Sole *et al* 2013a,b). There has been no investigation of such phenomena in UK waters to date.

3.4.7. Climate change

As discussed above, cephalopods are highly sensitive to environmental conditions and changes. The embryonic development and hatching, growth and maturation, timing of reproduction and migration and biogeographic distribution of many cephalopod species are influenced by temperature. Observed changes in abundance of the squid *Loligo forbesii* in Scottish waters appear to be related to climatic variation (Pierce *et al*., 2008). Important change in cephalopod biodiversity in the north-east Atlantic may occur within the next few decades. Global warming (sea temperature rise), for example, may result in the continued advance of certain cold-water species to higher latitudes and their loss from southern latitudes (Chen *et al*., 2006). Cephalopods may also be affected by the general rise in oceanic CO_2 concentration that has been observed in recent years. Ommastrephid squids have pH-sensitive blood-oxygen transport systems, and elevated CO_2 levels may consequently affect their growth and reproduction. The possible effects of climate change on cephalopod population dynamics are discussed in a recent major review (Rodhouse *et al.*, 2014).

Table 3.1. Potential threats to cephalopods in UK waters. Threats with documented or likely effects threats on species are indicated by "•" while the likely absence of a significant threat is indicated by a blank cell.

	Loligo sp.	*S. officinalis*	*E. cirrhosa*	Deep water sp.	Ommastrephids
Fishing pressure	•	•			
Heavy metal contamination	•	•	•	•	•
Oil and gas production / organic contaminants	•	•	•		•
Radionuclides	?	?	?	?	?
Climate change	•	•	•		•
Physical disturbance	•	•	•		
Underwater noise	?	?	?	?	?

4. Analysis of fishery data on cephalopod abundance

4.1. Overview

Loliginid (long-fin) squid have been exploited in UK waters for at least one century (available Scottish landings data go back to the early 1900s. The largest squid catches are currently taken from fishing grounds in the North Sea (ICES IVa,b,c), west of Scotland (ICES VIa,b) and the English Channel (ICES VIIe,d). Based on data collected in the 1990s, squid landings from northern, Scottish, waters (ICES IVa; VIa,b) are thought to be dominated by one species, *Loligo forbesii* (>99.9%), although it would be useful to carry out regular market sampling to confirm the species composition of landings, given that distribution shifts, for example of the congeneric *L. vulgaris*, might be expected due to ocean warming. In other areas, landings frequently include *Loligo vulgaris* and *Alloteuthis subulata*, with *L. vulgaris* becoming more abundant in southern waters (ICES IVc; VIIe,d). *Alloteuthis media* may also be present; these four loliginid species are not distinguished in UK fishery landings data. Again, routine monitoring of landings to determine species composition would be useful.

The main Scottish fishery for *L. forbesii* occurs generally in coastal waters and exhibits a marked seasonal peak around October and November, corresponding to the occurrence of pre-breeding squid (Young *et al*., 2006). Analysis of fishery data collected between 1980 and 1990 indicated that *L. forbesii* is widely distributed on the continental shelf and also occurs on offshore banks – notably Rockall (ICES VIb, Pierce *et al.*, 1994a).

Although reliable catch-per-unit-effort [CPUE] data could not be acquired (and may not be available in Scotland since 1997 due to a change in the way fishing effort was recorded), it appears that landings data (weight landed) may be a useful indicator of population size. The value of landings data to represent abundance is widely debated (e.g. Pauly *et al.*, 2013). However, there are circumstances when landings can be informative. As argued by Pierce et al. (1994a), in a species like *L. forbesii* that is rarely targeted, is routinely landed due to its relatively high value, and is not subject to any quota restrictions, landings-per-unit-effort [LPUE] may be expected to vary in proportion to abundance. Then, if fishing effort is reasonably consistent year to year, landings may indeed reflect abundance.

While there seems to be little consumption of squid in Scotland, there is a good export market and fishermen are thought to normally land squid catches unless the animals are damaged or the boat is undertaking an extended fishing trip, since squid cannot be preserved on ice for more than a few days (see Hastie *et al.*, 2009b). Much of the squid landed in Scotland is currently exported to Spain (GJP, Pers.

Obs.). An account of markets for squid in the UK in the early 1990s can be found in Shaw (1994) with a more recent global perspective given by Pierce & Portela (2014).

Real fishing effort may be expected to gradually increase due to technology creep, which could account for a gradual increase in landings. An additional complication, evident since the early 2000s, is that there has been some targeting of squid in the Moray Firth (see Young *et al.*, 2006). There is a need to separate landings from directed and by-catch fishing to better understand recent trends in total landings.

Here we focus on patterns and trends in squid landings into Scotland from the northern North Sea (ICES fishery subdivision IVa).

4.2. Case study: *Loligo forbesii* in ICES area IVa

4.2.1. Data sources and methods

For this analysis we used monthly and annual landings data since 1985. Although the landings time series could be extended further back in time, environmental series derived from satellite data are available only from the mid-1980s onwards

The landings data show a general upward trend between 1985 and 2013, although there is marked variation between years (sometimes by an order of magnitude) and also evidence of a cycle with a periodicity of around 7 years, as seen for the Northern North Sea area (Figure 4.1).

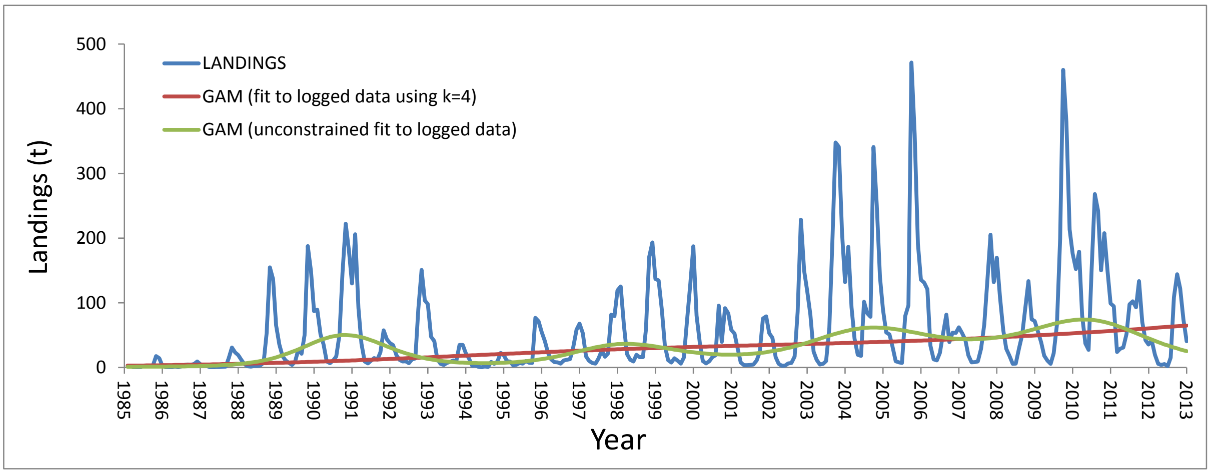


Figure 4.1. Monthly landings of squid (*L. forbesii*) from ICES IVa (1985–2013) in Scotland [Data from Marine Scotland]. Two trends lines are also shown. A constrained GAM fit to logged (normalised) data confirms a general upward trend although the unconstrained fit highlights the occurrence of peaks and troughs. The height of seasonal maxima can vary between years by an order of magnitude.

Even if the upward trend could be linked to high effort (which is essentially unverifiable), it seems highly unlikely that the 7-year cycles, sharp year-to-year fluctuations and strong seasonal cycle of squid landings in Scotland could be explained by changes in fishing effort. There is a need to disentangle the relative contributions of the squid life cycle (leading to seasonal variation but also acting via a possible stock-recruitment relationship), environmental conditions and fishing pressure in determining abundance.

A range of environmental datasets was listed for possible links with squid abundance (proxied by landings) (Table 4.1). Some series do not go back to 1985, being based on more recently launched satellites. The North Atlantic Oscillation Index (NAO) is based on differences in air pressure between the Azores and Iceland and is linked to the strength of inflow of warm Atlantic water into the North Sea via the north Atlantic current (see, e.g., Hurrell *et al.*, 2003).

Sea water temperature may affect *Loligo forbesii* landings indirectly, by influencing egg development time, trophic interactions, survival, growth, and maturation rates. Variables linked to productivity would also be expected to affect squid growth and survival, e.g. through effects on food supplies. Rainfall, as an indicator of land run-off, may affect salinity, turbidity, trophic interactions (nutrients) and water quality (pollutants), affecting shallow, coastal areas where *Loligo forbesii* spawn. High rainfall thus potentially has a negative effect on abundance (e.g. Sobrino *et al.*, 2002; see Pierce *et al.*, 2008a for a review).

Table 4.1. Environmental datasets available for testing against northern North Sea squid (*Loligo forbesii*) fishery data (ICES IVa).

	Available		
Parameter	time-series (N)	Source	Comments
SST (^{o}C)	1985 – 2012 (28)	Satellite data	NASA (Oceancolor)
Rainfall (mm)	1985 – 2012 (28)	UK Met Office	UK stations bordering IVa
NAO	1985 – 2013 (28)	Satellite data	NASA (Oceancolor)
Chlorophyll	1998 – 2012 (15)	Satellite data	NASA (Oceancolor)
PAR	1998 – 2012 (15)	Satellite data	NASA (Oceancolor)
ZEU (m)	1998 – 2012 (15)	Satellite data	NASA (Oceancolor)

Parameters: SST = sea surface temperature, NAO = North Atlantic oscillation, PAR = photosynthetically active radiation, ZEU = euphotic depth. Satellite data: NASA Oceancolor website (http://oceancolor.gsfc.nasa.gov/)

As Figure 4.2 shows, a strong seasonal pattern in SST is evident, with temperatures generally ranging from about 7^{0}C in March, to 14^{0}C in August each year. Individual monthly data must therefore be pooled to generate annual values (thus reducing N to 28 years in this case). Seasonal patterns in rainfall are also apparent (Figure 4.3), albeit less clearly defined.

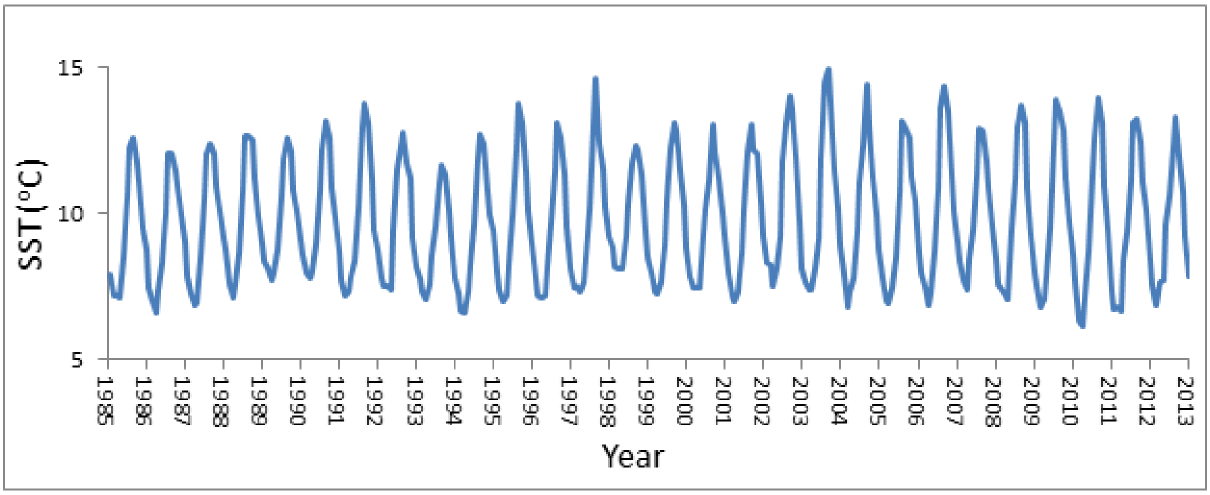


Figure 4.2. Monthly mean sea surface temperature (SST) recorded in the northern North Sea (ICES area IVa) during 1985–2013 (Source: NASA Oceancolor).

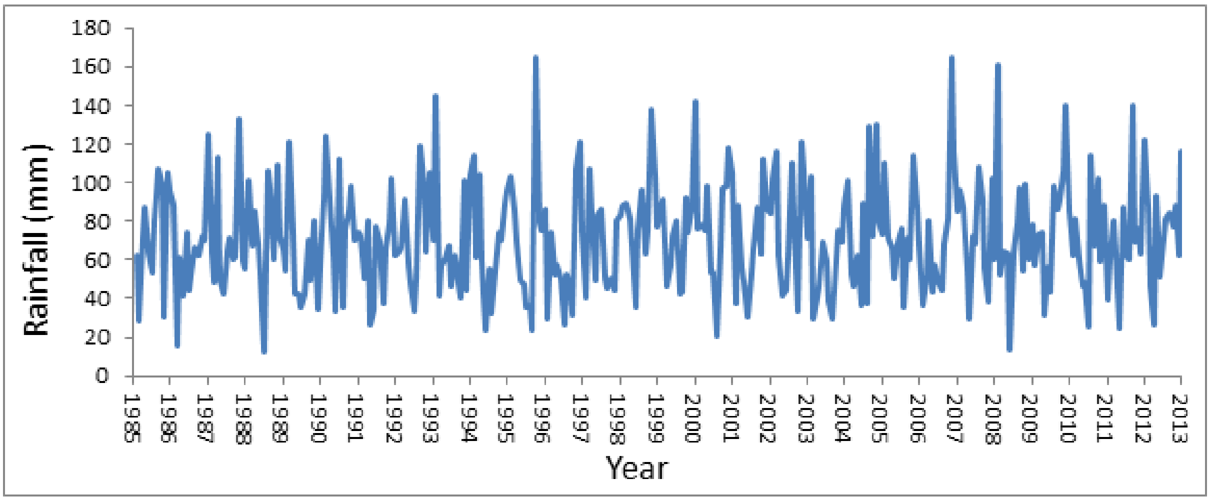


Figure 4.3. Mean monthly rainfall patterns in the northern North Sea, based on data from UK coastal weather stations bordering ICES IVa (Source: UK Met. Office).

Much of the information in monthly series of landings and environmental variables reflects seasonal cycles. This means that strong (but uninformative) relationships between landings and environmental series are inevitable. Thus, in order to analyse relationships between abundance and environmental conditions, annual data are more suitable – but this clearly shortens the series. Consequently, at this stage, it is not possible to construct models with more than one or two independent environmental descriptors (GAM models generally cannot be fitted with more than N/10 parameters, where N = number of points). With the continued collection of landings and environmental data, this situation will gradually improve, allowing more complex models to be tested in future.

Autocorrelation in the time series could produce spuriously high correlations between landings and environmental variables. There is significant positive autocorrelation in the annual landings series at a time-lag of 1 year (see autocorrelation plot in Figure 4.4). However, while in one sense this is a statistical problem it also informative. There is a positive relationship between landings in the current year and landings in the previous year, at least for landings of up to around 700 t (see the GAM smoother plot in Figure 4.4). This could indicate existence of a stock-recruitment relationship or simply reflect autocorrelation in environmental conditions (i.e. good years tend to be followed by good years). It does however suggest that high landings are not negatively affecting abundance in the following year.

Given the likely existence of autocorrelation, the analysis of environmental influences was based on running both GAMs and GAMMs. In both cases model residuals were checked for autocorrelation. In the GAMMs, following exploration of the appropriateness of alternative correlation structures, the autocorrelation in the landings series was initially taken into account using a lag-1 moving average correlation structure (corARMA (0,1)). Finally, we fitted models which included the previous year's landings as a predictor alongside candidate environmental variables.

