Investigating the link between *Nephrops norvegicus* burrow density and sediment composition in Scottish waters.

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Nephrops norvegicus is a burrowing decapod crustacean, found in the North Atlantic Ocean and Mediterranean Sea, at depths of between 10m – 1200m. It is currently the most valuable single species exploited by the commercial fishing industry in Scotland. It constructs and inhabits extensive burrow complexes in suitable muddy sediments, the composition of which is believed to limit the extent of burrow construction, and hence population size. Due to variable and sex specific emergence patterns of *Nephrops*, catch rates from traditional trawl surveys are not considered a good estimator of population size. *Nephrops* populations around Scotland are currently assessed using an underwater TV (UWTV) survey method to estimate burrow density, which is assumed to be a proxy for population density and, raised to total area of muddy sediments in the region of interest. Sediment samples are collected at the end of each UWTV deployment. This study explores the relationship between *Nephrops* burrow density and sediment composition in two areas off the coast of Scotland over the period 2002-2007, and attempts to answer the question of whether changes in population size have represented a colonisation of less favourable sediment types or have reflected an overall increase in burrow density.

Introduction

The Norway Lobster, *Nephrops norvegicus* (L.) (hereafter referred to by genus alone) is a marine decapod crustacean, widely distributed in the north-east Atlantic, from Iceland to Mauritania, and throughout the Mediterranean Sea (Figueiredo & Thomas, 1967). It is a highly commercial species, with estimates of annual total *Nephrops* landings in the North-eastern Atlantic and Mediterranean area around 60,000 tonnes (ICES, 2007a). It is found on muddy shelf and shelf-edge sediments, at depths of between 10m and 1200m (Rice & Chapman, 1971; dos Santos & Peliz, 2005), where it constructs complexes with distinctive "crescent shaped" entrances (fig. 1). The variability in emergence patterns from these burrows associated with seasonality, sex, time of day and prevailing light conditions result in trawl catch rates which are thought to be poorly representative of the *Nephrops* population as a whole (Chapman & Rice, 1971).

Concerns have been raised about the validity of analytical assessments of some *Nephrops* stocks as a basis for setting international landings limits due to problems with misreporting of catches, unreliable measurement of effort and poorly parameterised growth models (ICES, 2006a; 2006b). Additionally, *Nephrops* lack hard structures bearing marks indicative of age, which makes it difficult to apply standard age-based assessment methods. Consequently, the population sizes of a number of *Nephrops* stocks are assessed using underwater television (UWTV) surveys. The methods used in UWTV assessment of *Nephrops* populations were developed in Scotland during the 1980s (Chapman, 1985; Bailey et al., 1993), and refined by a number of EU-funded study projects (Marrs et al., 1996; Tuck et al., 1997; Marrs et al., 1998). The approach is now used as standard for assessing *Nephrops* populations in

UK and Irish waters, with developmental surveys being investigated in a number of other countries (ICES, 2007a). A towed sledge mounted with TV cameras (fig. 2) has been used by Fisheries Research Services (FRS) to carry out regular UWTV surveys of *Nephrops* populations around Scotland since 1994.
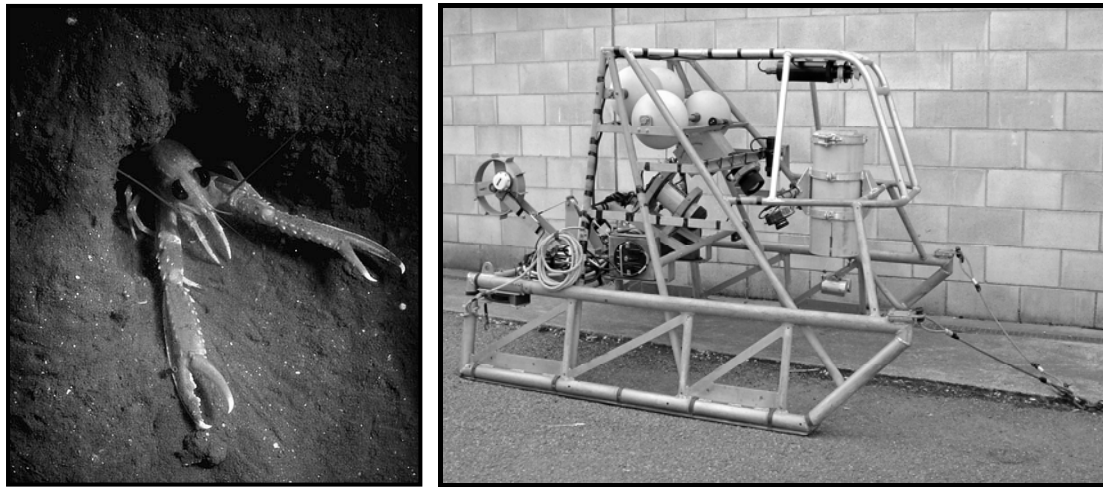

Figure 1. (left) A *Nephrops* emerging from a characteristically shaped burrow.
Figure 2. (right) The UWTV sledge used by FRS for surveys of Scottish *Nephrops* stocks. The mini-Van Veen grab can be seen hanging below the tubular housing to the front of the sledge.

Nephrops live on patches of muddy sediments all around the coast of Scotland. These are subdivided for assessment purposes into relatively discrete "functional units". This study focuses on relationships between *Nephrops* and sediments in two of these functional units, the Fladen, in the central northern North Sea, and the North Minch, lying off the west coast of Scotland between the mainland and the Hebridean islands, to the north of the Isle of Skye. These areas of mud are both essentially glacial in origin (Eisma, 1987), with the muddy sediments to the west of Scotland being generally shallower, of a finer composition and more highly sorted than those from Fladen. This has been attributed to fluvial sorting during holocene periods of low sea level (Ting, 1937).

