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Intermediate-Scale Physical Processes and their Influence on the Transport and Food Environment of Fish

THE INFLUENCE OF HYDROGRAPHIC FACTORS ON *NEPHROPS* DISTRIBUTION AND BIOLOGY

N Bailey, C J Chapman, M Afonso-Dias and W Turrell

SOAFD Marine Laboratory
PO Box 101, Victoria Road
Aberdeen, AB9 8DB
Scotland, UK

SUMMARY

The Norway lobster, *Nephrops norvegicus*, is a burrowing, non-migratory crustacean occurring in areas of mud sediment throughout European waters. This sediment is distributed discontinuously resulting in a number of geographically separate populations of *Nephrops* - these support important fisheries which are assessed individually by an ICES Working Group. The larvae of *Nephrops* is planktonic and it is presently unclear for many areas the extent to which larvae remain in and recruit to the area of production. The issue raises questions about the role of hydrographic processes and whether these lead to stock separation through larval retention or whether, for some stocks, dispersal mechanisms operate leading to larval transport .

The timing of the larval phase in Scottish waters generally coincides with the onset of seasonal stratification. Seasonal, density driven gyres associated with isolated areas of weak tidal stirring within certain areas of the continental shelf result in significant circulation patterns independent from other forcing mechanisms such as those arising from wind and tide (Hill, 1993). At the centre of the gyre, circulation is weak leading to accumulation and settlement of fine material onto the seabed. The centre frequently coincides with *Nephrops* grounds such as the Fladen Ground in the North Sea. Larvae released from the muddy areas within gyres are likely to become entrapped in the circulation thus providing a mechanism for larval retention. *Nephrops* populations also exist however, in inshore areas such as the major Firths of Scotland. Here, circulation patterns may also exist but be influenced by mechanisms other than seasonal stratification.

Hydrographic factors may also have more subtle, local effects. Observations have been made of differences in population characteristics within an area of mud supporting *Nephrops*. Variation in density, and size composition have been observed and found to be correlated with the composition of the mud. It is presently unclear if the sediment regime has a direct effect or whether other factors, perhaps hydrographic, operate to

influence coincidentally both se- ɿent composition and Nephrops density (through differential settlement of post larvᴗı juveniles).

Physical processes could also have a temporal effect. Inter-annual variability in the physical-biological interaction may result in variable recruitment. Examination of time series of fishery statistics suggests such variability and hydrographic factors have been implicated in some studies. The paper proposes an integrated examination of larval-adult distributions and physical processes. This may well reveal important implications for assessment procedures and for management policy which presently operates on a rather large scale, aggregating stocks according to ICES divisions.

INTRODUCTION

Nephrops is presently the most important shellfish species in Scotland with landings of around 20,000 tonnes. In terms of first sale value the species ranks second behind haddock and supports a well developed processing industry. Important *Nephrops* fisheries also exist in other European countries and several stocks are prosecuted by more than one country. Owing to the multinational dimension, assessment advice is provided by a Working Group of ICES (eg Anon, 1995) in support of which an ICES Study Group coordinates basic research (eg Anon, 1994). As a result of the distribution of *Nephrops* and variations in biological and fishery characteristics, the Working Group uses groupings of statistical squares to define numerous stocks or "Functional Units" (FUs) (Anon, 1990), which are assessed separately. For management purposes at EU level, however, FUs are aggregated to ICES sub division level, an approach which may compromise the long term viability of individual FUs. There are clearly practical problems in managing small units, but in addition, the lack of knowledge on the extent to which FUs constitute isolated and "separate" stocks, hampers discussion about more acceptable aggregations.

Although there has been considerable research on *Nephrops* (see Farmer, 1975; Chapman, 1980; Sarda, 1995 for reviews), studies of the effects of environmental parameters are rather few. There is a particular need for greater understanding of the role that physical factors play in influencing *Nephrops* distribution and stock dynamics.

This paper discusses a number of ways in which hydrographic processes are likely to have a bearing on the population biology of *Nephrops*. The paper concentrates on three aspects of possible hydrographic mediation of *Nephrops* biology. Much of the discussion is speculative and inference is drawn from existing, rather limited data. Although frequent reference is made to *Nephrops* populations on the continental shelf around the UK, the principles discussed may equally apply elsewhere. It is hoped that this paper will generate interest in a coordinated effort to further investigate hypotheses concerning the relationship between physical processes and the recruitment and population dynamics of *Nephrops*.