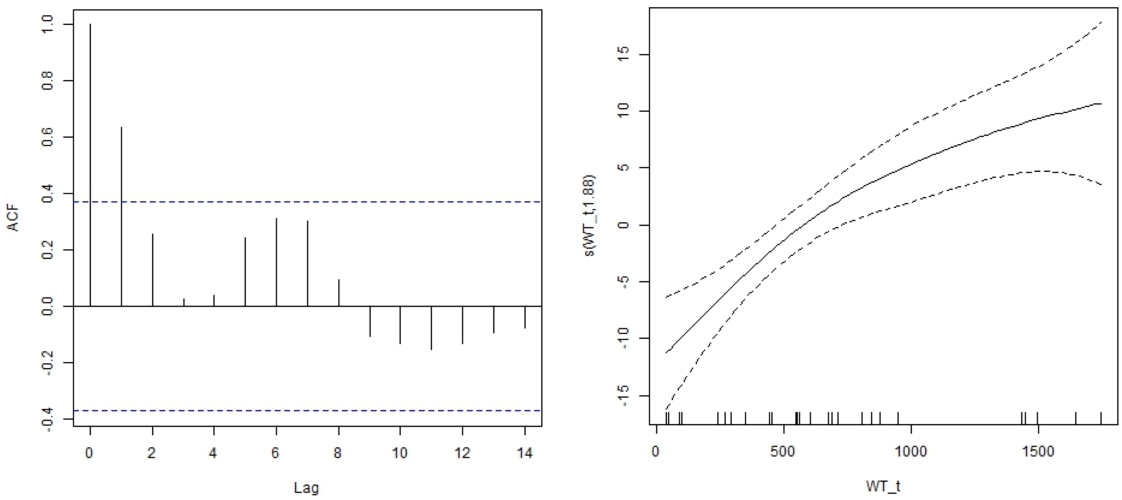


Figure 4.4. *Loligo* landings in Scotland from ICES area IVa. Left: autocorrelation plot. Right: GAM output illustrating the effect of landings from the previous year on landings in the current year.

Thus, the GAM and GAMM models used annual landings data as the dependent variable, and various environmental parameters as explanatory variables. Landings data were square-root transformed to give a better fit to a normal distribution.

4.2.2. Results and discussion

The two sets of models gave broadly similar results (Table 4.2). It should be noted however that the GAMMs did not always successfully remove all autocorrelation but alternative correlation structures generally did not produce more satisfactory results. In addition, in some cases, there was no autocorrelation in the GAM residuals, implying that autocorrelation could be attributed to the explanatory variables.

Squid caught in a given calendar year may span two generations, which to some extent complicates interpretation. Spawning adults will be present at the start of the year while their offspring will make up the bulk of the annual catches, mainly taken towards the end of the year.

Landings were significantly related to year, confirming the general upward trend. As indicated by the exploratory analysis, Landings were also positively related to the previous year's landings. This relationship persisted in the GAMM, indicating that the correlation structure did not completely capture the relationship between landings in successive years[1]. The positive correlation with previous landings is consistent with the assumption that landings reflect abundance: there is certainly no evidence that high landings have a negative effect on the following year's population.

[1] In this case, using MA2 correlation structure did however successfully remove autocorrelation.

Table 4.2. Gaussian GAM and GAMM results for annual *Loligo forbesii* landings (IVa) against environmental parameters measured in the current and previous years. The models used square-root transformed landings, with an AR1 autocorrelation structure in the GAMMs and a single explanatory variable. Results given are degrees of freedom (a value of 1 indicates a linear fit), the direction of the slope of the fit (+ positive, - negative, U = U-shaped curve, none= no trend, parentheses indicate non-significant trend), the F value and associated probability (P) and the sample size (N). For the GAMs and GAMMs we also report on autocorrelation in the residuals (Res AC), indicating time-lags with significant AC as well as its direction.

	GAMs						GAMMs					
Explanatory variable	**df**	**Direction**	**F**	**P**	**N**	**Res AC**	**df**	**Direction**	**F**	**P**	**N**	**Res AC**
Year	8.799	variable	13.94	<0.0001	28	none	1	+	14.1	0.0008	28	1+
Annual NAO	3.87	none	1.26	0.312	28	1+	1	none	0.026	0.874	28	1+
Winter NAO	1	none	0.744	0.396	28	1+	1	none	0.072	0.79	28	1+
Summer SST	1	+	20.91	<0.0001	28	none	1	+	6.807	0.0147	28	1+
Autumn SST	1	(+)	3.862	0.06	28	1+	1	none	0	0.989	28	1+
Spring rainfall	1	-	4.25	0.0492	28	1+	2.333	none	1.504	0.236	28	1+
CHL spring peak	1	none	0.184	0.675	15	none	1	none	0	0.988	15	none
Feb-Oct PAR	2.368	(+)	3.302	0.0591	15	none	3.55	U	18.96	<0.0001	15	1+
Spring PAR	1.764	-	7.584	0.0061	15	none	1	-	10.93	0.0055	15	none
Autumn ZEU	1.294	(+)	4.042	0.0513	15	none	1	(+)	2.954	0.109	15	none
Annual NAO (year-1)	1	none	1.424	0.244	27	1+	1	none	0.172	0.682	27	1+
Winter NAO (year-1)	1	none	0.353	0.558	27	1+	1	none	0.205	0.654	27	1+
Summer SST (year-1)	1	+	32.52	<0.0001	27	none	1	+	17.11	0.0003	27	none
Autumn SST (year-1)	1	+	12.76	0.0014	27	1+	1	+	9.788	0.0043	27	1+
Spring rainfall (year-1)	1	-	10.78	0.0029	27	none	1	-	4.35	0.0472	27	1+
CHL spring peak (year-1)	1	none	1.227	0.29	14	none	1	none	1.179	0.299	14	none
Feb-Oct PAR (year-1)	1	none	1.51	0.243	14	none	1.362	none	1.414	0.259	14	none
Spring PAR (year-1)	1.66	none	0.702	0.519	14	none	1.42	none	0.632	0.486	14	none
Autumn ZEU (year-1)	5.104	none	1.262	0.369	14	none	1	none	0.02	0.889	14	none
Landings (year-1)	1.879	+	11.67	0.0002	27	none	2.142	+	6.939	0.0036	27	none

SST = sea surface temp (oC), ZEU = euphotic depth (m), PAR = photosynthetically active radiation, CHL = chlorophyll level. Previous year = year -1

There were positive effects of SST on landings, for summer SST in the same year and for both summer and autumn SST of the previous year. This implies effects both on the recently hatched squid of the same year and on squid in the previous generation. The latter effect could indicate that higher temperatures favour better spawning success, perhaps operating through higher food availability during maturation, thus leading to higher abundance in the following year.

The strongest effect detected was of summer SST in the previous year, which in the GAM explained approximately 57% of deviance in landings. If the previous year's landings were also included as a predictor, effects of both SST (P=0.0156) and landings (P=0.0176) were significant and deviance explained rose to 83.4%, both effects being broadly positive (Figure 4.5).

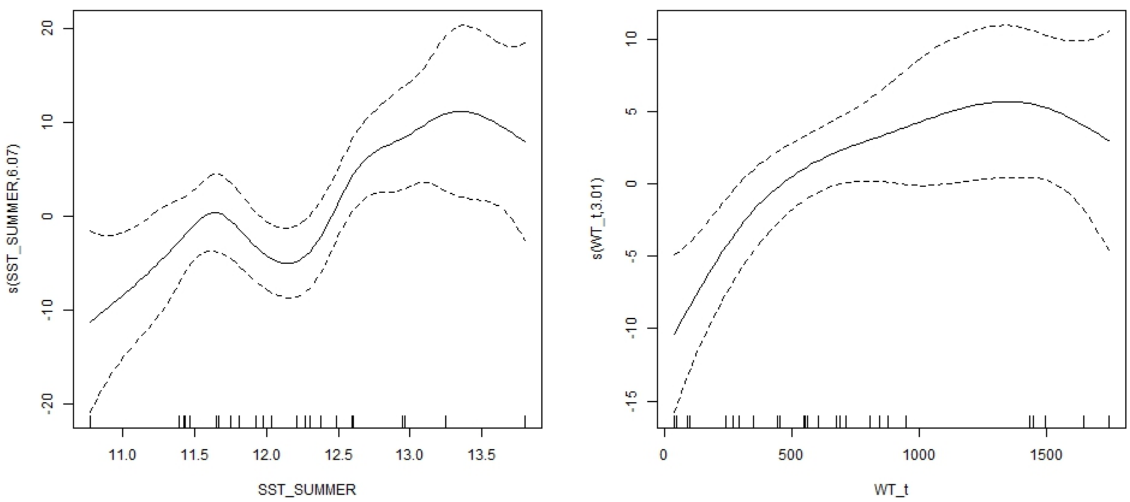


Figure 4.5. Smoothers showing the effects on squid landings into Scotland from the northern North Sea of (left) the previous year's summer SST and (right) the previous year's squid landings.

There were also negative effects of spring rainfall, both a weak effect in the same year and a stronger effect of rainfall in the previous year. As mentioned above, it is likely that this operates through an effect on spawning success.

Finally, photosynthetically active radiation (PAR) in the same year affected landings. PAR represents the amount of solar radiation available for photosynthesis (i.e. waveband 400–700 nm). In principle, PAR may influence *Loligo forbesii* stocks indirectly by driving productivity. Given that landings are generally highest in the last quarter of the year, high productivity earlier in the year might be expected to produce good growing conditions for young squid. However, results of the present analysis do not support this interpretation. Spring PAR had a negative effect on landings while the effect of February to October PAR was non-linear, with lowest landings seen at intermediate values. Negative effects could arise if high productivity favoured predators of young squid but clearly further study is needed in this case.

The results of these analyses indicate the potential value of using of using certain environmental data as indicators of *Loligo forbesii* stocks, as well as the pitfalls of interpreting such relationships when the mechanism is unclear. What seems likely is that both the timing and location of suitable environmental conditions will be important and that more meaningful analyses could be undertaken given knowledge of the main spawning and recruitment areas. The southern part of the Moray Firth appears to be an important recruitment area (Young *et al.*, 2006) and in generally new recruits are likely to live closer inshore than older animals: results in Viana *et al.* (2009) and Smith *et al.* (2013) are consistent with an ontogenetic migration away from the coast as new recruits grow larger. An opposite movement of mature animals is also plausible, although the fact that most records of eggs arise from coastal areas (e.g. Lum-Kong *et al.*, 1992) may reflect sampling bias.

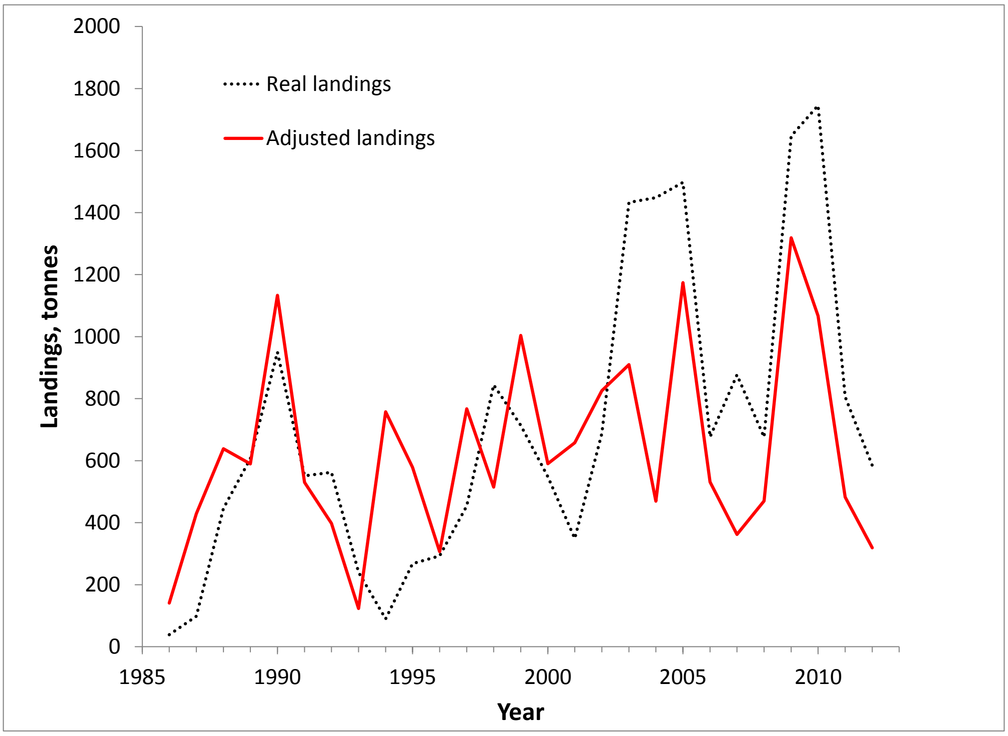
The analysis is also limited by the length of the time-series and the fact that accurate CPUE data are also not available at present. With better knowledge of squid movements and longer time series, and possibly CPUE data, more useful predictive models may be developed in future.

4.2.3. Conclusion

In terms of pointers towards what might constitute good environmental status, it is evident that there has been a general upward trend in landings over the years, but with up to tenfold year to year variation in peak landings and an apparent longer term cyclic pattern. The existence of reasonably strong relationships between landings and environmental conditions suggests that “standardised abundance” series, which factor out the effect of, say, SST, could be extracted and a baseline thus defined.

To provide an example, we fitted a simple linear regression to the untransformed landings data, using summer SST of the previous year as the explanatory variable. The effect of standardising for the effect of SST can then be visualised by using the regression equation to predict abundance for a fixed SST (we used the average, 12^{o}C) and then adding the residual (unexplained variation) to each year’s value. It can be seen that Interannual variation is somewhat reduced but substantial unexplained variation remains. Repeating the exercise but using a regression against the previous year’s summer SST and spring rainfall, and standardising to 12^{o}C and 175 mm of rainfall, variation is further reduced (Figure 4.6). In principle this unexplained variation could be reduced even further using additional explanatory variables but, as noted above, the short time series precludes fitting complicated models.

Even if a baseline could not easily be defined, a consistent decline in landings over longer than a 3 or 4 year period might suggest reduced abundance and hence a less desirable population status. Thus, at worst, monitoring squid landings could have a sentinel role. It is also worth considering whether the relationship between landings and abundance is changing, for example due to more targeting of squid, such that high catches may now be having a negative effect on abundance.



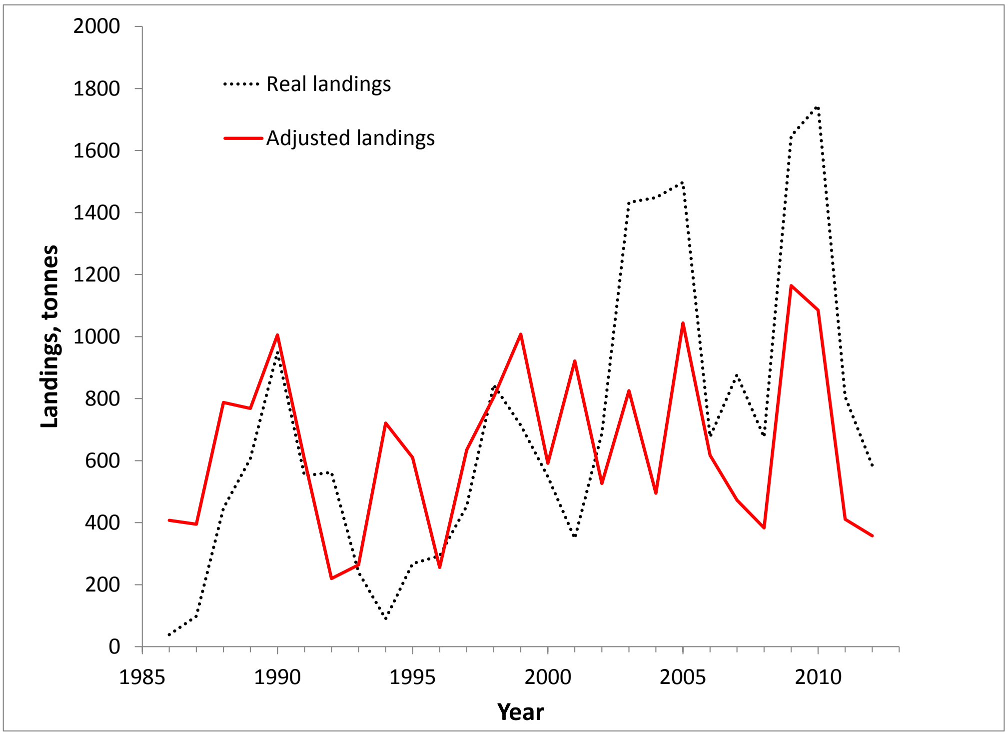


Figure 4.6. Annual landings of squid in Scotland from the northern North Sea: raw data and data standardised to (above) fixed summer SST value (12 ^{o}C) in the previous year and (below) to fixed summer SST (12 ^{o}C) and spring rainfall (175 mm) in the previous year.