Afonso-Dias (1998) proposed a 'dome-shaped' relationship between *Nephrops* burrow density and fineness of the sediments in which they live. The explanation for this relationship was linked to the burrowing behaviour of *Nephrops.* In coarse, sandy sediments, population density is low due to the instability of the sediment and the tendency of burrows made in it to collapse. In medium-grained mud sediments, *Nephrops* are able to construct stable burrows and population density peaks. Finally, in very fine grained, soft muds, *Nephrops* are able to excavate extensive burrow complexes, and competition for space once more reduces population density (fig. 4).
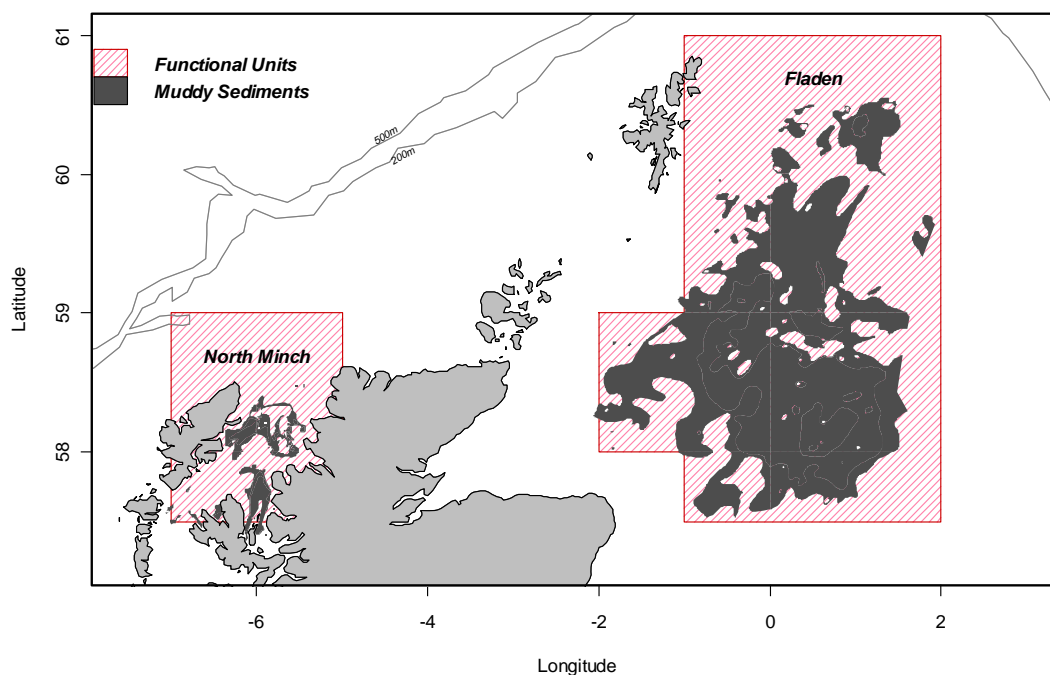
Figure 3. The North Minch and Fladen functional units, and distribution of muddy sediments within these (British Geological Survey, 2002).
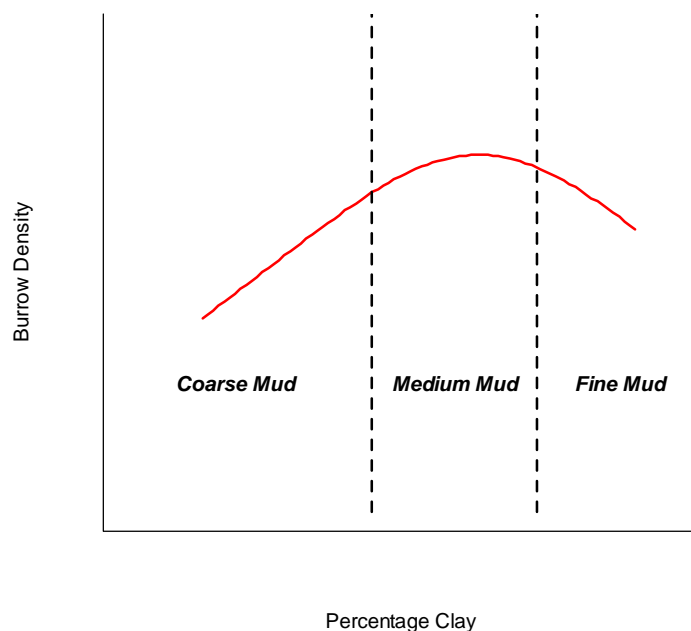

Figure 4. Putative relationship between *Nephrops* burrow density and sediment composition (Afonso-Dias, 1998). Currently, surveys assess the *Nephrops* population within the distribution of Folk sediment types, muddy sand, sandy mud and mud.

Because of this proposed relationship, FRS survey sampling effort has been stratified on the basis of the distribution of Folk sediment types, taken from British