1. Hydrographic Factors and Larval Retention/Stock Separation

Adult *Nephrops* live on soft mud bottoms composed of varying proportions of clay, silt and sand; it is rare to find them in sediment with a combined silt clay fraction below 10% (although *Nephrops* are reported from levels as low as 4% in the Irish Sea (Tully and Hillis, 1995)). Superficial sediments of this type originate principally from Pleistocene glacial debris which have been reworked to a lesser or greater extent (Farrow, 1983). The present discontinuous distribution, mapped recently by the British Geological Survey (eg BGS 1987), has resulted from an interplay of topographic, bathymetric and hydrographic factors. In general, fine sediments occur in low energy environments where prevailing conditions result in processes of deposition.

The distribution around Scotland of areas of sediment and the corresponding *Nephrops* grounds are shown in Figure 1. It is unclear to what extent the resultant discrete populations of adult *Nephrops* are indicative of stock separation to the point where each stock is totally isolated. Tagging studies (Chapman, 1982) indicate that large scale movements of postlarval, benthic stages do not take place. On the other hand, limited data from allozyme analysis (employing electrophoretic techniques) suggest that there is little genetic difference between populations (Atkinson, pers. com.) - this implies some transfer between populations.

Opportunities for transfer could take place during the planktonic larval phase of *Nephrops* which lasts from 3-8 weeks (depending on temperature) and consists of five stages (one prezoeal, three zoeal and one post-larval pelagic phase, (Farmer, 1975; Smith, 1987). Following hatching of eggs from the underside of the female abdomen during March to July, larvae move up into the water column to about 20-30 m below the surface until subsequent metamorphosis and settlement. The question is whether, during this phase, larval advection takes place or whether mechanisms occur to retain larvae in the area of production. Existing information on *Nephrops* larval distributions and prevailing hydrographic conditions provide examples of both processes.

Observations of the distribution and duration of various larval stages of *Nephrops*, led Jorgensen (1925) to conclude that some larvae produced at the Firth of Forth Ground drifted south eastward along the Northumberland coast to the Farn Deeps. Observations of larvae along a wide stretch of the same north east coast were also made by Garrod and Harding (1980) although no drift was proposed. Examination of plankton samples collected over a wide area around Scotland revealed that *Nephrops* larvae were present in the water column above *Nephrops* grounds and also in areas unsuitable for adult *Nephrops* (Fraser, 1965). A notable example of this was to the north west of Scotland where it was speculated that larval production from the North Minch was being transported to the Noup ground west of Orkney. Hydrographic observations made in this area using drift bottles (Craig, 1959) and also those made during the monitoring of Caesium-137 (Jeffries, Preston and Steele, 1973) indicate a northerly moving residual current through the North Minch. Some of this coastal water moves in a north easterly direction out of the Minch and to the west of Orkney - passing at this time over the Noup ground. There is also evidence that, in the event of encountering an unsuitable sedimentary regime, *Nephrops* can delay moulting from the third zoeal stage (Smith, 1987) giving the opportunity for larvae to drift to more suitable areas prior to settlement.

Evidence for potential larval retention mechanisms arises from recent observations associated with seasonal stratification - a phenomena with which the larval phase of *Nephrops* often coincides. It has been demonstrated that seasonal, density driven gyres within certain areas on the European continental shelf result in significant organised coherent circulation patterns, independent from other forcing mechanisms such as those arising from wind and tide.

During the summer months, surface heating over isolated areas of weak tidal stirring, such as topographic depressions, can lead to the formation of "domes" of cold dense bottom water trapped beneath the thermocline. The water dome is isolated horizontally from adjacent water by bottom fronts which drive a cyclonic, near surface circulation around the dome (Hill, 1993). At the centre of the gyre, circulation is weak, often resulting in the accumulation and settling of fine sediments on the sea bed. These areas frequently coincide with *Nephrops* grounds (see above). *Nephrops* larvae released from the muddy areas within gyres are likely to become entrapped within their circulation system and hence the gyre is one possible mechanism for larval retention.

A particularly good example is the gyre observed within the western Irish Sea (Hill, 1993; Hill *et al.*, 1994). This gyre has been demonstrated by tracking drifter buoys and by intensive hydrographic surveys. Modelling has revealed the extent of the gyre and confirmed its dynamics and there has been recent speculation that it provides a physical retention mechanism for *Nephrops* norvegicus larvae (Brown *et al.*, 1995).