5. Analysis of research survey data: Cefas surveys

5.1. Overview

In principle the International Council for the Exploration of the Sea holds copies of fish survey data from its member countries within its DETRAS database. However, previous enquiries have indicated that data on cephalopod catches during surveys are incomplete, reflecting the fact that presently cephalopods are not assessed or subject to quota management. Indeed, in relation to DETRAS, the Manual for the International Bottom Trawl (IBTS) Surveys (Revision VIII; ICES, 2012) states that "there is no standardized approach to the submission of data on the catches and size distribution of cephalopods". In the present project, both Cefas and MSS were directly involved and we have therefore sourced survey data on cephalopod distribution and abundance directly from Cefas and MSS.

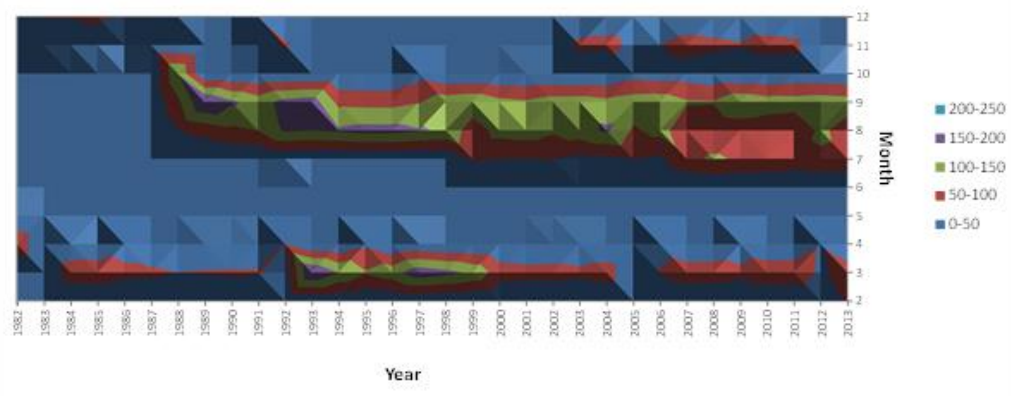
Data on cephalopod catches are available from several survey series undertaken by Cefas, the most relevant of which are summarised in Table 5.1 below. In some cases data are available since the late 1980s although it is also the case that some series have been discontinued. Because a wide range of fishing gears has been used across the different survey series we have treated each series separately and, if necessary, included gear type as a factor in the analysis.

Table 5.1. Details of available survey datasets for cephalopods in UK waters from Cefas. The table indicates the area surveyed and the months in which the surveys take place, the years for which data are available and the main gear types used. (GOV = Grande Ouverture Vertical, the standard gear for the IBTS surveys).

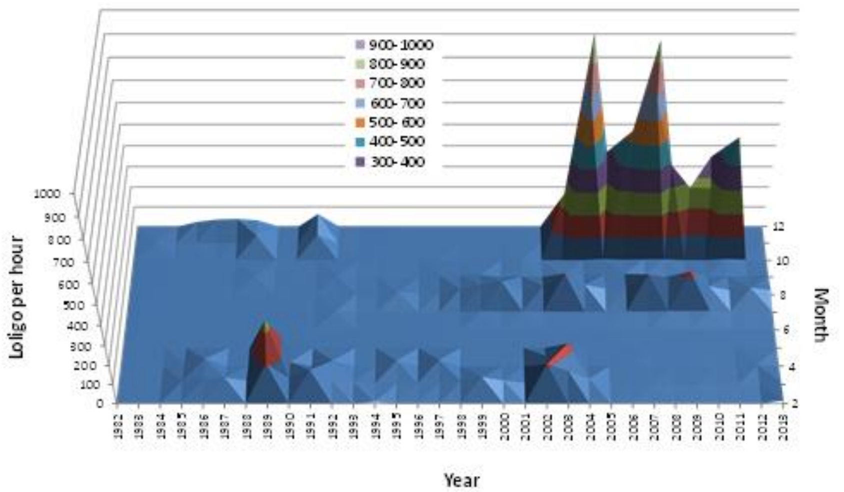
Series code	Location (ICES subdivision)	Seasonality	Years	Gears used
BTS7D	Eastern English Channel (VIId) and southern North Sea (IVc)	July - August	1989-present	Beam trawl
Q1SWBEAM	Western English Channel (VIIe)	February - April	2006-2013	Beam trawl and GOV
Q4WIBTS	Irish Sea (VIIa), Celtic Sea (VIIg,h), western English Channel + Bristol Channel (VIIe,f)	November - December	2003-2011	GOV
IBTS3E	North Sea (IVa-c)	August - September	1992-present	GOV (+ ring net)
WCGFS	Celtic Sea (VIIg-j), Bristol Channel (VIIf), western English Channel (VIIe)	February – April + November - December	1989-2003	High headline trawl, beam trawl, GOV (+ring, frame, Engels, Neuston)
NWGFS	Irish Sea (VIIa), Bristol Channel (VIIf)	March-April August - October	1988-present	Beam trawl +Granton trawl

Putting together all the Cefas trawl survey series, including those listed above (Figures 5.1, 5.2), it is evident that survey coverage has been most complete in quarters 1 and 3 of the year and has extended all around most parts of the UK coast except for western Scotland. Considering overall average catch rates per cephalopod category, since 2000 the highest loliginid catches have been recorded in the last quarter of the year, notably in the North Sea and Celtic Sea. Numbers of octopus caught were much lower but were highest in the west and during 2006-2013. Cuttlefish were most numerous in the English Channel and Western Approaches, especially in the third quarter of the year. Ommastrephid catches were generally low, being highest off the west coast of Ireland. Until 2002, numbers were highest in the first quarter of the year but from 2003 highest numbers were recorded in quarter 4. Sepiolids were caught in significant numbers only in the last quarter of the year during 2004–2011 and mainly in the Irish Sea and Celtic Sea.

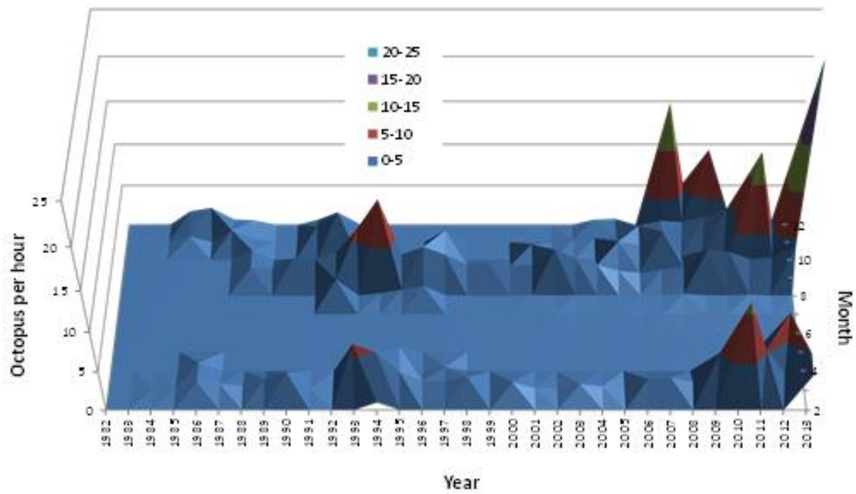
Figure 5.1



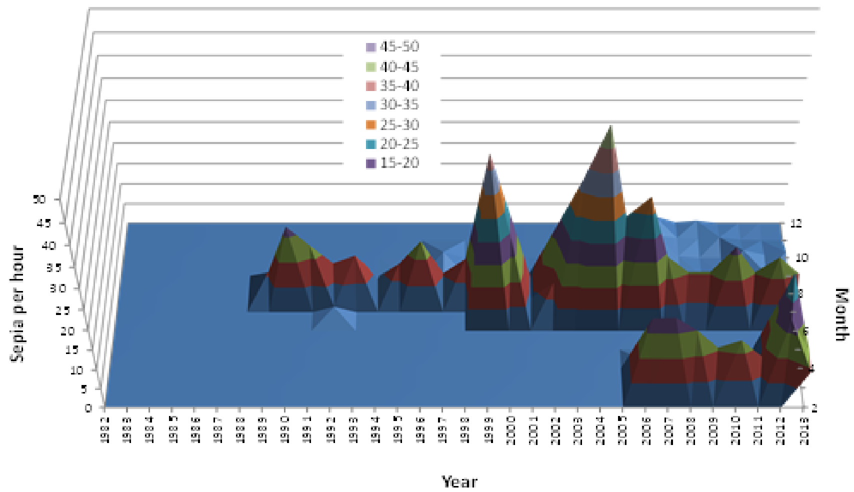
a. Number of hauls versus year and month



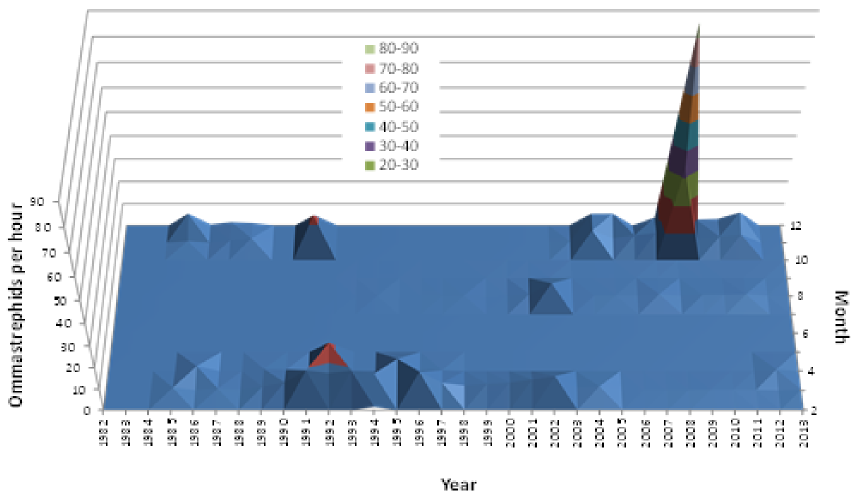
b. average number of loliginids caught per hour versus year and month



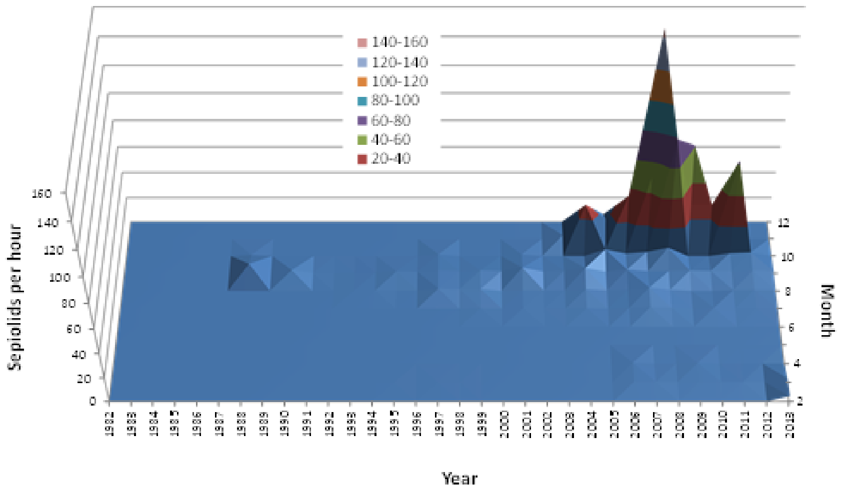
c. average number of octopus caught per hour versus year and month



d. average number of cuttlefish caught per hour versus year and month



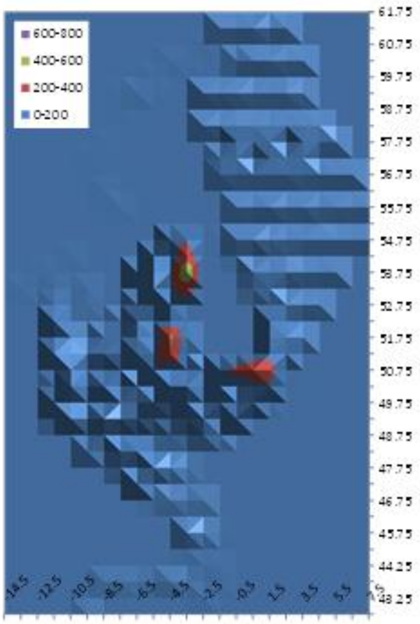
e. average number of ommastrephids caught per hour versus year and month



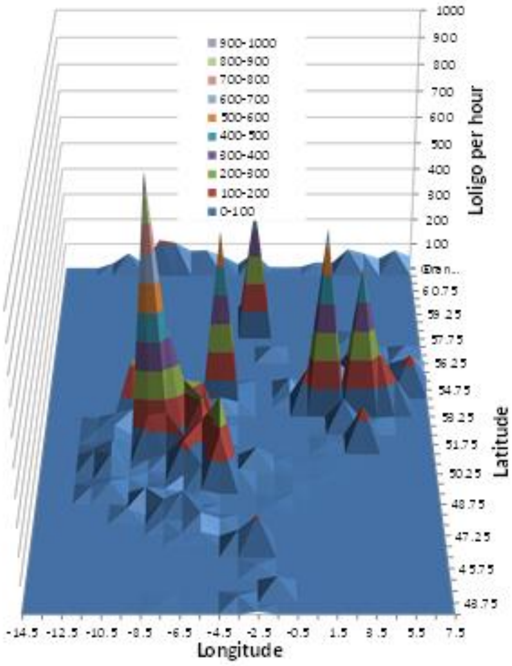
f. average number of sepiolids caught per hour versus year and month

Figure 5.1. Temporal trends in total number of hauls (a) and overall average numbers caught per hour for (b) loliginids, (c) octopus, (d) cuttlefish, (e) ommastrephids, (f) sepiolids. Based on combined Cefas trawl survey data 1982-2013.