Geological Survey (BGS) charts for the North Minch (fig. 5), and maps of percentage clay for the Fladen generated from samples taken in the early 1990s, taken from Afonso-Dias (1998), with each area divided into four parts to ensure adequate spatial coverage of the survey. This stratification is designed to minimise the within-strata variance and consequently reduce the uncertainty surrounding the estimate of population size when average burrow densities are raised to areas of strata.
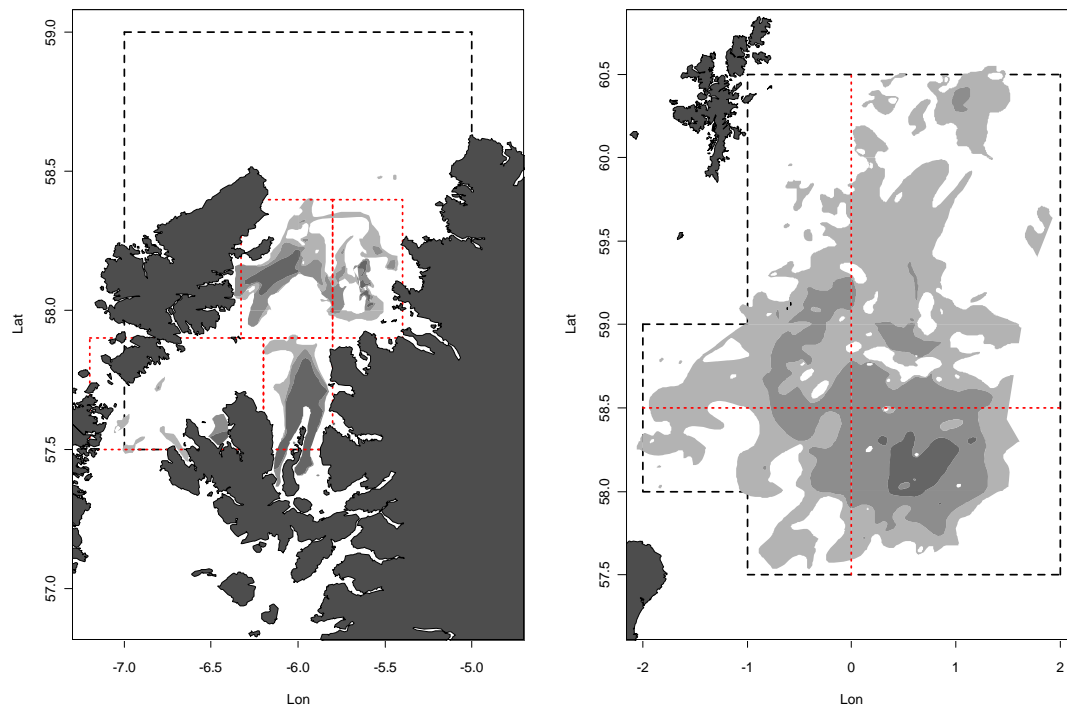
Figure 5. Distribution of Folk sediment types in Fladen (right) and the North Minch (left) - Muddy Sand – light grey, Sandy Mud – medium grey, Mud – dark grey (BGS, 2002). The four sampling subareas within each functional unit are denoted with dashed lines.
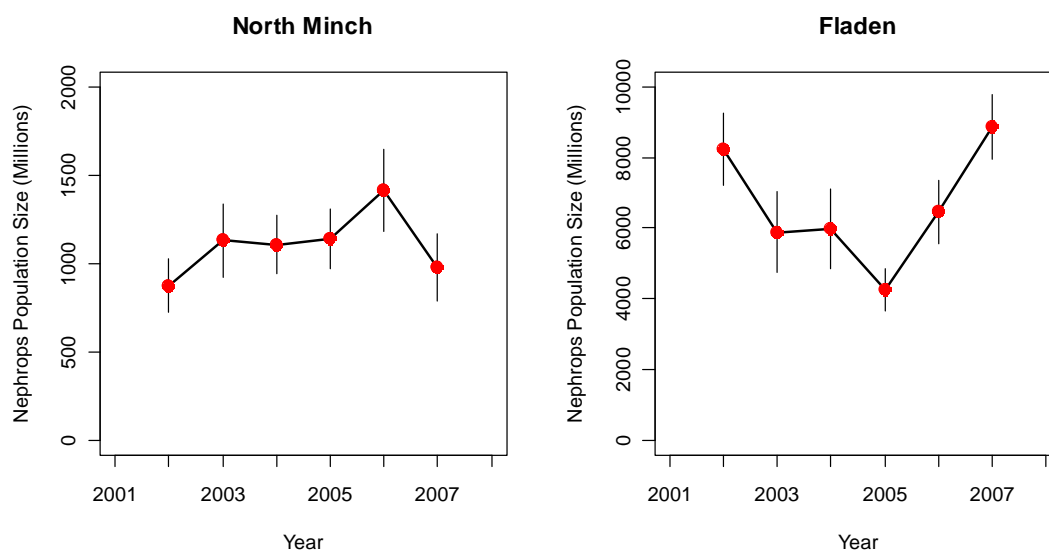
Figure 6. Estimates of *Nephrops* population sizes in the North Minch and Fladen functional units.

There has been considerable fluctuation in the size of the *Nephrops* population in Fladen and, to a lesser extent, the North Minch between 2002 and 2007 (fig. 6) (ICES; 2007b, 2007c). This paper examines the relationship between *Nephrops* burrow density and sediment type in the North Minch and Fladen and examines whether this changes over time, given the changes in the underlying *Nephrops* population size.

Methods

Survey positions in each functional unit are generated randomly within three strata, based on the distribution of mud, sandy mud and muddy sand sediments, taken from BGS sediment maps in the North Minch, or four strata based on the 10%, 40%, 55% and 80% contours of clay composition of the sediment (Afonso-Dias, 1998). Total numbers of stations in each year and functional unit for which valid sediment data and burrow density measurements were obtained are shown in table 1. Data is missing for Fladen (2003) and North Minch (2006) due to a technical problem, it is hoped to reanalyse these samples in the near future.

Year	North Minch	Fladen
2002	38	46
2003	29	-
2004	35	52
2005	40	43
2006	-	58
2007	39	82

Table 1. Numbers of sites for which UWTV density estimates and sediment composition data were obtained, by year and functional unit, 2002-2007.

Burrow density estimates

The UWTV sledge is a custom-built tubular aluminium frame (2.1m x 1.6m x 1.5m) designed so that the attached camera has an uninterrupted oblique view of the sea bed below and to the front of the sledge, in the direction the sledge is moving (Shand & Priestly, 1999). The frame is mounted on two strips of mild steel, approximately 75mm wide, which provide support and act as skids, reducing the depth which the frame sinks into soft sediments. An odometer, mounted at the rear of the sledge records the distance covered, while a rangefinder measures the distance between the camera and the seabed, from which the width of the field of view is calculated. At each survey station the sledge is towed over muddy sediment for ten minutes, covering a distance between 140-200m, depending on visibility. All *Nephrops* burrow openings identified in the field of view are allocated to a burrow complex and the numbers of burrow complexes which cross a defined line on the TV screen are counted. In the case of FRS surveys of Scottish *Nephrops* stocks, this line is the lower edge of the viewed area. Openings are allocated to burrows by experienced counters in a subjective manner, based on the orientation of burrow entrances and distance between openings. Calibration exercises have shown that there is a high degree of similarity in allocation of openings to burrows between counters (ICES, 2007a). Estimates of density at each station are then calculated from the *Nephrops* burrow count for a known viewed area (width of view x length of track).