Gyre systems have also been identified in other areas supporting *Nephrops* stocks. A seasonal eddy system has been observed at the Fladen Ground (Svendsen *et al.*, 1991; Turrell, 1992; Turrell *et al.*, 1992). A cold, dense lens of bottom water remains trapped beneath the seasonal thermocline, and remains there throughout the summer (Fig. 2). Drifter tracks and Acoustic Doppler Current Profiler (ADCP) measurements have partly confirmed the existence of a gyre, although its northerly extent is not yet delineated. Simple two layer models suggested that the observed currents resulted from the bottom front generated by the trapped cold water (Svendsen *et al.*, 1991). The seasonal circulation of the larger northern North Sea basin may itself be the result of the formation of the cold, dense bottom water (Turrell, 1992). The Fair Isle and Dooley currents which circulate around its perimeter may themselves be partly density driven during the summer months. However, unlike the Irish Sea, the effects of wind and tidal rectification may be of greater importance in this system (Turrell *et al.*, 1990, 1992). An additional complicating factor is that the seasonal pycnocline is enhanced by the westward spread of Norwegian coastal water above the thermocline (Sætre *et al.*, 1988).

Gyres have been identified in other areas in the North Sea, including the German Bight and the Outer Silver Pit (Hill, 1993; James, 1989; Dippner, 1993). The latter, together with the Botney Gut, constitutes an important *Nephrops* Ground (Anon, 1995). Elsewhere, a gyre system in the Bay of Biscay has been studied (Le Fevre, 1986) and similar mechanisms are thought to exist in the Celtic Sea and Porcupine Bank; each of these areas supports extensive *Nephrops* fisheries.

Seasonal gyre like circulation patterns occur over some inshore coastal *Nephrops* grounds, though their production may involve different physical mechanisms. Recent measurements in the East Shetland Basin suggest the presence of a cyclonic gyre between Pobie Bank and the edge of the Norwegian Trench (Turrell *et al.*, in press), and recent drogue releases in the southern Minch area reveal that a cyclonic confined gyre exists there, at least during the spring (A E Hill, pers. com.).

Other potential retention mechanisms exist in inshore areas, including gyres controlled not by seasonal stratification but by additional mechanisms. For example, a cyclonic circulation around the Firth of Forth is generated partly by coastal flows driven by freshwater inputs in the area. However, the result on sedimentation at the centre of the gyre, and on larval retention may well be similar to that within the seasonal gyres.

The discussion has thus far centred on *Nephrops* populations in northwest European waters where a relatively large area of continental shelf is present. Stocks to the south of Europe frequently occur in areas where the shelf is more restricted. For example, off the coast of Spain and Portugal *Nephrops* distribution appears to be associated with the shelf edge region, where mud sediments occurring at suitable depths are generally deposited in a relatively narrow band along the coast. It remains unclear just how continuous the distribution of mud is and to what extent *Nephrops* stocks are isolated. A paucity of hydrographic data means that the prevailing physical processes and their effect on larval dispersion are also poorly understood. It is possible, however, to speculate that a retention mechanism may be active in the vicinity of the Algarve *Nephrops* population involving seasonal upwelling and possibly the outflow/inflow system of the Mediterranean Sea.

2. Hydrographic Factors and Stock Variability

A consistent feature of *Nephrops* populations is that density and size composition vary markedly both between and within grounds (often over quite short distances) (eg Chapman and Bailey, 1987; Hillis, 1988). Variations in fishing effort may partly be responsible (Tully and Hillis, 1995) but since differences were observed in some areas before the presence of significant fisheries (Thomas, 1965) other factors also appear to be important. Collection of sediment composition data in a number of areas has revealed relationships between *Nephrops* density, mean size and sediment grain size. Data from some areas (eg west coast Scotland, Chapman and Bailey, 1987) suggest an inverse relationship between *Nephrops* mean size and grain size and a direct relationship between density and grain size - in other areas the opposite relationships were observed (eg Irish Sea, Hillis, 1988). The contradictory results were explained by the fact that rather different ranges of particle size pertained in the different areas. A plot combining data from all areas revealed a non- linear relationship with peak abundance and smallest *Nephrops* sizes at intermediate particle sizes (Anon, 1988). Recent analysis of *Nephrops* burrow abundance information from underwater television surveys conducted in a number of areas around Scotland has confirmed that the non linear feature is evident within a single ground. Figure 3 illustrates abundance against a fairly wide range of particle size in both the Firth of Forth and Fladen Ground. In both areas a "dome shaped" plot is evident although it is interesting that the position of greatest abundance on these grounds appears to differ. Additional factors, for example organic carbon content, may also affect the relationship.

There has been considerable speculation about possible mechanisms underlying the observed relationships (Chapman and Bailey, 1987). Density dependent growth has been suggested as an explanation for the occurrence together of small size and high density but it is more difficult to account for the variation in density with different sediment. Certain features of the sediment or benthic regime may control abundance through the provision of optimal conditions at some intermediate grain size- for example survival may be favoured by rather specific conditions which post-larval *Nephrops* actively select. Alternatively, settlement may be more general but different factors subsequently could operate at the extremes of very coarse and very soft muds to limit population numbers - for example unsuitable sediment for burrow construction and competition with other species.