Figure 5.2



a



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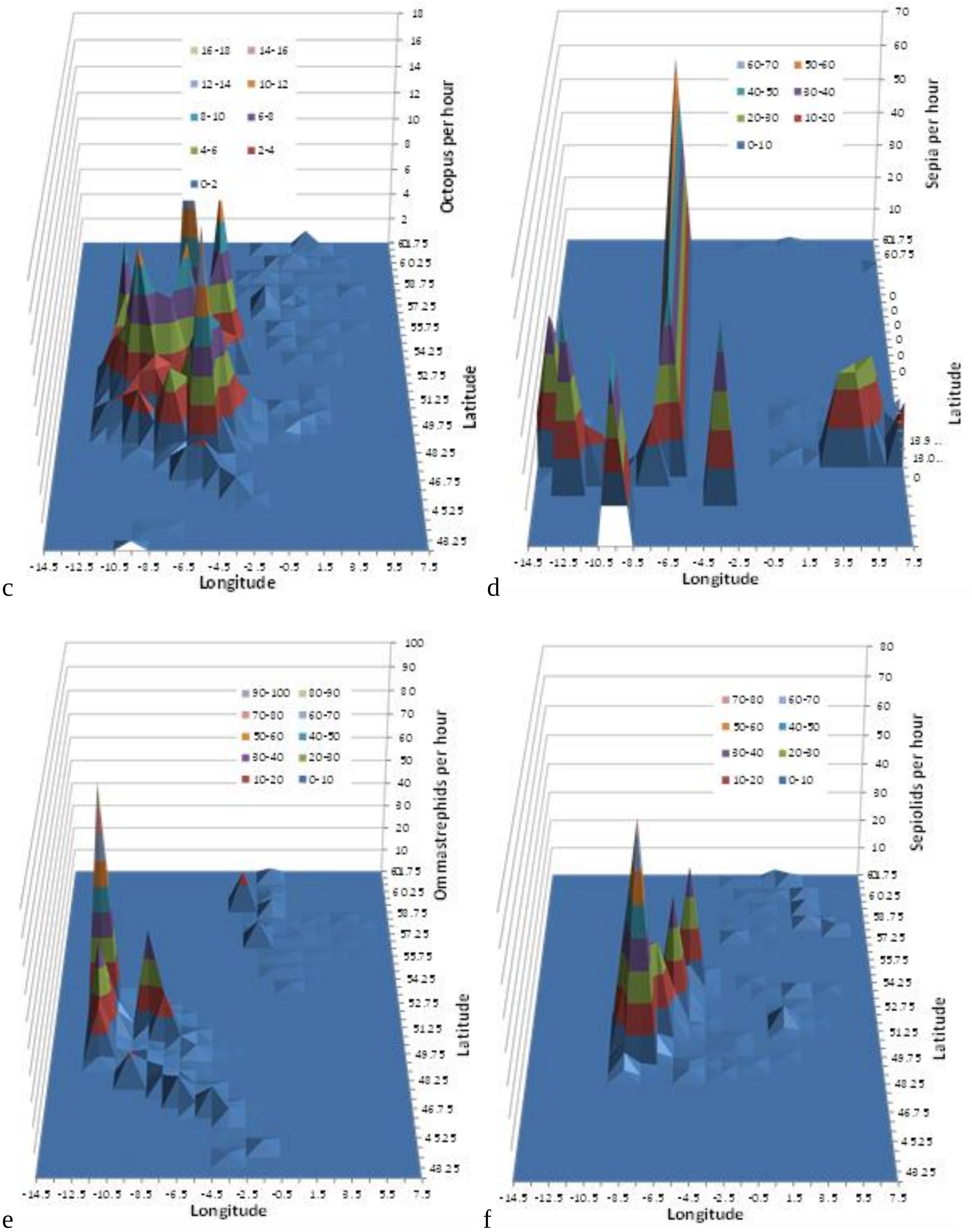


Figure 5.2. Spatial patterns in (a) total number of hauls and in average numbers caught per hour for (b) loliginids, (c) octopus, (d) cuttlefish, (e) ommastrephids, (f) sepiolids. Based on combined Cefas trawl survey data 1982-2013.

5.2. An example: loliginid squid in the English Channel beam trawl survey

5.2.1. Introduction and methods

The English channel beam trawl surveys (BTS7D) took place during July and/or August in the years 1988 to 2013. As for all survey data, catch rates were analysed using generalised additive models (GAMs). In principle it should have been possible to standardise or weight the catch data according to distance towed, given that trawl speed may vary. However, tow distances could only be approximated from the start and end positions of each haul. Catches were therefore standardised to a 30-minute trawl and tow duration was included as an explanatory variable to allow the detection of any effect of tow length on the catch rate. Since two different gear codes appear in the data, implying use of different nets or net settings, the gear code was included as an additional explanatory variable.

Catch rates were characterised by a highly skewed distribution, i.e. many hauls with zero or few squid and a few hauls with many squid. This can be accommodated by assuming that the data follow a negative binomial distribution. This distribution has a parameter, theta, which relates to the length of the tail of the distribution. The first stage of the modelling process was to estimate the value of theta.

Then, the effects of the various explanatory variables were explored. These variables were: latitude, longitude, depth, hour of the day, day, “year fraction” (i.e. day of the year, included to capture any seasonal pattern), year, tow duration, and gear category. All but gear category are continuous variables, for which we cannot assume linear relationships and generalised additive models (GAMs) were therefore used.

While GAMs are routinely used for this kind of analysis, two issues need to be borne in mind. Firstly, GAMs sometimes result in “over-fitting”, suggesting the existence of implausibly complex (and biologically unrealistic) relationships between response and explanatory variables. This can be overcome by restricting the number of “knots” in the fitted “smoothers” (curves). The opposite problem may also occur in relation to year-to-year and spatial variation in abundance, for which there is no expectation that simple patterns will be seen, and the true complexity of patterns may be obscured by low the default setting for the value of k (in the software).

Spatial variation can be expressed in terms of effects of latitude and longitude and the interaction between both effects. In a GAM this can be achieved by fitting a so-called 2-way smoother, which allows variation in space to be visualised. In the present application, for both spatial and year-to-year variation, the number of knots (*k*) in the smoother was set higher than the default to ensure that smoothers could capture as much detail in the data as possible. Conversely, where simple relationships were expected to exist, as for the effects of tow duration or haul depth, *k*=4 was used to exclude unrealistically complex fits.

A backwards selection process was used to obtain the final model and standard model validation checks were carried out. The deviance explained of final model was compared with that obtained if the effect year was removed, thus providing an indication of the importance of interannual variation.

We tested whether interannual variation appeared to have a strong environmental component by replacing year in the final model with one or more environmental variables. Annual and winter NAO indices were used as examples of (annual) environmental variables.

Finally, we generated predictions and 95% limits from the model, standardised to average values of the explanatory variables except year. For visual comparison, the predictions were plotted alongside average (unadjusted) catch rates.

5.2.2. Results and discussion

The final model of loliginid catch rate indicated substantial spatial variation as well as a seasonal decline in catches towards the end of August. The gear used had no effect (i.e. both types of beam trawl had similar catch rates) and the effects of tow duration effect and time of day were weak (Table 5.2).

Table 5.2. Summary of GAM results for loliginid catch rate in the English Channel beam trawl (BTS7D) survey. The fitted model assumed a negative binomial distribution of catch rate(Deviance explained = 33.9%, N = 2503).

Variable	**Direction of effect**	**Chi-squared (or z value)**	**P-value**
Gear code	None	(Z=0.000)	1.0
Year	(Complex)	120.84	<0.0001
Day of year	Negative	21.96	0.0013
Hour of day	Negative	4.86	0.0275
Tow duration	∩ shape	8.78	0.0304
Latitude x longitude	(Complex)	326.31	<0.0001

Year to year variability in catch rate was more pronounced earlier in the series – without further investigation we could not at present rule out sampling issues - but catch rate was rather consistent during 1998 to 2008 although it may have declined somewhat thereafter (although the wide confidence limits imply that the drop is not statistically significant). The effects of the explanatory variables on catch rate are illustrated in Figure 5.3 below.

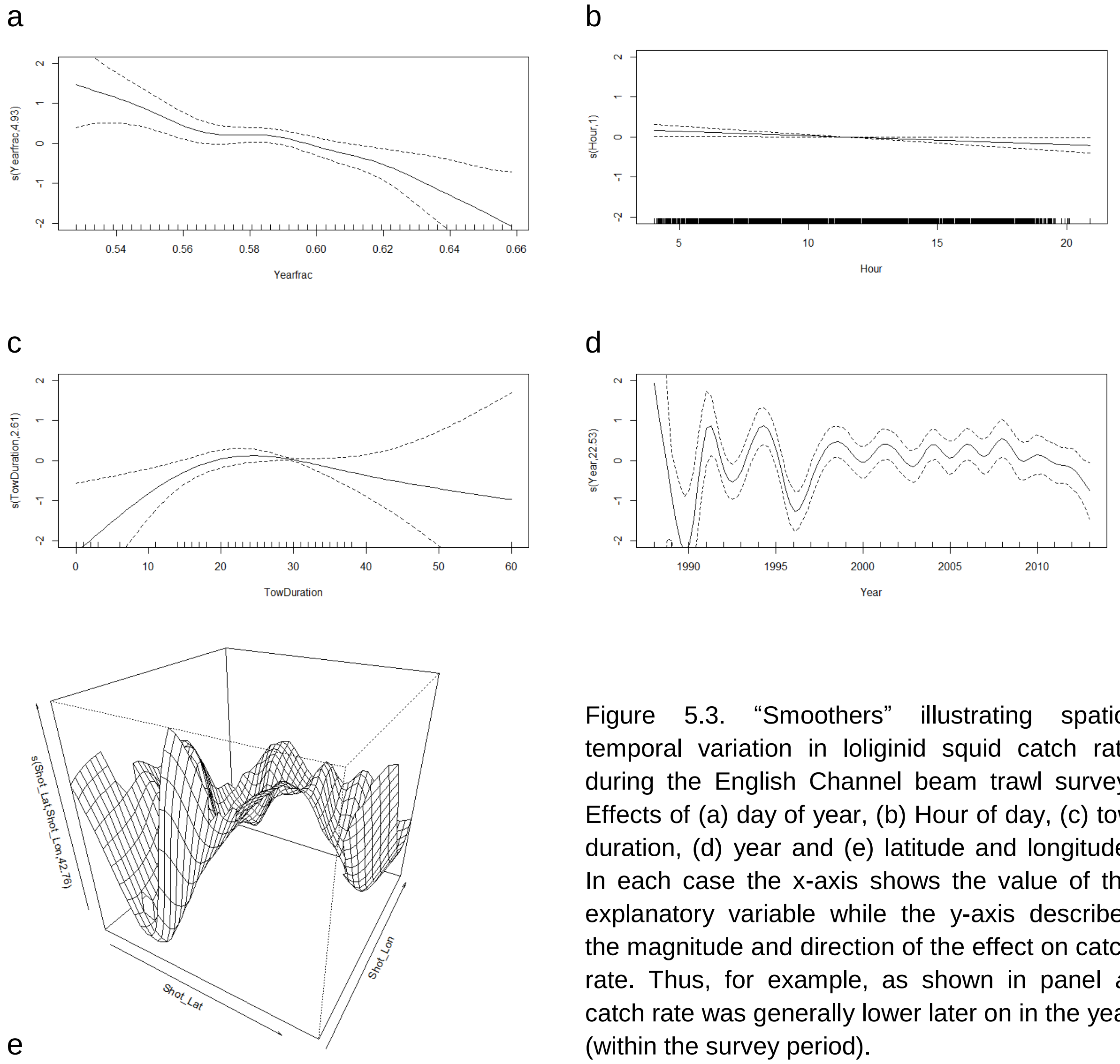


Figure 5.3. "Smoothers" illustrating spatio-temporal variation in loliginid squid catch rate during the English Channel beam trawl survey. Effects of (a) day of year, (b) Hour of day, (c) tow duration, (d) year and (e) latitude and longitude. In each case the x-axis shows the value of the explanatory variable while the y-axis describes the magnitude and direction of the effect on catch rate. Thus, for example, as shown in panel *a*, catch rate was generally lower later on in the year (within the survey period).

Predictions for each year, based on setting all explanatory variables except year to their overall average values, are shown in Figure 5.4. The units are squid caught per 30 minute haul. The predictions follow the uncorrected average squid catch rate fairly closely in this data set. However, it appears that the increasing trend between 2005 and 2010 is absent from the predicted series, implying that it could have been an artefact of different timing or spatial distribution of sampling effort.

While the predicted trend factors out the spatial and seasonal patterns in the data, it should be noted that around 70% of deviance (i.e. 70% of variation in catch rate per haul) remains unexplained. Nevertheless, as noted above, the results suggest some stability in summer squid abundance from 1998 to 2008.

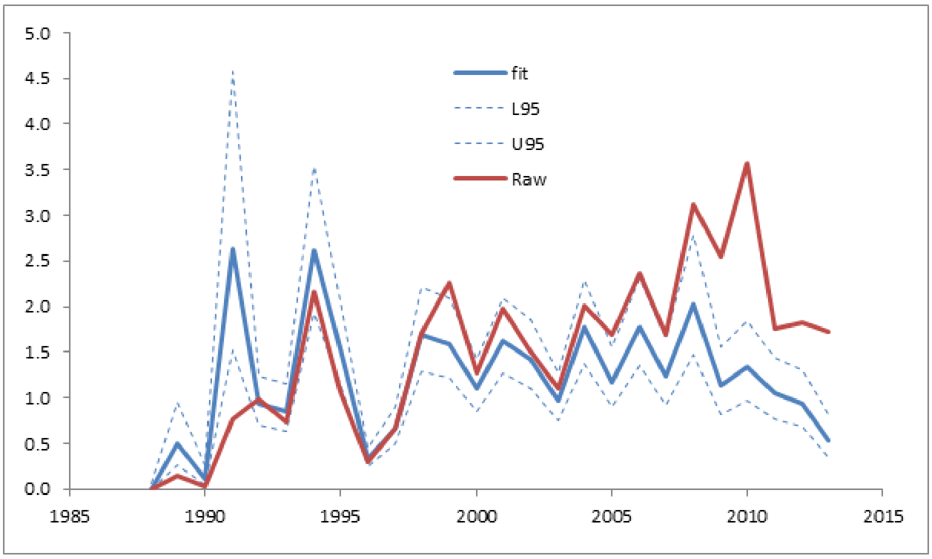


Figure 5.4. Annual average catch rate for loliginid squid in the English Channel beam trawl survey: raw data and predicted values based on average values for all explanatory variables except year.

Substituting winter NAO and/or annual NAO in place of year in the final model, their separate effects were significant (P=0.0017 and P=0.0001, respectively) while if both were included, again both had significant effects (p<0.0001) (Figure 5.5).

This confirms that at least part of the interannual variation in catch rate (and hence presumably in abundance) is likely to be environmentally driven, but further screening of additional environmental drivers is needed.

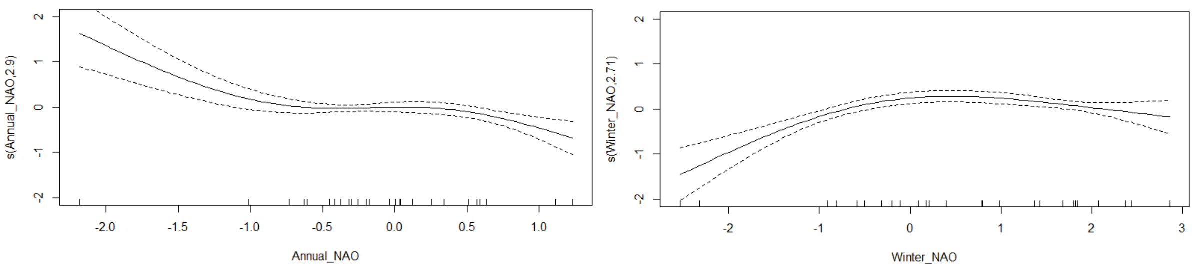


Figure 5.5. "Smoothers" illustrating temporal variation in loliginid squid catch rate during the English Channel beam trawl surveys (BTS7D). Effects of (left) annual NAO and (right) winter NAO.

5.3. Variation in cephalopod catch rates in Cefas surveys

5.3.1. Overview

In this section we summarise results of analysis of variation in catch rates for all cephalopod categories in the main Cefas survey programmes. The methodology used essentially followed that described in Section 5.2 above although we used a slightly extended set of explanatory variables, namely gear type (when more than one was used in a given survey programme, although data for gears used rarely were excluded), tow duration, latitude x longitude, day of year and hour of day. Year or NAO variables were then added. Comparing models with and without year effects, and with and without NAO effects, allowed us to quantify interannual variation and the extent to which the latter might be environmentally driven.