Sediment Analysis

Sediment samples were collected from the end point of each UWTV deployment, using a stainless steel Eijkelkamp Van Veen grab, sampling an area of 126cm^2, and collecting a volume of approximately 0.5 litres of sediment. This grab is mounted in a plastic housing on the front of the sledge, coupled to a high-torque motor in such a way that on activation, the grab drops around 50cm and embeds in the sediment. The motor is then reversed, closing the grab and retracting it back into the housing to protect the integrity of the sample. On retrieval of the sledge, the grab is removed from its housing, the sediment sample thoroughly mixed and a sub-sample of 20ml placed in a plastic bag and frozen for subsequent particle size analysis.

In the laboratory, samples were freeze dried to remove water and then analysed by a laser diffraction granulometer (Mastersizer 2000, Malvern Instrument, UK). The Mastersizer is a light-scattering based particle sizer comprised of an optical measurement unit and computer. The angle through which light is scattered by a particle is proportional to the particle's size, and this property is used to determine the particle size distributions of the different deposits.

In this paper, we use percentage composition, by volume, of the sediment which has a particle size below 63μm. In terms of Folk sediment types, 10-50% clay is roughly equivalent to muddy sand (mS), 50-90% clay is sandy mud (sM) and 90%+ equates to mud (M). All these sediment types contain less than 1% gravel. The slightly gravelly equivalents to these sediments, which contain 1-5% gravel, are excluded from the assessed area, although Afonso-Dias found *Nephrops* burrows in these sediments (1998).

Data Analysis

Analysis of data was carried out using the R statistical software environment, version 2.7.1 (R Development Core Team, 2008) and the *mgcv* package (Wood, 2006).

Results

Data Exploration

The relationship between expected sediment type, based on BGS sediment maps, as used by *Nephrops* assessments, and the actual sediment type revealed by PSA analysis of sediment samples was investigated (table 2).

North Minch						
	Sediment type revealed by PSA analysis					
Sediment type as mapped by BGS	*Mud*	*Sandy Mud*	*Muddy Sand*	*Rocks*	*Sand*	*% Correct*
Mud	29	14	4	-	-	*61.7*
Sandy Mud	6	32	12	-	-	*64.0*
Muddy Sand	-	13	50	2	-	*76.9*
Fladen						
	Sediment type revealed by PSA analysis					
Sediment type as mapped by BGS	*Mud*	*Sandy Mud*	*Muddy Sand*	*Rocks*	*Sand*	*% Correct*
Mud	-	13	-	-	-	*0.0*
Sandy Mud	-	81	28	-	-	*74.3*
Muddy Sand	-	10	82	-	-	*89.1*

Table 2. Comparison of sediment types as predicted by sampling position and BGS sediment maps with results of PSA analysis of sediment samples.

This revealed that in some cases BGS sediment maps were a poor predictor of the sediment type found at a position - we found the accuracies of the sediments mapped ranged from 0.0 % to 89.1%. The largest discrepancy was in the distribution of mud sediments in Fladen, with no sediments of this composition being found by PSA analysis. This does not pose a problem for FRS surveys in this area, which are stratified on the basis of sediment percentage clay from in-house data, rather than Folk sediment type.

Preliminary investigation revealed that there was no significant differences in the distribution of the muddy (i.e. *Nephrops* suitable) Folk sediment types with depth within or between the two functional units (fig. 7), however there was a trend for coarser sandy sediments to be found at shallower depths than more fine ones in both areas.
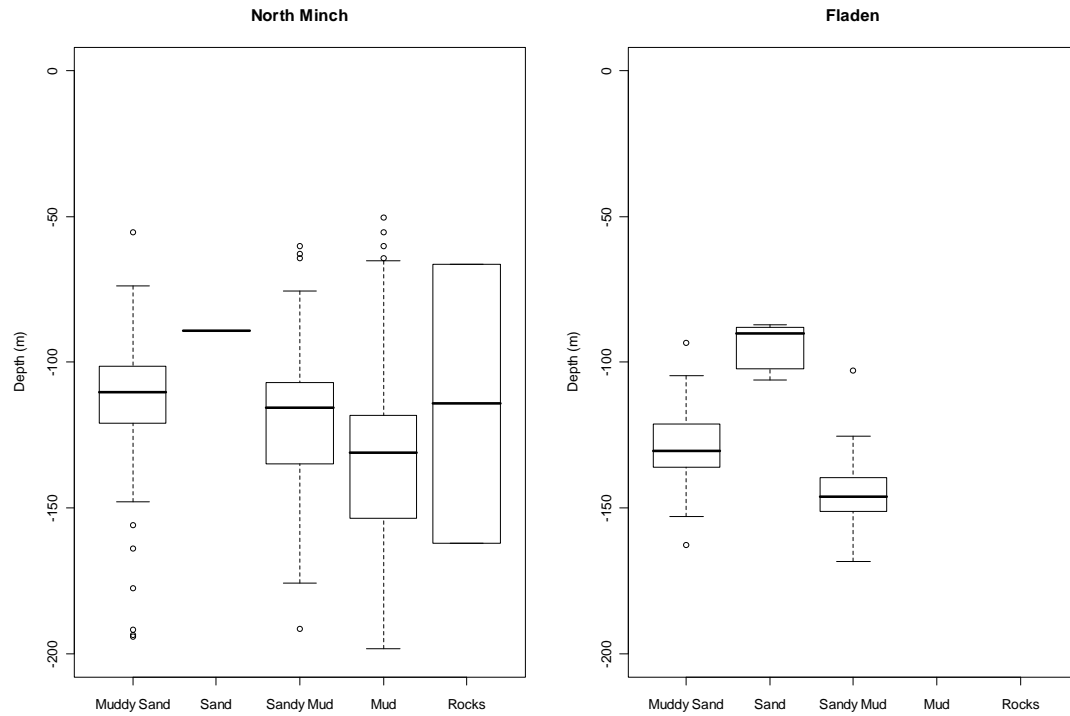
North Minch