Results of these analyses, between 20% and 64% of deviance (variation) in catch rate was explained by a combination of gear type, tow duration, latitude and longitude, day of year and time of day, indicating that a substantial degree of standardisation of catch rates is possible. This is illustrated by comparing predictions (with 95% confidence limits) with raw data. Predictions are based on setting all variables except year to their average values

Year-to-year variability accounted for between 0.2% and 22% of deviance in catch rate per haul. Again, there was evidence that a part of this variation, sometimes a substantial part, could be attributed to environmental effects. Using NAO to illustrate environmental effects, we found that between 0.3% and 13.7% of deviance in catch rate could be attributed to the influence of NAO variables (Table 5.3).

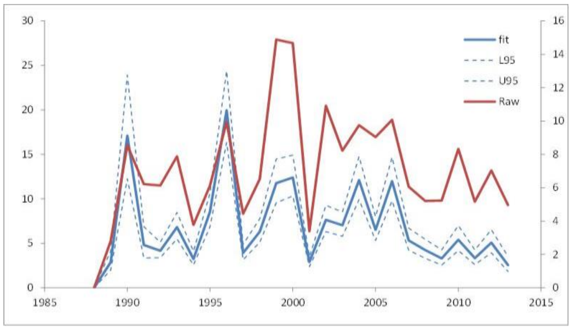
5.3.2. Cuttlefish abundance

The two beam trawl surveys in the English Channel yielded the highest catch rates for cuttlefish (Sepiidae) (Figure 5.6). These two surveys also suggest similar Interannual trends in abundance (e.g. a peak in catch rate in 2007). The BTS7D survey results suggest that abundance can vary by a factor of 4 from year to year. It might also be inferred that a standardised average catch rate of around 5 animals per 30-minute tow represents a reasonable reference level. The BTS7D survey series is ongoing so could be used for future MSFD monitoring.

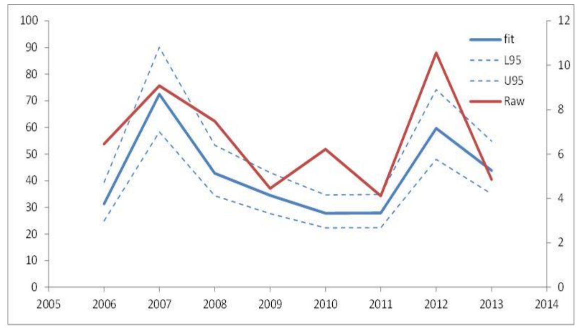
Cuttlefish abundance in two other surveys (Q4SWIBTS and NWGFS, in the Irish Sea and Celtic Sea) was much lower and did not follow the same interannual trends. Only in Q4SWIBTS was year-to-year variation clearly related to the NAO signal. Of course we cannot rule out links with other environmental variables but this analysis does not strongly support the idea that abundance can be standardised to account for environmental variation.

Table 5.3. GAMs summary. For each survey/taxon combination we give the value of theta (parameter of the negative binomial distribution) and sample size (N, number of hauls) for the model, and list the effects of all explanatory variables (NA = not available, NS = p≥0.1, ~ = p<0.10, * = p<0.05, ** = p<0.01, *** = p<0.001), and deviance explained (%DE1) for the model excluding year. We then report the effect of adding year to the model (significance, % deviance explained and the proportion of %DE that is explained by year). Finally we report the effect of adding both NAO variables in place of year (significance, % deviance explained and proportion of deviance explained by NAO). Survey/category combinations for which no models could be fitted are not listed.

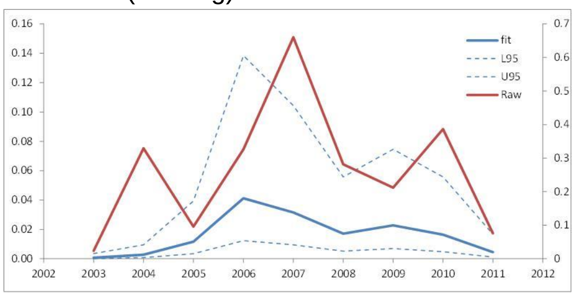
Data set used		**Model specifications**									**Add year**			**Or add NAO variables**			
Survey programme	Cephalopod category	Theta	N	Gear type	Tow duration	Lat x Lon	Depth	Hour of day	Day of year	%DE 1	Year	%DE 2	Year signal %	Annual NAO	Winter NAO	%DE 3	NAO signal %
BTS7D	Cuttlefish	0.638	2483	NA	NS	***	***	NS	*	50.4	***	60.2	9.8	***	***	52.7	2.3
NWGFS	Cuttlefish	0.213	3730	NA	NS	***	*	NS	***	65.9	***	76.6	10.7	***	***	69.6	3.7
Q1SWBEAM	Cuttlefish	1.265	712	NS	~	***	NS	NS	NS	68.4	***	70.6	2.2	*	***	70.3	1.9
Q4SWIBTS	Cuttlefish	5.846	624	NA	***	***	*	NS	*	64	***	72.4	8.4	***	***	72.3	8.3
BTS7D	Loliginid	0.419	2503	NA	*	***	NS	*	***	27.3	***	33.9	6.6	***	**	30.7	3.4
IBTS3E	Loliginid	0.044	1707	NA	NS	***	***	NS	NS	48.6	***	51.2	2.6	***	*	50.7	2.1
NWGFS	Loliginid	0.028	3741	NA	NS	***	NS	NS	***	20.6	***	24.2	3.6	NS	*	21.6	1.0
Q1SWBEAM	Loliginid	0.408	713	***	*	***	NS	*	*	58.1	NS	58.3	0.2	NS	~	58.4	0.3
Q4SWIBTS	Loliginid	0.179	626	NA	NS	***	***	*	NS	36.1	**	40.1	4.0	*	*	40	3.9
WCGFS	Loliginid	0.167	1945	***	NS	***	***	**	NS	32.9	***	45.7	12.8	NS	*	33.7	0.8
NWGFS	Octopus	0.289	3739	NS	***	***	**	**	***	53.1	***	55.3	2.2	***	~	53.8	0.7
Q1SWBEAM	Octopus	2.665	713	***	NS	***	***	NS	NS	53.9	***	70.1	16.2	***	***	67.6	13.7
Q4SWIBTS	Octopus	0.377	626	NA	*	***	*	NS	NS	35.4	***	44.8	9.4	***	***	43.6	8.2
WCGFS	Octopus	0.611	1945	NS	NS	***	NS	NS	***	25.9	***	48.7	22.8	**	***	31.2	5.3
IBTS3E	Ommastrephid	0.113	1706	NA	NS	***	NS	NS	*	44.4	***	56	11.6	***	NS	47	2.6
Q1SWBEAM	Ommastrephid	(50)	713	NS	NS	***	**	NS	NS	30.9	*	33.1	2.2	NS	NS	32.1	1.2
Q4SWIBTS	Ommastrephid	0.072	626	NA	NS	***	NS	NS	NS	63.2	*	65.8	2.6	***	NS	73.1	9.9
WCGFS	Ommastrephid	0.176	1944	***	NS	**	***	NS	***	41.4	***	59.2	17.8	NS	***	47	5.6
BTS7D	Sepiolid	0.053	2503	NA	NS	*	***	~	NS	20.7	***	31	10.3	*	**	20.8	0.1



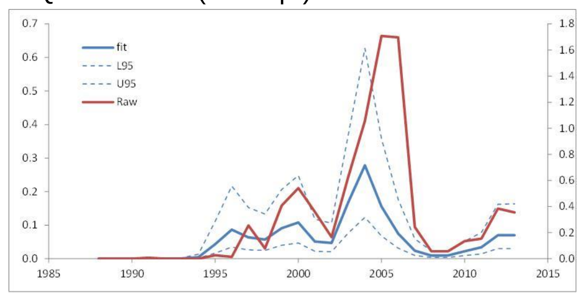
a. BTS7D (Jul-Aug)



b. Q1SWBEAM (Feb-Apr)



c. Q4SWIBTS (Nov-Dec)



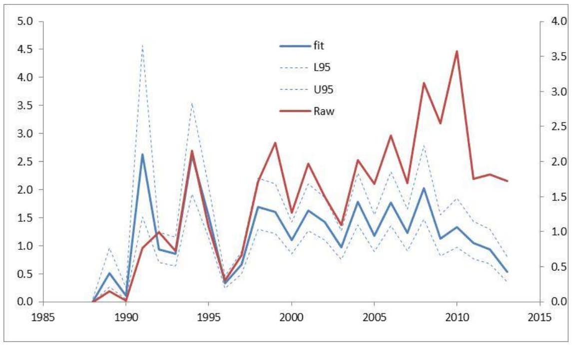
d. NWGFS (Mar-Apr + Aug-Oct)

Figure 5.6. Cuttlefish catch rate (numbers per 30-minute haul) trends in four Cefas surveys. Red lines = average of raw data (right y-axis). Blue lines = fitted trends with 95% confidence limits (left y-axis). The fitted trends control for spatial and temporal differences in the sampling regime between years. Note that differences in absolute values, between raw data and fitted trends, are not informative since the fitted values are contingent on the choice of sampling regime used as the basis for standardization.

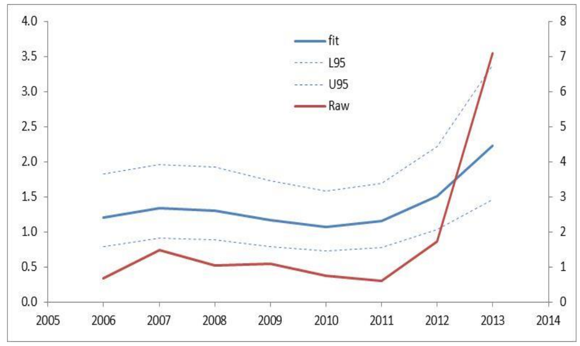
5.3.3 Loliginid squid

Six of the survey series yielded abundance indices for loliginid squid (Table 5.3), with a wide range of catch rates observed (Figure 5.7). The gear used and the months in which the surveys were conducted probably account for much of this variation: catches were lowest in beam trawls and highest in the last quarter of the year (when abundance of *Loligo forbesii* is normally at its highest, Pierce *et al.*, 1994a). Thus, the Q4SWIBTS and the WCGFS surveys are likely to have been the most informative although both have now been discontinued. In the former series, the (relatively small) year to year changes appeared to be related to NAO indices.

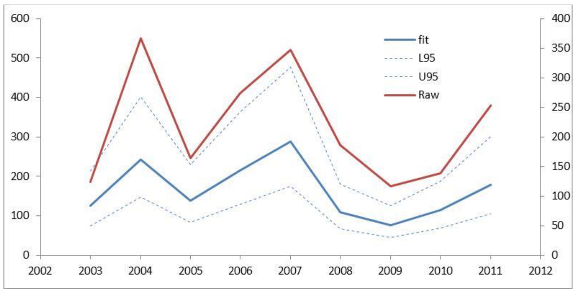
Results from BTS7D beam trawl survey suggest that the typical standardised catch rate from the beam trawl survey, at least from the late 1990s until 2008, is around 1.5 animals per 30-minute tow, which could be viewed as a baseline level. The summer IBTS survey in the North Sea is well-timed to record recruitment of *Loligo forbesii*. However, the wide confidence limits around the fitted values make it difficult to quantify trends. This is likely due to the concentration of squid close inshore at this time of year (Viana *et al.*, 2009).



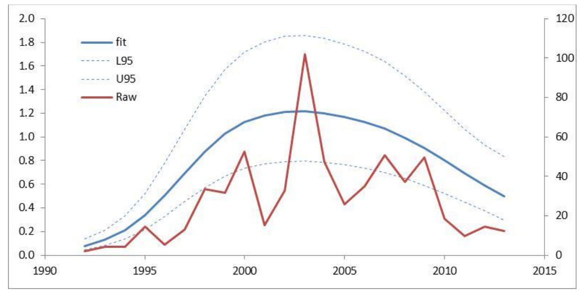
a. BTS7D (Jul-Aug)



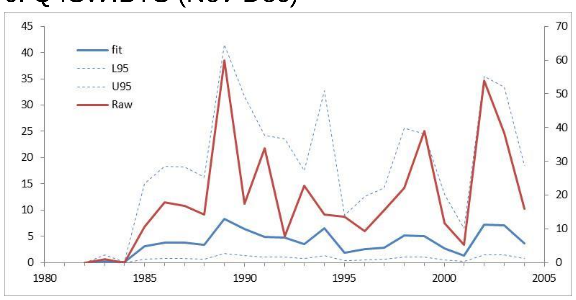
b. Q1SWBEAM (Feb-Apr)



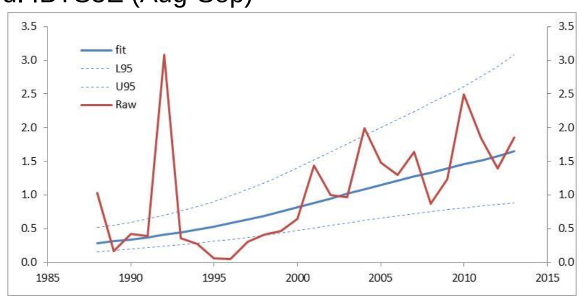
c. Q4SWIBTS (Nov-Dec)



d. IBTS3E (Aug-Sep)



e. WCGFS (Feb-Apr + Nov-Dec)



f. NWGFS (Mar-Apr + Aug-Oct)

Figure 5.7. Loliginid catch rate (numbers per 30-minute haul) trends in six Cefas surveys. Red lines = average of raw data (right y-axis). Blue lines = fitted trends with 95% confidence limits (left y-axis). The fitted trends control for spatial and temporal differences in the sampling regime between years. Note that differences in absolute values, between raw data and fitted trends, are not informative since the fitted values are contingent on the choice of sampling regime used as the basis for standardization.

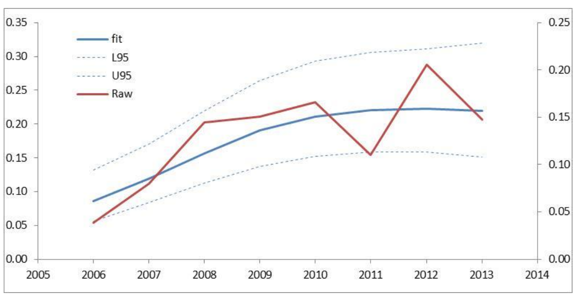
5.3.4. Ommastrephid squid

Unlike the loliginid squids, the family Ommastrephidae is mainly pelagic. In practice the distinction between pelagic and demersal species is less clear among those loliginid and ommastrephid squids regularly present in coastal waters. However, it should be borne in mind that demersal trawling may not be the best way to sample these species.

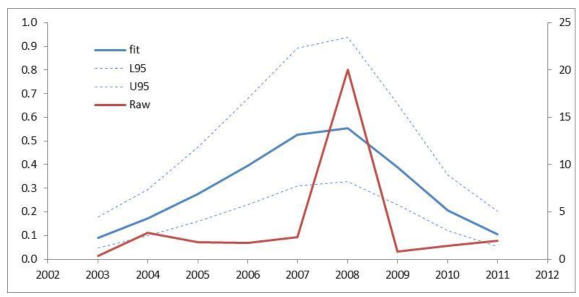
Catch rate series for ommastrephids were available from four survey programmes (Table 5.3, Figure 5.8). Perhaps unsurprisingly, the lowest catch rate was in the beam trawl survey and highest catch rates from the west coast groundfish survey. Aside from the beam trawl survey, high interannual variation in catch rate was apparent and as for the other cephalopod categories, some of this variation was related to NAO variation.

Of the four series, only the (summer) IBTS3E survey is ongoing and this showed wide variation in catch rate, reflecting the fact that fewer than 100 of the approximately 1700 hauls analysed caught any ommastrephids.

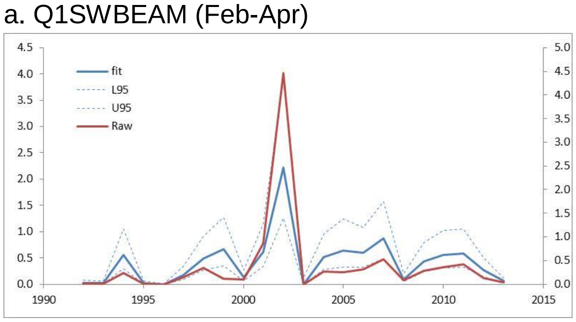
In general, wide year-to-year variation in abundance is a feature of ommastrephid squids and sporadic outbreaks of high abundance are also well-known (see Pierce *et al.*, 2010; Pierce & Portela, 2014). Given that three or different four ommastrephid species may occur in UK survey catches, that the family is known for wide fluctuations in abundance), and that it is relatively poorly sampled by ongoing survey programmes, it is probably unsuitable for indicator development.



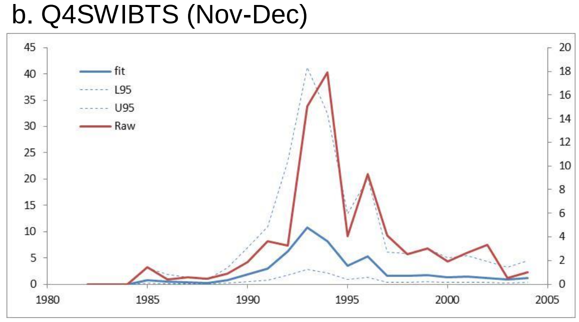
a. Q1SWBEAM (Feb-Apr)



b. Q4SWIBTS (Nov-Dec)



c. IBTS3E (Aug-Sep)



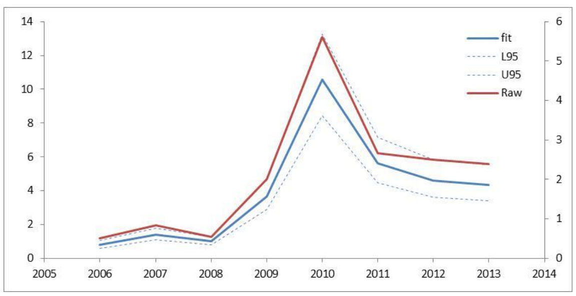
d. WCGFS (Feb-Apr + Nov-Dec)

Figure 5.8. Ommastrephid catch rate (numbers per 30-minute haul) trends in four Cefas surveys. Red lines = average of raw data (right y-axis). Blue lines = fitted trends with 95% confidence limits (left y-axis). The fitted trends control for spatial and temporal differences in the sampling regime between years. Note that differences in absolute values, between raw data and fitted trends, are not informative since the fitted values are contingent on the choice of sampling regime used as the basis for standardization.

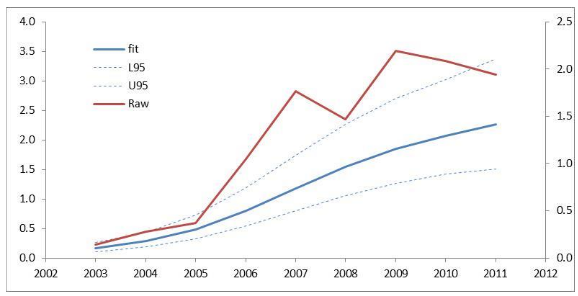
5.3.5 Octopus

Octopus series were available for four survey programmes (Table 5.3, Figure 5.9), only one of which is ongoing. All showed relatively low catch rates. Some common features are evident in the interannual trends, namely peaks in catch rates in the early 1990s and around 2010. The beam trawl (Q1SBEAM) series is a short series so caution is needed, but year-to-year variation in abundance in this series showed a strong environmental signal (Table 5.3).

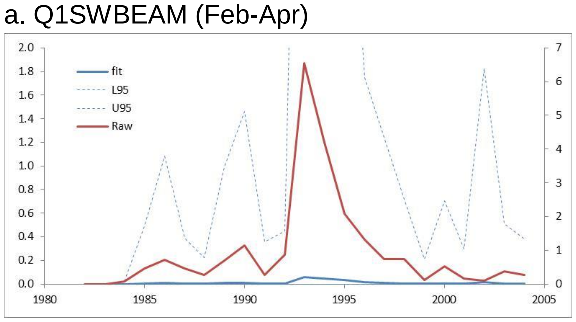
Because of its location, the ongoing survey series, NWGFS, probably only catches *Eledone cirrhosa*, although *Octopus vulgaris* occurs in southern English waters. Given the relative stability of standardised abundance seen for this series (Figure 5.9d), a standardised catch rate of around 2 animals per 30 minute tow could be proposed as a reference point. For all the cephalopod series, the utility of the data could be improved by better identification to species. Although deep-water octopus species may also be caught occasionally, the two most common species in coastal waters, *Eledone cirrhosa* and *Octopus vulgaris* are easy to distinguish: the former has one row of suckers on the arms, the latter has two rows.



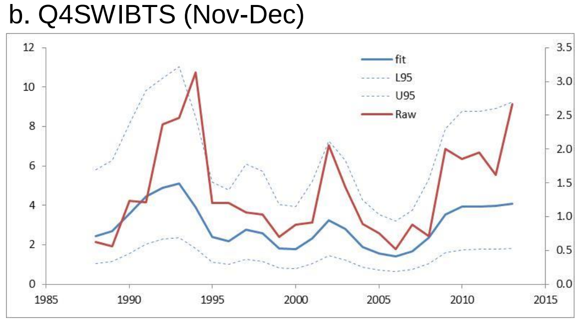
a. Q1SWBEAM (Feb-Apr)



b. Q4SWIBTS (Nov-Dec)



c. WCGFS (Feb-Apr + Nov-Dec)



d. NWGFS (Mar-Apr + Aug-Oct)

Figure 5.9. Octopus catch rate (numbers per 30-minute haul) trends in four Cefas surveys. Red lines = average of raw data (right y-axis). Blue lines = fitted trends with 95% confidence limits (left y-axis). The fitted trends control for spatial and temporal differences in the sampling regime between years. Note that differences in absolute values, between raw data and fitted trends, are not informative since the fitted values are contingent on the choice of sampling regime used as the basis for standardization.

5.3.6. Sepiolids

The bobtail squids have no commercial value in UK waters and their small size (mantle length of a few centimetres) means they are unlikely to be efficiently sampled by trawling gear. Eight species in four genera from this family occur in the northeast Atlantic: *Neorossia caroli, Rondeletiola minor, Rossia glaucopis, Rossia macrosoma, Sepietta neglecta, Sepietta oweniana, Sepiola atlantica* and *Sepiola aurantiaca* (Hastie *et al.*, 2009).

We have analysed one catch-rate time series, from the BTS7D survey programme. Catch rate varied considerably between years (Figure 5.10) although the NAO signal was weak (Table 5.3). Given the large number of species, the likely difficulty in identifying them all and the poor sampling by trawl surveys, it is doubtful that this group can be used for MSFD monitoring.

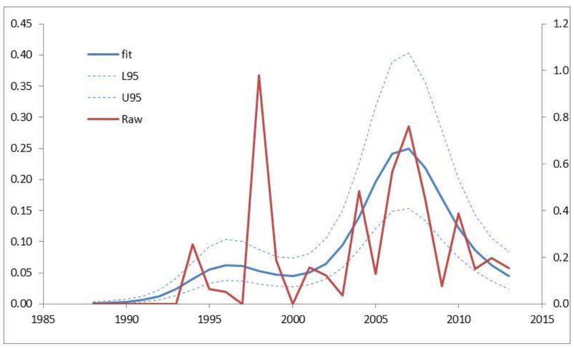


Figure 5.10. Sepiolid catch rate (numbers per 30-minute haul) trends from the BTS7D beam trawl survey. Red line = average of raw data (right y-axis). Blue line = fitted trend with 95% confidence limits (left y-axis). The fitted trend controls for spatial and temporal differences in the sampling regime between years. Note that differences in absolute values, between raw data and fitted trends, are not informative since the fitted values are contingent on the choice of sampling regime used as the basis for standardization.

5.3.7. Conclusions

The various Cefas survey programmes are/were carried out in various areas at different times of year and use(d) several different gear types. Extant survey programmes can be identified that adequately record catch rates some cephalopods (e.g. BTS7D for cuttlefish, IBTS3E for loliginids, NWGFS for octopus).

Reference abundance levels (based on standardised data) can be suggested for cuttlefish, octopus, and loliginid squid, at least for some areas, based on relative stability of standardised catch rates over a number of years. In other cases, for example the North Sea, it is possible that focusing on sub-areas could produce more consistent data, e.g. for loliginid abundance in coastal waters in late summer. Existing knowledge of species distribution and movements can be used to inform such selections.

Although further work is needed to explore different environmental drivers, in most cases only a part of the year to year fluctuation in abundance is demonstrably environmentally driven. However, it remains plausible that further standardisation of abundance series, accounting for environmental influences, can be achieved.

Results from this analysis of survey data suggests that development of baselines, indicators and monitoring programmes (based on existing monitoring) are feasible for the three above-mentioned cephalopod groups.

Nevertheless, the fact that it was necessary to analyse trends by broad taxonomic category highlights a major limitation, namely that each group includes more than one common species (three cuttlefish, two octopuses and four loliginid squids). Ideally these should be routinely distinguished in any survey programme used for MSFD monitoring. This is probably most important in the case of the loliginids, for which commercial catches comprise two main species, *Loligo forbesii* and *Loligo vulgaris*, at least in the English Channel.

6. Scottish research survey data: *Loligo forbesii* distribution and abundance

6.1. Introduction

Longfin squid (*Loligo* sp.), assumed to be mainly *L. forbesii*, has been recorded routinely over many decades during trawl surveys carried out by Marine Scotland Science. This species is perhaps the best documented of all UK cephalopods, having been a major focus of several European research projects as well as a number of PhD theses. Nevertheless, previous studies have been limited by the short time series available and by the slow progress of research on age determination, essential for understanding growth patterns.

Although some data were collected as long ago as the 1920s, it appears that squid were recorded more consistently during surveys since 1980 and, in line with previous analyses (e.g. Pierce *et al.*, 1998), this year was used as a starting point. It should also be noted that *L. vulgaris* is occasionally recorded commercial landings in Scotland and *Alloteuthis subulata* likely occurs routinely; it is possible that misidentification of the latter as *Loligo* has occurred on occasion. The Scottish trawl surveys also catch ommastrephid squid, octopus (*Eledone cirrhosa*), cuttlefish and sepiolids. For octopus only a four-year series was available, which has recently been analysed (see MacLeod *et al*., 2014). Cuttlefish were relatively rarely caught while, as seen in section 5, sepiolids tend not to be well-sampled by standard trawling surveys.

Some survey programmes (e.g. pre-recruit fish surveys in the North Sea and off the West Coast in the first quarter of the year) have continued throughout the study period; others operated during only part of the period. In addition to several different vessels, two main nets were used in the surveys, the Grande Ouverture Verticale (GOV) and the 48’ Aberdeen trawl; there were also variations in gear settings and haul duration (see Knijn *et al*., 1993). It should ultimately be possible to control for most of this variation but I the present analysis all data from 1980 were grouped together.

The purpose of the analysis presented here was to evaluate spatiotemporal variability in occurrence and abundance of *Loligo*. In relation to the MSFD, we need to know whether we can identify what constitutes GES, such that we could propose indicators and reference points and whether prospective indicators of distribution and abundance can easily be monitored.

6.2. Exploratory analysis

As documented by Pierce *et al.* (1998), *c*atches of *Loligo* during trawling surveys undertaken by MSS have been patchy in space and time: 3542 hauls out of 10261 undertaken during 1980-2012 contained *Loligo*, with estimated per-haul hourly catch rates ranging from 1 to over 20,000 squid per hour, the latter reflecting a high catch of pre-recruits 3-5 cm in length. Some of this variability is likely to reflect variation in fishing power (due to use of different nets and boats, and the use of small-mesh bags on the cod-end during some surveys). For this is exploratory analysis we therefore analysed both total biomass (which should be relatively insensitive to catches of many very small squid) and presence-absence data.

Sampling was most consistent during the first and third quarters of the year in the North Sea (ICES area IV), the first and fourth quarters off the west coast (area VIa), and during the third quarter in the offshore Rockall area (VIb). The number of hauls per area per quarter, typically ranged between 30 and 90 hauls, depending on the survey programme.

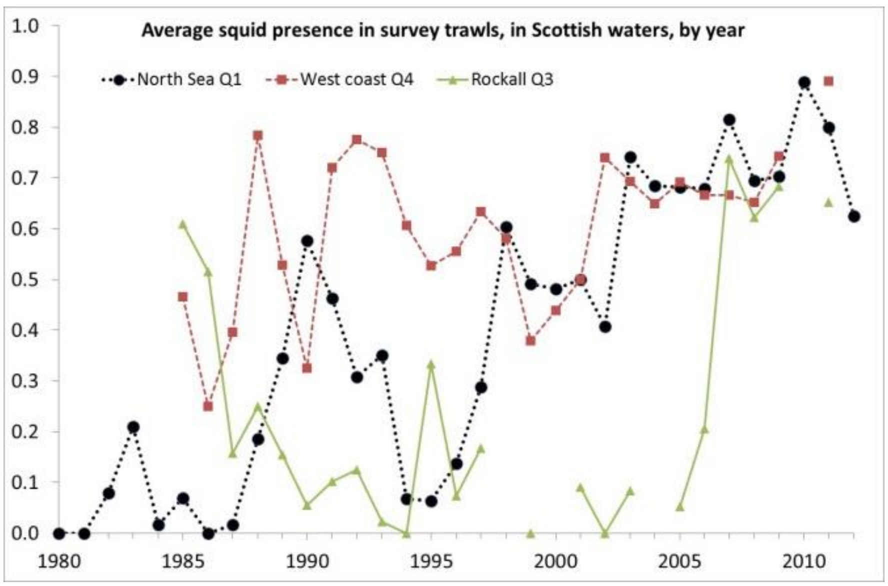
Sampling of squid unsurprisingly follows a similar seasonal and geographical pattern. In the North Sea, presence of squid is well-sampled in quarters 1 and 3 of most years and there was a generally rising trend during 1980-2012, although with a low point around 1995-1996. Data for the second quarter of the year are available mainly in the 1990s but appear to depict a similar year-to-year trend to those seen in quarters one and three. In general, presence was higher in quarter one than in quarter three. There are few data available for the North Sea in quarter four.

On the west coast, data are available mainly for quarters one and four. There was a rising trend in squid presence from 1980 to 1993, followed by a fall up to 2000 and then a further rise. In the Rockall area, data are available mainly for quarter three, from surveys targeted at haddock. *Loligo* presence at Rockall fell from 1980 to 1993, briefly recovered in 1995 and then remained low until 2007 when it rose to a similar value to that in the early 1980s. The decline in the 1980s is consistent with the disappearance of the Rockall squid fishery (see Pierce *et al.*, 1994).

As summarized above, trends in *Loligo* presence over time in the three areas have been dissimilar, although all three areas show high presence since 2007. Trends in biomass were more similar for areas IV and VIa while, again, all three areas show high values in the second half of the 2000s (Figure 6.1).

In addition, GAMs were fitted following a similar approach to that used for the Cefas surveys, but using the whole dataset. We did however exclude data from south of 53^{o}N, with a view to avoiding areas where *Loligo vulgaris* might make up a significant part of the *Loligo* catches. Further work will thus be needed to account for variation in fishing power.

As for the Cefas survey series, we used a negative binomial distribution for catch rate. Here we have attempted to account for environmental and fishery effects by including the annual and winter NAO indices and the previous year's Scottish fishery landings of squid, respectively in the models. As discussed in section 4, one limitation was the absence of a reliable fishing effort series.