Fladen

Figure 7. Boxplots of depth distribution of samples on Folk sediment types in the North Minch and Fladen. Boxes represent interquartile ranges, with horizontal lines displaying the medial value, whiskers represent 95th percentiles of data, with any values outside this range displayed as individual points.
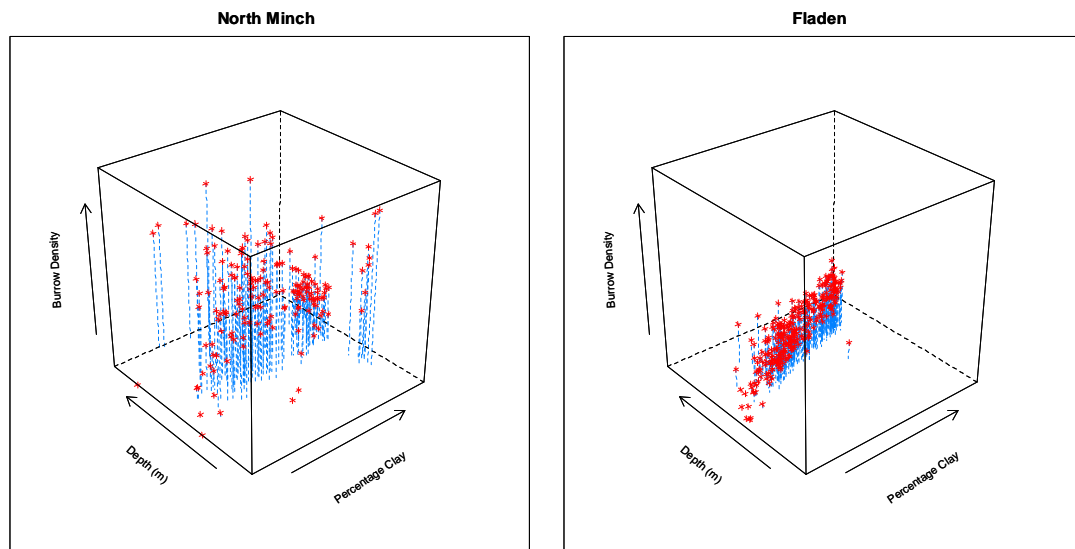
North Minch

Fladen

Figure 8. Plot of burrow density against sediment percentage clay and depth of survey station.

When burrow density was plotted against percentage clay and depth, it emerged that these factors (percentage clay and depth) are strongly correlated in Fladen. There was no evidence of such a relationship in the North Minch data (fig. 8).

Burrow density and percentage silt/clay

Preliminary analysis of the data shows that in both areas *Nephrops* burrows were not found in sediments composed almost entirely of sand (i.e. <10% sediment below 63µm). In the North Minch, *Nephrops* burrows were found in mud composed of 10% to 100% silt and clay. In the Fladen, *Nephrops* burrows were found in mud composed of 10% to 90% silt and clay.
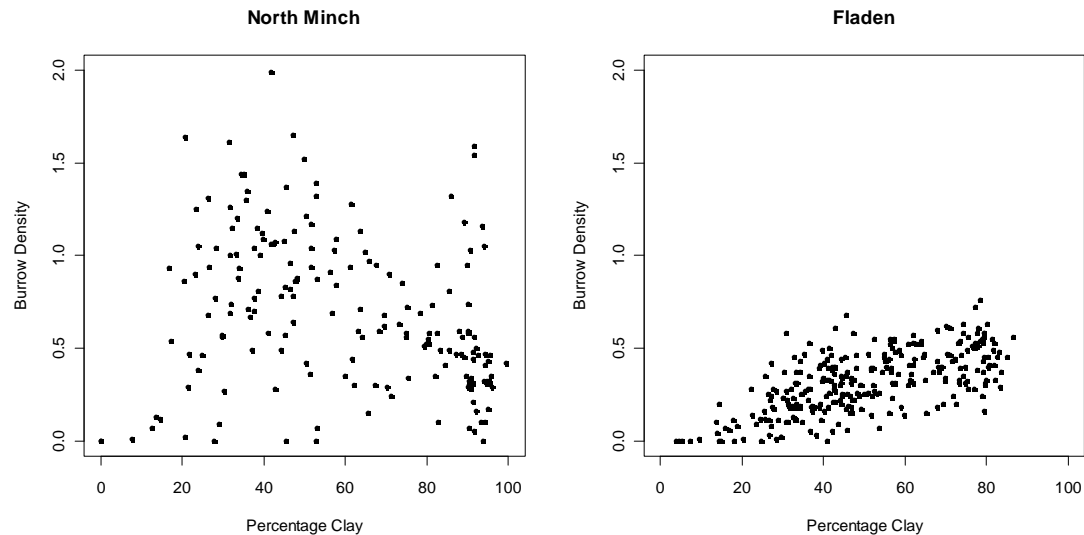

Figure 9 Scatterplots of *Nephrops* burrow density against sediment percentage clay.