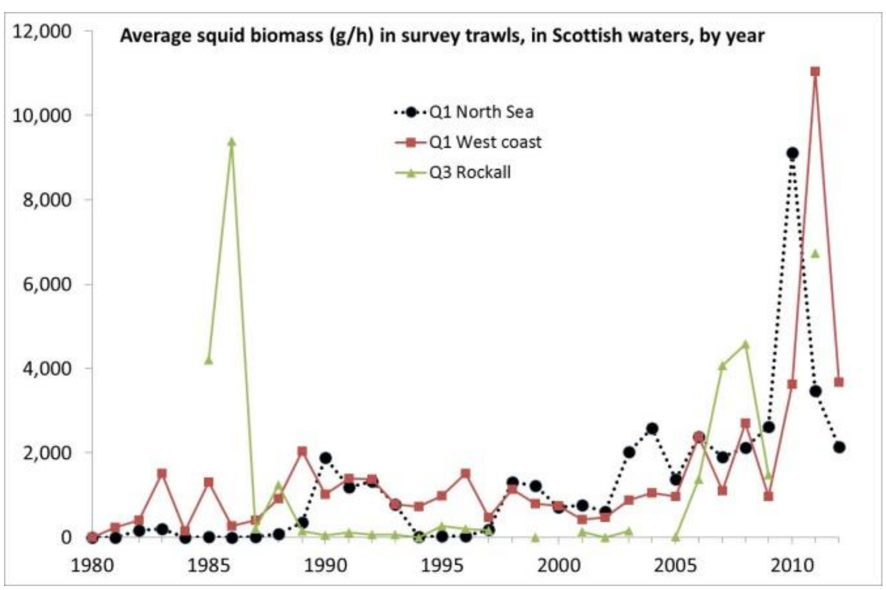


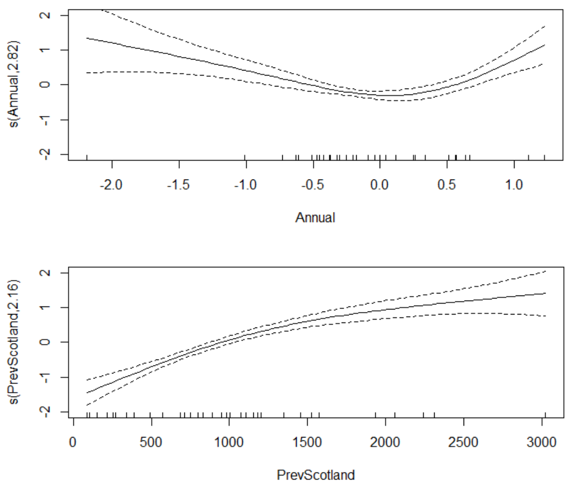
Figure 6.1. Average catches of *Loligo* during MSS surveys: (above) proportion of hauls with *Loligo* present and (below) average total *Loligo* biomass per haul, by season and area.

The basic GAM model included effects of latitude x longitude and day of the year. Some of the haul data available lacked information on time of day so this was not included. As with the analysis of Cefas data, then (a) year was added to see the extent to which deviance explained increased, and (b) year was substituted by the NAO indices (for the same and previous years) and previous year's landings (as a proxy of abundance combined with fishing pressure), in different combinations.

Results are summarized in Table 6.1. The deviance explained for the base model is relatively low, but this is not surprising given the likely heterogeneity of the catch rate data. Of more interest is the amount of interannual variation (around 6% of deviance); again this seems low but it must be remembered that it is a very heterogeneous dataset. Somewhat over 1/3 of the interannual variation seems to be related to the previous year's landings, and this relationship is positive (Figure 6.2), suggesting that it reflects the positive influence of previous abundance more than a (likely negative) effect of previous fishing mortality. Less than one fifth of the interannual variation was related to NAO indices, with abundance apparently lowest at intermediate NAO values (Figure 6.2) although NAO and landings together accounted for almost 2/3 of the Interannual variation (Table 6.1).

Table 6.1. Percentage deviance in *Loligo* catch rate in MSS surveys (1980-2012) explained by different combinations of explanatory variables. Models are ordered using another goodness of fit measure, the AIC. Results were based on negative binomial model with theta = 0.014 (N=10089 hauls).

Model (base = lat x lon, day of year)	**% Deviance explained**	**Improvement over base model**	**AIC**
Base + year	25.3%	5.8%	45160.6
Base + annual NAO + previous landings	23.1%	3.6%	45176.18
Base + previous Landings	21.7%	2.2%	45193.53
Base + annual NAO	20.6%	1.1%	45221.24
Base + winter NAO	20.3%	0.8%	45228.91
Base + previous annual NAO	20%	0.5%	45232.56
Base + previous winter NAO	20%	0.5%	45235.34
Base	19.5%	-	45240.86



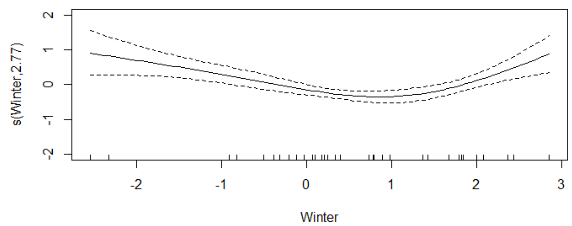


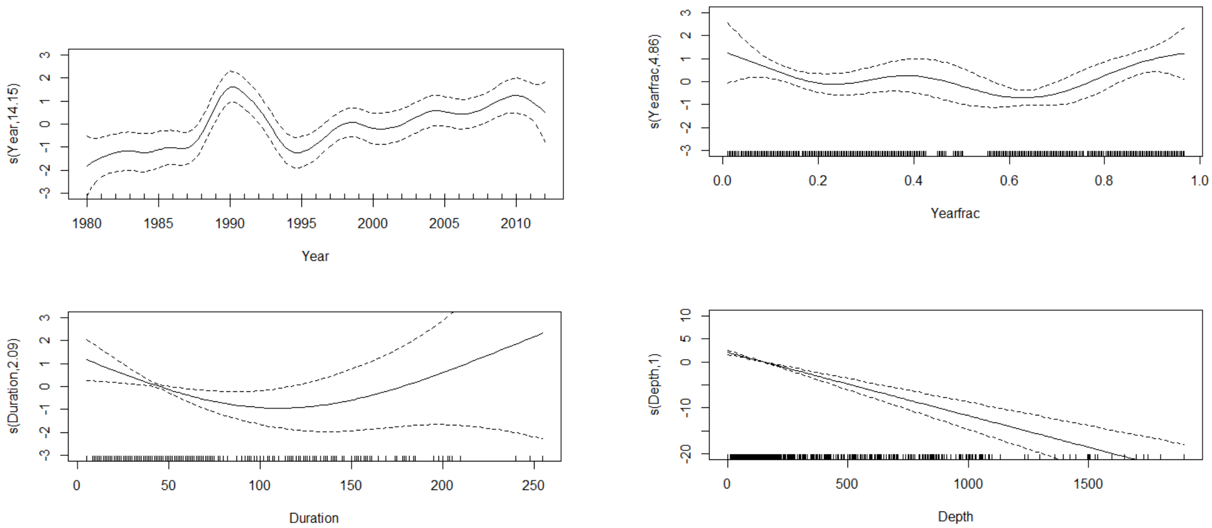
Figure 6.2. GAM smoothers illustrating effects on survey catch rate (*Loligo* count per hour) of (top left) annual NAO, (top right) winter NAO and (bottom left) the previous year's fishery landings of squid in Scotland.

The simple spatiotemporal model of squid catch rate described above could be improved by including effects of haul depth and haul duration, bringing total deviance explained up to 29.1%. Aside from a strong spatial pattern, it was seen that catch rates were lower in deeper water, slightly reduced in longer tows, and highest at the beginning and end of the year (Figure 6.3). GAM predictions from this model, with all explanatory variables except year held constant, provide a view of standardized annual abundance indices (Figure 6.4). The standardized data display a clear peak in 1990 as well as a gradual increased between 1995 and 2010, albeit with wide confidence limits.

6.3. Conclusions

Squid (*Loligo forbesii*) abundance is well-recorded in several quarterly survey programmes undertaken by Marine Scotland Science, especially for quarters 1 and 3 in the North Sea, quarters 1 and 4 on the West Coast, and quarter 3 at Rockall.

Squid presence and abundance are patchy and abundance data are highly right skewed, but this can be captured by a negative binomial distribution. Squid presence and abundance have fluctuated widely over the last three decades; there was a general increase between 1995 and 2010. However, the trend at Rockall has differed from that in coastal waters. At Rockall, high abundance in the early 1980s was followed by a long period of near absence. Abundance has increased again since the mid-2000s.



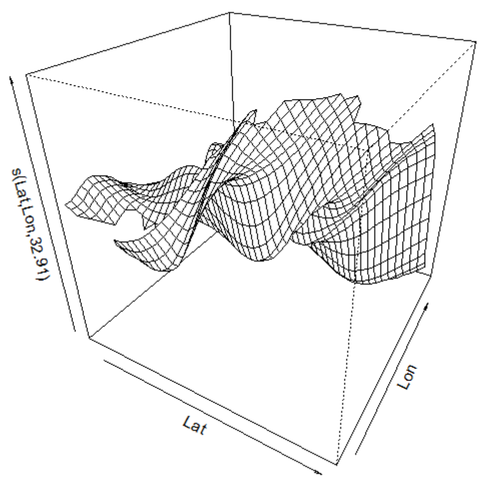


Figure 6.3. GAM smoothers illustrating effects on survey catch rate (*Loligo* count per hour) of Survey catch rate (count per hour) of loliginid squid: smoothers for effects of (top left) year, (top right) day of year ("yearfrac"), (middle left) tow duration, (middle right) haul depth and (bottom left) latitude x longitude.

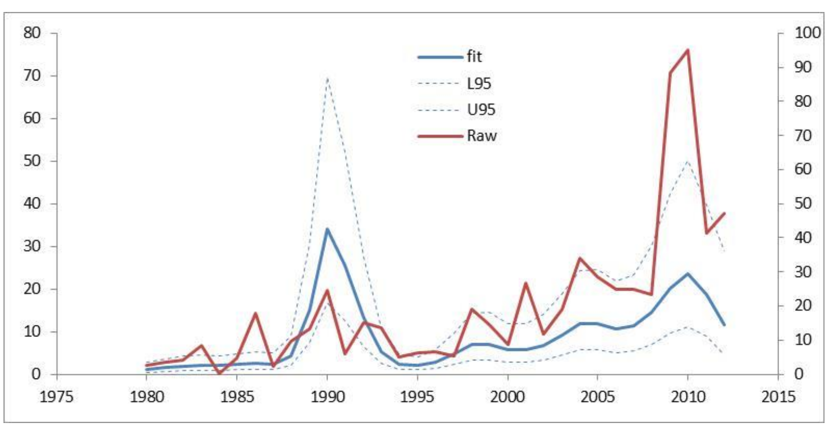


Figure 6.4. Loliginid squid abundance (numbers per 30-minute haul) trends in Scottish surveys, 1980-2012.
Red line = raw data (right y-axis).
Blue lines = fitted trends with 95% confidence limits (left y-axis).

The analysis provides some evidence of a positive effect of high abundance in the previous year and a possible effect of the NAO (as also indicated in several previous publications). However, further analysis and modelling is needed to separate stock size, fishery mortality and environmental signals in these data. In addition, by analysing different survey series separately, it should be possible to account for much of the variation in fishing power likely to be present in the data

The good availability of data (also including fishery data) and the fact that previous analyses have revealed significant environmental effects, suggest that indicators of abundance and distribution could be developed for this species, and that data would be available from existing monitoring programmes. The main issue remains the difficulty in defining reference points.

There is a possible issue with misidentification of the smallest squid, although the highest numbers of very small squid are found in late summer when the species is recruiting and assignment of these squid to *Loligo forbesii* is therefore plausible. Nevertheless, as commented previously, for use of abundance of this species within an MSFD indicator, assurances about identification of catches to species would be needed.

7. Cuttlefish in the English Channel (IFREMER survey data)

IFREMER survey data are available online and cover the English Channel, western approaches, southern North Sea and parts of the Bay of Biscay. Analysis of some of these data was undertaken by Nada El Shanawany and the results of this analysis, summarized here, appear in her MSc thesis (El Shanawany, 2014).

An IFREMER dataset, based on October groundfish surveys of the English Channel (ICES VIId) (1998-2012) was used to assess the influence of environmental variables on the distribution of cuttlefish *Sepia officinalis.* The information extracted, from the surveys and from online databases of satellite-derived environmental variables, included abundance, average depth, haul duration, swept surface area, sea surface temperature (SST), Chlorophyll (CHL), photosynthetic active radiation (PAR), euphotic depth (ZEU), depth (DEP), depth slope (DEPSL), and depth aspect (DEPASP) and sediment type (texture), for each sampling unit (ICES rectangle). Exploratory GAM models were constructed, using cuttlefish abundance as the response variable.

Results (not shown) indicated that both temperature and euphotic depth significantly affect spatial and temporal variation in abundance of *S. officinalis*. A model for temporal (interannual) variation explained 48% of deviance. SST alone accounted for 35% of the deviance explained. The influence of euphotic depth was most apparent in 2005 and 2009.

Spatial variation of *Sepia officinalis*, by contrast, appeared to be influenced mainly by sea bottom sediment type, which explained 59% of deviance ($p = 0.00423$). Cuttlefish distribution appeared to be negatively related with soft (mud / sandy mud) sediment types.

Several caveats apply to these findings. The dataset which was analysed covered only a small area and additional information which might be useful, e.g. the time of day when hauls were taken, is not available online. In addition, the survey area overlaps with that covered by the Cefas surveys. Nevertheless, the analysis adds weight to the idea that standardized abundance indices for cephalopods can be derived from survey data.

8. Analysis of growth patterns in *Loligo forbesii*

8.1. Background and objectives

Although age determination of cephalopods is not new, the process of preparing and reading statoliths is both difficult and time-consuming. Until recently few age data were available for *Loligo forbesii* and it remains the case that almost nothing has been published.

Age and length data were available from 749 individual squid (*Loligo forbesii*)[2] captured in Scottish waters in 1990, 1997 and 2007-09. Ages were determined by counting daily growth rings on excised statoliths which had been stored since the original sampling date. Some of the statoliths were read during the PhD of Sansanee Wangvoralak (Wangvoralak, 2011), by Sansanee herself or by Alexander Arkhipkin; comparison of results from the two readers suggested good agreement. The remaining statoliths (from 1990 and 1997) were read during 2014 by Alexander Arkhipkin. It is intended to continue data collection to include further years but the data available are sufficient for the purposes of the present analysis.

The main question was whether age-length relationships were sufficiently predictable to use length as a proxy for age. This being so, indicators based on length distributions could be proposed. However, bearing in mind the annual life cycle of squid, these indicators would not necessarily be similar to, say, the large fish indicator.

8.2. Analysis

To linearize the relationship between length (mantle length, ML) and age, ML data were log-transformed. Preliminary analysis confirms that there is a consistent relationship between ML and age, although with a wide spread of lengths at any age (Figure 8.1). It should be noted that the minimum age of sampled animals was around 120 days and the maximum age around 430 days, although only a small proportion of animals were more than 1 year old. It is likely that animals younger than 120 days old do not recruit to the fishery due to small size and/or living close to the coast.

[2] At the time of writing, additional samples had become available but it was not possible to include analysis of these in the present report. Results from the full data set will be published separately.