Exploration of the relationship between burrow density and sediment composition data revealed evident differences between the two functional units (fig. 9). Samples taken from the North Minch follow the predicted "dome-shaped" relationship more closely than those from the Fladen, which show a more linear relationship. The North Minch data also suggests a bimodal relationship, with some sites which have a high clay percentage in the sediments also having unusually high burrow densities. On examination of the temporal and spatial distribution of these sites, it was found that they were from a number of years, at the south-western part of the North Minch, particularly the area around Uig Bay, where a number of small, isolated patches of suitable sediments exist. As there is evidently a very different relationship between sediment composition and *Nephrops* burrow densities between the two functional units, the data from each was analysed separately.

Whilst it may have been statistically more valid to analyse raw count data and include the viewed area as an offset variable to avoid overweighting of outlying values, the standard survey methodology means that nearly all stations cover an area of 180-200m^2, therefore this source of error has been discounted.

Analysis of Fladen Data

The relationship between sediment percentage clay and *Nephrops* burrow density in the Fladen functional unit was best described by a generalised linear model with a Poisson distribution containing an over-dispersion parameter to allow for increased variability and using the identity link function. As the survey is designed to cover only muddy sediments, the small number of stations which had been carried out on

sandy sediments (percentage clay < 10%), which were generally devoid of *Nephrops*, were excluded from further analysis.

The most satisfactory model was:

Burrow density ~ (Percentage Clay -10) + Year + ε

The results of this are presented in table 3 and figure 10.

	Estimate	Standard Error	Z value	Pr (> |z|)	Significance
Intercept	0.1300	0.024335	5.339	1.98E-07	P < 0.001
% Clay	0.0056	0.000367	15.186	2.00E-16	P < 0.001
2004	-0.0267	0.025432	-1.051	0.294208	P > 0.05
2005	-0.0843	0.025042	-3.367	0.000872	P < 0.001
2006	-0.0990	0.023736	-4.17	4.10E-05	P < 0.001
2007	0.0089	0.024156	0.367	0.714152	P > 0.05

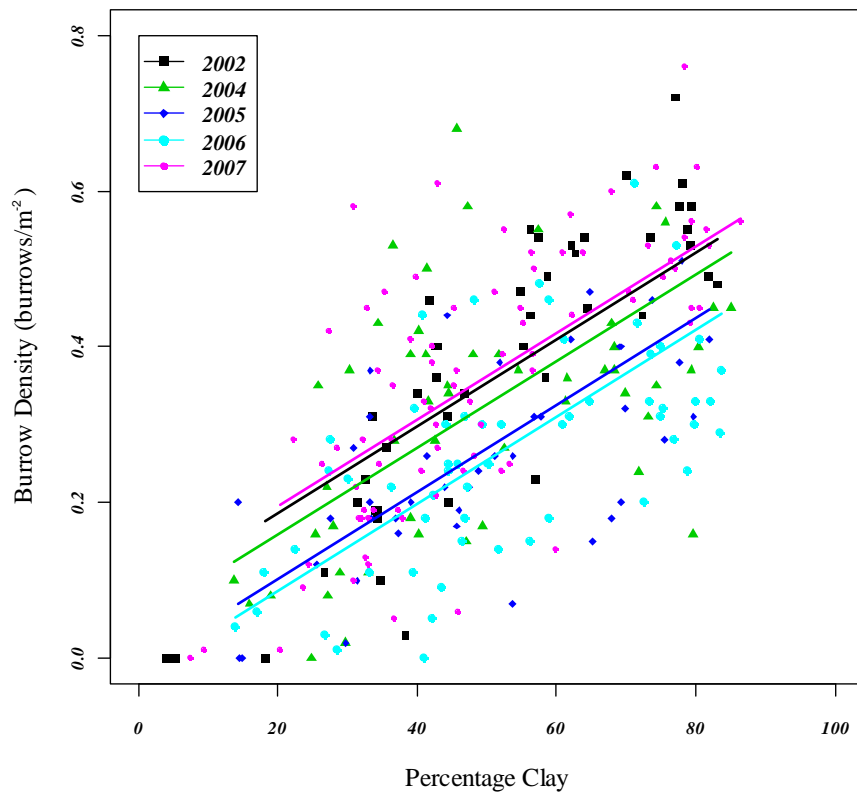Table 3. Coefficients of GLM fitted to Fladen data.

Figure 10. Results of GLM fitted to Fladen data.

Analysis of North Minch Data

To investigate the relationship between burrow density and sediment composition, a generalised additive model (GAM) was used to model trends in burrow density relative to three predictors; year, depth and sediment percentage clay. As the intention was to model the relationship between burrow density and sediment composition within areas of suitable *Nephrops* habitat, nine stations with zero or very low densities (c. 0.01 burrows/m^{-2}) were excluded from further analysis. These comprised 4.9% of all valid stations, and their removal was unlikely to strongly affect results. As all values were positive, a Gamma distribution was used, along with a log link function, to account for variance heterogeneity in the residuals. Through a process of backwards-selection, the best model was:

$$\text{Burrow density} = s(\% \text{ clay}) + s(\text{depth}) + \text{year}$$

The scatterplot smoother used was the cubic spline, *s* (Hamming, 1973). Model fit was assessed using generalised cross validation (GCV) scores. Details of this model are shown in fig. 11 and table 4.
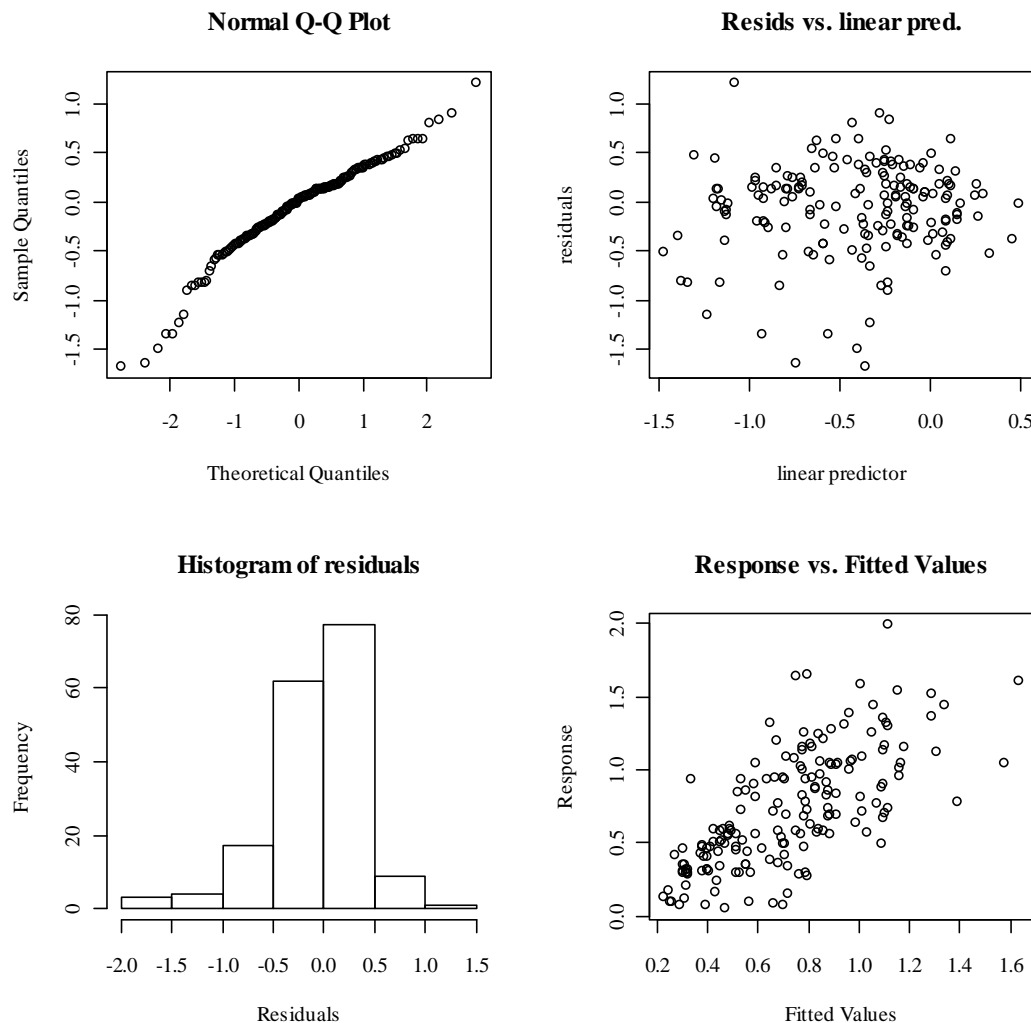

Figure 11. Distribution of residuals, response and fitted values for the North Minch model.

Parametric coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	Significance
Intercept	-0.586	0.08148	-7.191	2.38e-11	$p<0.001$
Year = 2003	0.435	0.12680	3.434	0.000758	$p<0.001$
Year = 2004	0.356	0.11637	3.073	0.002496	$0.001 < p < 0.01$
Year = 2005	0.199	0.11445	1.739	0.083914	$0.05 < p < 0.10$
Year = 2007	-0.074	0.11813	-0.627	0.531882	$p > 0.1$

Approximate significance of smooth terms:

	E.D.F.	Est. rank	F	p-value	Significance
s(Percentage_Clay)	6.537	9	11.927	2.94e-14	$p<0.001$
s(Depth)	2.656	6	5.072	8.66e-05	$p<0.001$

Table 4. Parameters and significance of terms in the North Minch model.
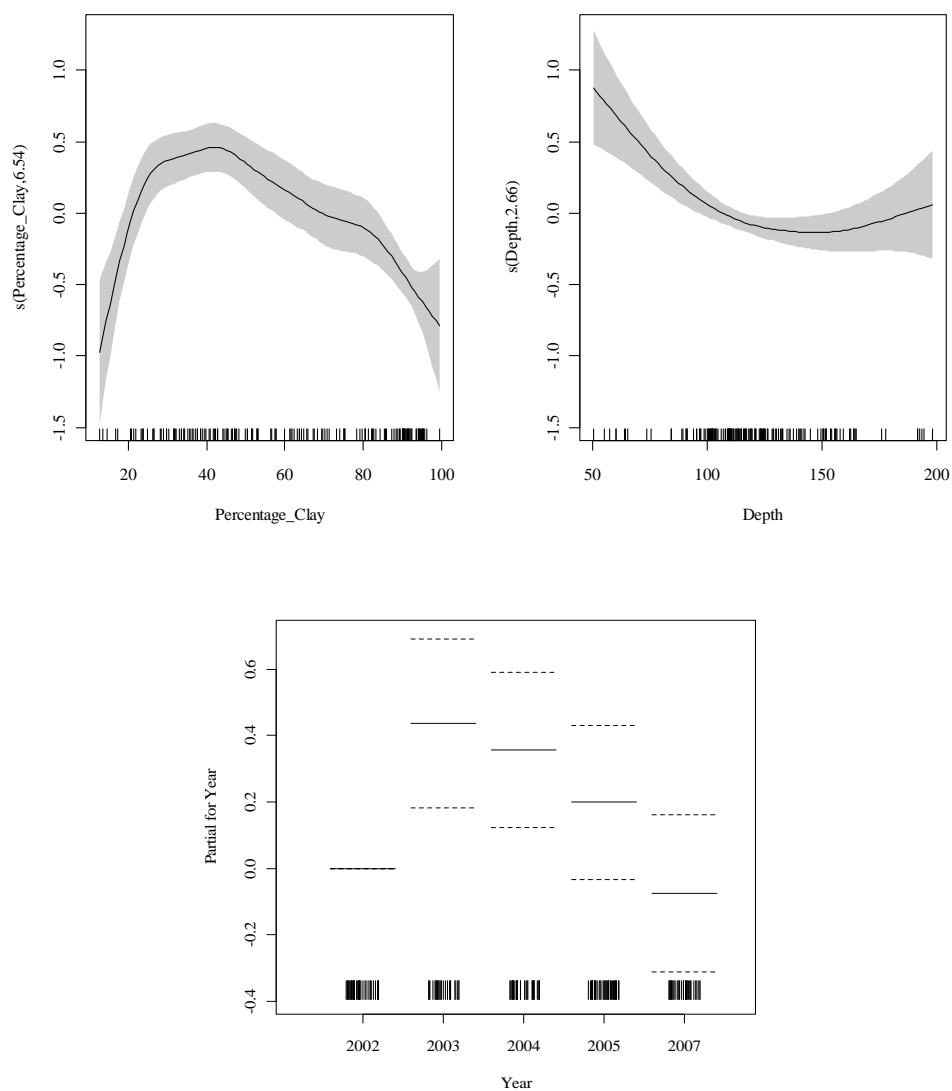

Figure 12. Results of the GAM fitted to North Minch data.

The model fit was not improved by including separate smooths, by year, for percentage clay, depth and both depth and percentage clay. The implications of this model is that the relationships between burrow density and percentage clay and burrow density and depth have remained stable over the period 2002-07, while the density of burrows has increased then decreased over the same period. It is interesting to compare the year-effect plot of figure 12 with the trends in the population shown in figure 6.

Discussion

This work supports the findings of previous researchers in demonstrating a clear relationship between density of *Nephrops* burrows and composition of the sediments in which they live. This relationship appears to remain constant over time, and supports the continued use of sediment composition as a means of stratifying survey design and population assessments of *Nephrops.* There is a strong correlation between the estimated year-effect derived from the North Minch and Fladen models and the assessed population size in each respective functional unit (fig. 13) (ICES, 2007b,c). Year effect could be seen as an index of population size, and used as a means of error-checking the assessment process.
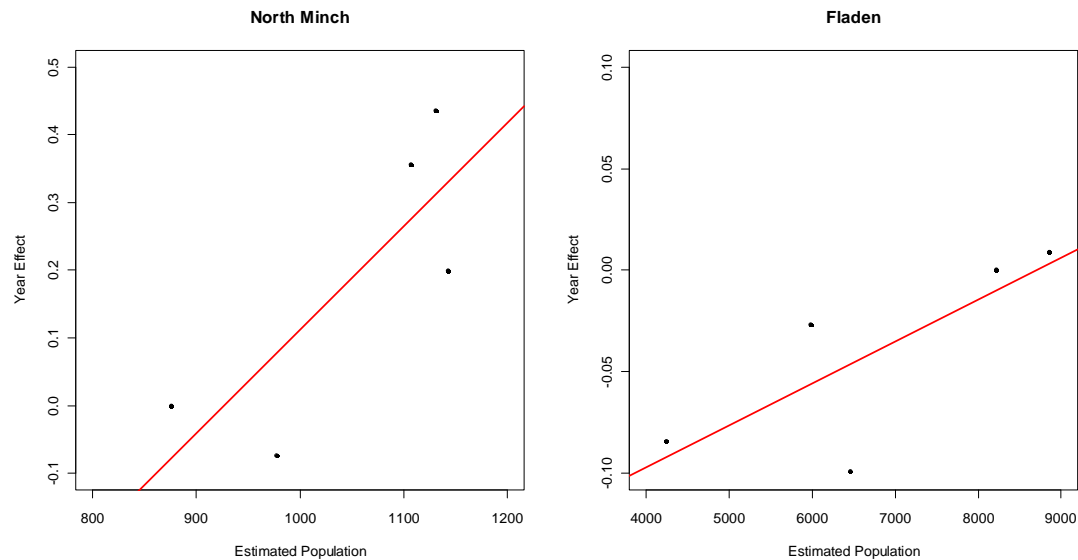

Figure 13. Correlation between assessed population size in Fladen and North Minch functional units and estimated year effect from our models.

The most important implication from this work in terms of assessment of *Nephrops* populations is the inaccuracies found in BGS sediment maps. In Fladen, the "in house" sediment map developed by Afonso-Dias (1998) covers an area of 28,150km^2, as opposed to 30,300km^2 of muddy sediments in this functional unit according to BGS data. Burrow densities raised to this area can be considered as a conservative estimate of the total population size. In the North Minch, the functional unit is divided into four regions for survey purposes, and the number and distribution of UWTV stations within each region is dependent on the area of each sediment type within that region. For assessment purposes, the average burrow density within each region is raised to the total area of all muddy sediments within

that region. Given the expected sediment type was found at between 61-77% of stations, it is likely that survey effort is being misallocated, possibly skewing estimates of average burrow density. Furthermore, eight sediment samples collected at random positions in a large area of slightly gravelly muddy sand (according to BGS maps) in the central North Minch in 2007, which would be considered unsuitable habitat for *Nephrops* and excluded from the assessed area by current practice, were revealed to be sandy mud and muddy sand by PSA (A. Weetman, unpublished data). This suggests that our idea of the extent of suitable *Nephrops* habitat in this functional unit could be considerably different to its actual extent.

The variability of sediment composition throughout *Nephrops* functional units raises further questions about the assessment process. Currently, it is assumed that one burrow complex is inhabited by one *Nephrops*. Although some workers have investigated burrow occupancy of *Nephrops* (Rice & Chapman, 1971), these have focussed on populations at diveable depths and may not be representative of populations at commercially exploited depths or on other sediment types. The stability of burrows is also likely to be dependent on sediment composition, and the time that a burrow survives after its occupying *Nephrops* has died, been caught or moved on is unknown, as is the speed with which burrow entrances are re-opened after being filled in by trawl nets. There is evidently a need for comprehensive sediment sampling coupled with UWTV investigation of the presence or absence of *Nephrops* at sites throughout the North Minch functional unit.

Acknowledgements

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