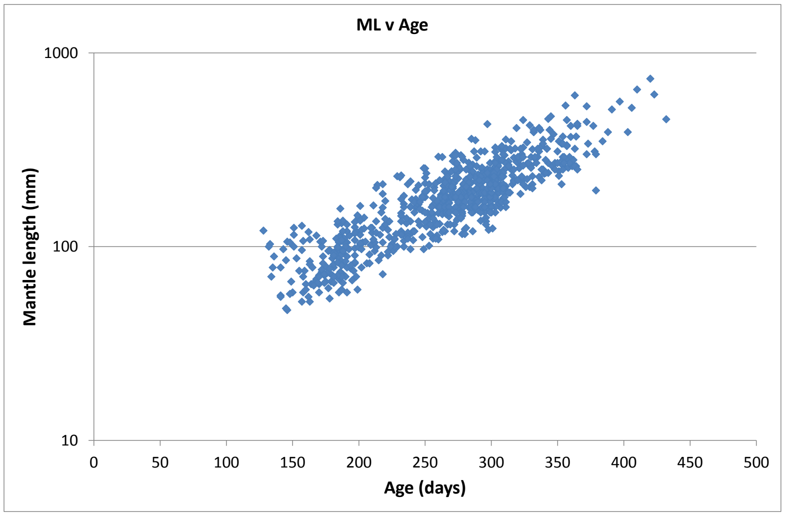


Figure 8.1. Mantle length (mm) versus age (days) in *Loligo forbesii* (note the logarithmic scale on the Y-axis).

It is also of interest to understand the relationship, if any between capture date and hatch date. Some structure is imposed on the data by the absence of young squid, hence a substantial lag between hatching and capture. For most capture dates, squid caught could have hatched during 6 to 8 different months of the year. Conversely for a given hatching date, squid could be caught during up to 10 different months of the year, although animals hatched in summer tended to be caught only early in the year. Most animals caught during the main fishing season (September-December) hatched during the first 4 months of the same year or the last quarter of the previous year (Figure 8.2).

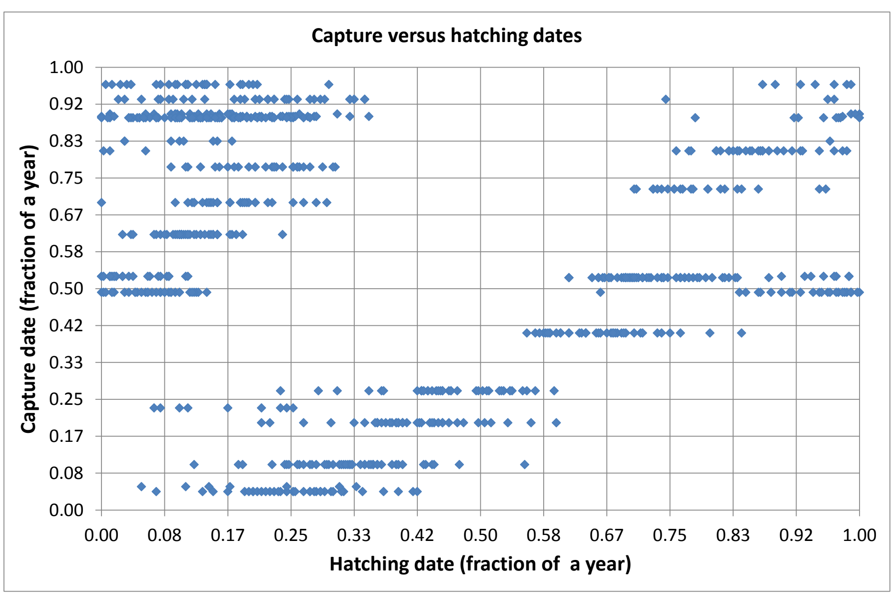


Figure 8.2. Capture date versus estimated hatching date in *Loligo forbesii.*

Gaussian generalised additive models were fitted to log-transformed mantle length. The explanatory variables used were age, sex (male female or unknown [usually very small animals]), age, the age-sex interaction, hatching date (as a fraction of the year), year, and reader. The length-age relationship was derived separately for each sex and the results compared with a model with a single age-length relationship; the former significantly improved the goodness of fit.

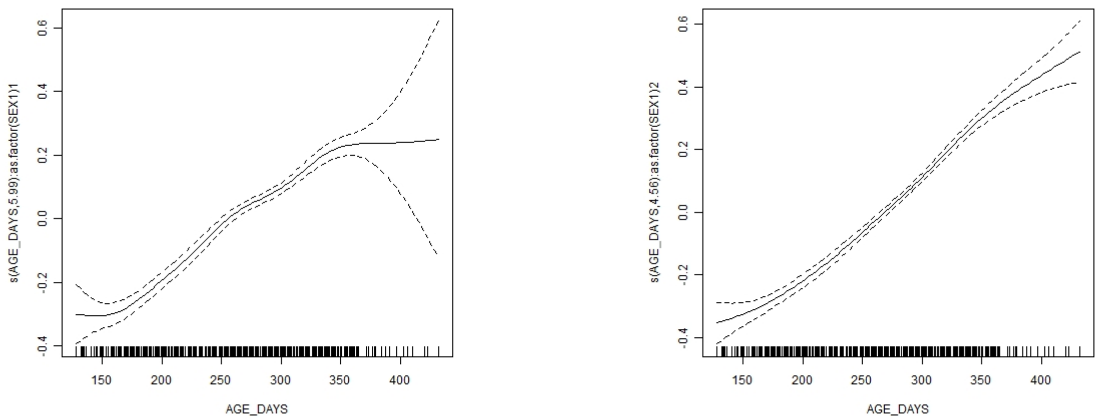
Results indicated that effects of all explanatory variables had significant effects (Table 8.1), including the expected sexual dimorphism and a strong effect of hatching date. The year-to-year differences were statistically significant but mainly reflected difference between 1990 and other years; animals from 1990 were larger than those in other years for a given age. Overall the model explained almost 85% of deviance in the length-age relationship and model diagnostics indicated a good fit to the data.

Table 8.1. GAM results for log mantle length in *Loligo forbesii* versus explanatory variables including hatching date. Model 1 used hatching date while model 2 used capture date.

	Model 1		**Model 2**	
Explanatory variable	**F value**	**P value**	**F value**	**P value**
Capture year	11.93	<0.0001	12.82	<0.0001
Sex	25.81	<0.0001	23.31	<0.0001
Reader	25.34	<0.0001	15.60	<0.0001
Age (females)	124.57	<0.0001	58.98	<0.0001
Age (males)	263.59	<0.0001	168.22	<0.0001
Age (immature)	10.67	0.0014	11.54	0.0007
Hatching date	11.21	<0.0001		
Capture date			18.39	<0.0002

In terms of the form of the relationships, males continued to increase in ML at all ages while female growth apparently reached an asymptote. Animals hatching in spring had the highest length-at-age; those hatching in late summer have the lowest length-at-age (see Figure 8.3).

The results suggest that age-length keys, by sex, could be useful, provided that the hatching date is taken into account and sample size were sufficient to overcome sampling error. Clearly, however, hatching date cannot be known unless age is determined which at first sight appears to be an insurmountable obstacle. A second model was therefore fitted using capture date as an explanatory variable. The theoretical basis for this model is weaker but it has the advantage, in terms of an age-length key, that capture date is known at the time a squid is collected, and length and sex are also easily determined.



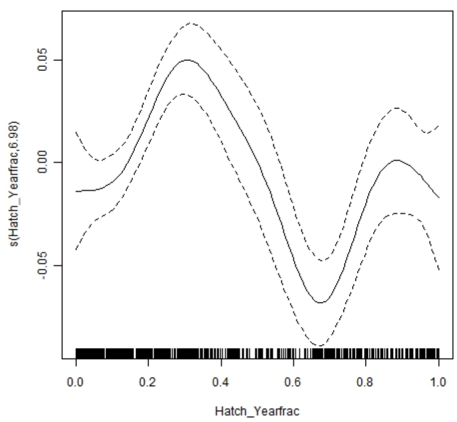


Figure 8.3. Results from GAM model 1. Smoothers illustrating the effects of age, sex and hatching date on squid length. For females (top left), length appears to reach an asymptote after around 350 days whereas in males (top right), length continues to increase with age even in the oldest animals. Bottom left: hatching date has a clear influence on length at age, with animals hatched in spring being largest (fastest growth) and those hatched in early autumn being smallest (slowest growth).

The model using capture date performed as well as the previous model (Table 8.1). Animals captured during the middle portion of the year tend to be the smallest at age (Figure 8.4).

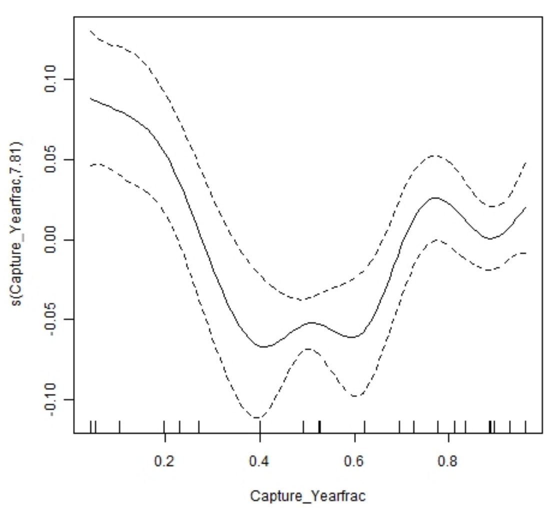


Figure 8.4. Results from GAM model 2. Smoother for the effect of capture date on log-transformed mantle length in *L. forbesii.*

Some additional insights can be obtained by comparing models with and without various explanatory variables, in terms of percentage deviance explained (Table 8.2), it can be seen that age and sex together explain 80% of deviation in length-at-age, with hatch date or catch date accounting for slightly more than 2%, year to year differences accounting for around 1%, reader differences 0.6% and around 15% of deviance unexplained. Results from this exercise suggest that it is feasible to predict age from length.

Table 8.2. Percentage deviance explained (%DE) and AIC for various GAMs to predict *Loligo* mantle length from explanatory variables (age, sex, reader, year, catch or hatch date). The model with the highest %DE and lowest AIC is the best model.

Model	**%DE**	**AIC**
Age, sex	80.2%	-1366.59
Age, sex, reader	80.8%	-1389.59
Age, sex, reader, hatch date	83.0%	-1465.43
Age, sex, reader, hatch date, year	84.1%	-1505.97
Age, sex, reader, catch date	84.2%	-1517.07
Age, sex, reader, catch date, year	85.2%	-1560.99

8.3. Implications for indicators, monitoring and management

The age data clearly support the idea that *Loligo forbesii* normally has an annual life cycle, although a few males were up to 14 months old. It also suggests that there is a period of around 3 months post-hatching during which squid are not normally taken by fisheries. It is also apparent that growth rate depends on hatching date.

Length in squid shows a strong seasonal pattern consistent with the approximately annual life cycle. There is also clear sexual dimorphism. Length-frequency distributions should therefore be derived separately for males and females, which often requires internal examination (opening the mantle cavity to examine the gonads) and can be difficult for very small specimens. Although not investigated here, previous analysis suggests an onshore-offshore migration such that the smallest squid are found close inshore in late summer and move offshore as they grow, likely migrating towards the coast again to spawn (e.g. Viana *et al.*, 2009).

Thus any change in the sampled length-frequency distribution needs to be judged in relation to the time of year and the sex ratio (although the latter may also vary predictably with season; see Pierce *et al.*, 1994b) and, in principle, location of the catches.

Fecundity in female *Loligo forbesii* shows a weak positive relationship with mantle length (Boyle *et al.*, 1995), so removal of larger animals potentially reduces spawning success more than removing smaller animals. Probably the simplest way to reduce fishing mortality on the largest animals would be to avoid fishing on them during the peak of the spawning season (around the end of the calendar year).

As so-called intermittent terminal spawners, i.e. with a single spawning cycle but perhaps spread over several spawning episodes, most captured females will have contributed little or nothing to the next generation regardless of their size. A high proportion of small squid in catches is clearly likely to signify growth overfishing.

A given biomass of small squid will obviously contain many more individuals than the same biomass of large squid. Furthermore, squid eggs are attached to the seabed substrate, probably concentrated in certain inshore spawning areas, and these areas are also likely to concentrate the hatchlings and pre-recruits. Trawling on such concentrations, as has apparently happened in the Moray Firth in some years, has the potential to damage the spawning grounds as well as directly reducing population abundance. Taking into account the annual life cycle and the consequent absence of a buffer of older animals, fishing on small squid therefore possibly represents the most serious threat. Evidence for this is anecdotal but it is very plausible.

We therefore propose what might be termed a "**small squid indicator"** (under descriptor 1 and/or descriptor 3), specifically referring to catches of very small squid in summer and autumn, normally taken close inshore, and which could have a negative impact on abundance.

In a sense this is no different to the need to protect young fish, which can for example be achieved by using large mesh sizes. However, because of the body form and schooling behaviour of squid, large mesh sizes may be ineffective in avoiding capture of very small specimens and, in any case, fishermen targeting squid in Scotland are allowed to use a smaller mesh than would be permitted if they were targeting other species.

The apparently relatively predictable annual cycle also suggests that sustained changes in the seasonal pattern of length distributions could indicate a change in **life cycle phenology**. This is as likely to occur due to natural environmental change as to human impacts and is thus not easily interpreted in terms of the status of squid populations. Indeed, there is evidence that such changes have occurred in the past (Holme, 1974;

Pierce *et al.*, 2005). Nevertheless, such changes, if not demonstrably following changes in the seasonality of prey abundance, could result in a mismatch of the life cycle with resource availability and might make populations more vulnerable to anthropogenic pressures.

9. Concluding remarks

Much of the analysis presented here has focused on analysing spatiotemporal trends in local abundance, with a view to isolating interannual variation and thus both establishing whether baseline conditions can be identified and demonstrating the value of the data collected for use as an indicator of status. While this could not be demonstrated for every data series we believe there is evidence that cephalopod abundance indicators, based on standardised abundance measures from existing trawling survey programmes, could be applied within the suite of indicators used for the MSFD.

Due to the great environmental sensitivity and wide abundance fluctuations typically seen in cephalopods, it will be necessary to distinguish natural changes in cephalopod populations from those due to anthropogenic pressures (notably fishing). Part of the rationale for the present project was that this could be achievable through statistical modelling of population abundance trends. This of course assumes that the abundance indices available (survey trawl catches and/or fishery landings) reliably track abundance.

In principle, abundance in a given year will reflect the previous year's stock size, the previous year's catch and environmental influences on spawning success, juvenile growth and mortality, and recruitment. In practice, based on the fishery data available for Scotland, landings data seem to reflect abundance and there is no evidence that high landings result in lower abundance the following year. However, published stock assessments for cephalopods in the English Channel suggest that fished cephalopod stocks are fully- or overexploited in this area.

"Baseline" values, targets and reference points for cephalopod abundance may not be absolute values due to the dependence on environmental conditions. For most of the cephalopod series examined, year to year variation was in part explained by environmental conditions, but the proportion of the variation explained was often not very large. Conversely, several series showed relative stability in standardised abundance of a number of years, which suggested that baseline values could be identified. In addition, and regardless of whether baselines can be defined with confidence, it is likely that any sustained fall in abundance would represent a departure from good environmental status.

In future, a greater focus on measuring fishing mortality in cephalopods may be desirable, although doubts exist as to whether this can easily be separated from natural mortality, since the latter probably cannot be assumed to be constant.

The analysis of growth patterns in *Loligo forbesii* indicated a surprisingly high degree of predictability in the age-length relationship. Given the life-cycle characteristics of most cephalopods, the presence of large numbers of small individuals in commercial catches could indicate overfishing, whereas the relative proportion of larger individuals may be less informative, albeit still relevant. The concept of a “small squid indicator” is proposed, essentially a statement of the undesirability of fishing on areas (and at times) where pre-recruits concentrate.

In relation to other MSFD descriptors (e.g. related to food webs, contaminants and underwater noise), use of cephalopod-based indicators is feasible but there is generally no ongoing monitoring that would provide the necessary information. Possibly the most relevant additional indicator would be pollutant concentrations in cephalopods, since they are known to accumulate cadmium and PCBs and could provide an early warning of high environmental levels.

Finally, one of the main limitations of the analysis that could be carried out was that it mostly refers to families or genera rather than species. There is a need to ensure that cephalopods are always identified to species level, ideally in fishery landings and certainly in research trawl catches. Clearly, this could be based on sub-sampling but it would require acquisition of the necessary identification skills by all observers involved in data collection.

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