The relationship may of course be entirely coincidental, with sediment distribution and *Nephrops* abundance under the control of, for example, local hydrographic conditions. In the same way that large scale sediment distribution (see section 1) is under the control of physical factors, so too is the finer scale distribution of different grades of soft mud sediments within each *Nephrops* ground. The distribution of post larval *Nephrops* prior to the time of settlement may also be controlled by these factors, although to account for the greatest densities of *Nephrops* on intermediate grain sizes, the process leading to the concentration of pre-settlement *Nephrops* may not necessarily equate exactly with that leading to the concentration and settling out of the finest sediments. On the other hand, a rather similar process could be proposed if there was a combination of hydrographic and benthic factors affecting the settlement and survival of *Nephrops*. For example, hydrographic factors could concentrate and facilitate settlement of *Nephrops* in the same way as the finest sediment particles but, subsequently, benthic conditions in the finest muds could lead to reductions in abundance.

3. Hydrographic Factors and Interannual Variability in Recruitment

In addition to influencing spatial distribution of *Nephrops*, physical factors may also have a bearing on temporal variability and could operate in a number of ways.

If the offshore gyres, discussed above, are controlled by the onset of seasonal stratification, then their presence will be transient and the timing of the retention mechanism controlled by external factors such as the weather. Interannual variability in recruitment might then be introduced by a match/ mismatch mechanism if the gyre circulation is not established in time for the release of larvae. Furthermore, irregularity in seasonal gyre establishment in offshore areas compared to the gyres in inshore areas (under the control of more regular and predictable processes) could lead to differences in the trends in recruitment and fishery landings between these areas.

Interannual variability in physical factors of the marine environment brought about by climatic factors could lead to variable recruitment through changes in mortality rates of early life stages. For example, differences in sea temperature or the extent of wind induced wave action might affect survival of larval *Nephrops* either directly or by regulating food supply. An investigation by Chapman (1984) of the correlation between sea surface temperature and *Nephrops* "landings per unit effort" (LPUE) suggested that there was a strong correlation between overall LPUE (all Scotland) and temperatures 3-6 years previously. *Nephrops* appears to recruit to the fishery at an age of 3-6.

Recent examination by one of us (MAD) of long term trends in *Nephrops* LPUE disaggregated to the ICES statistical square level has suggested similarities over quite wide geographic areas. Figure 4 illustrates monthly LPUE values from 1974 to 1994 for selected squares in the North and South Minches (A-E), Clyde (F), Fladen Ground (G), Moray Firth (H) and Firth of Forth (I). The trend lines are fitted by a locally weighted regression approach (Cleveland, 1981) which imposes no particular model. Rather consistent peaks in LPUE (particularly late 1970s , mid 1980s) are evident throughout a number of the more northerly squares. The pattern is similar on both the west coast and in the North Sea suggesting a more widespread effect perhaps under climatic control. It is noticeable, however, that the more enclosed areas of the Clyde and Firth of Forth do not exhibit the same patterns so the explanation is probably not a simple one.

CONCLUSIONS AND PROPOSAL

A number of ways in which physical factors could affect recruitment and population dynamics of *Nephrops* have been discussed under three main headings; the discussions have a bearing on the assessment and management of *Nephrops* stocks.

1. An important component of the management of commercially important stocks of *Nephrops*, is an understanding of the interrelationships between discrete adult populations. Given the circumstantial evidence for larval dispersion in some areas and retention in others, there is a clear need for a coordinated study better to understand these processes, to identify potentially vulnerable stocks which are isolated and to describe and quantify relationships between different grounds.

2. Fisheries models used in the assessment of *Nephrops* rely on the general assumption that fishing and the removal of *Nephrops* through fishing mortality generate measurable effects in terms of abundance and size composition. The above discussion illustrates that owing to environmental effects the situation is more complex and this may require to be taken into account in the choice of population models used in assessments. Existing evidence suggests there is a link between abundance and sediment but this may be coincidental and an understanding of the role of hydrographic factors is urgently required.

3. There appears to be evidence of variability in abundance over time and further research may reveal whether this is caused by physical factors operating in a more general way and perhaps under climatic control. If so this may offer a potentially powerful tool to assist in the forecasting of future recruitment and stock condition of *Nephrops*.

Throughout the paper, the potential role of hydrographic factors is repeatedly discussed and uncertainty remains in a number of areas. A coordinated study of the importance of these physical processes on the population dynamics of *Nephrops* is timely. The authors are presently preparing proposals for such a study which will deal with the three main issues discussed in this paper. It is hoped that a coordinated effort covering a number of *Nephrops* grounds in the north east Atlantic will be possible. Anybody interested in becoming involved in this study should contact the authors at the address above.

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Distribution of Nephrops around Scotland

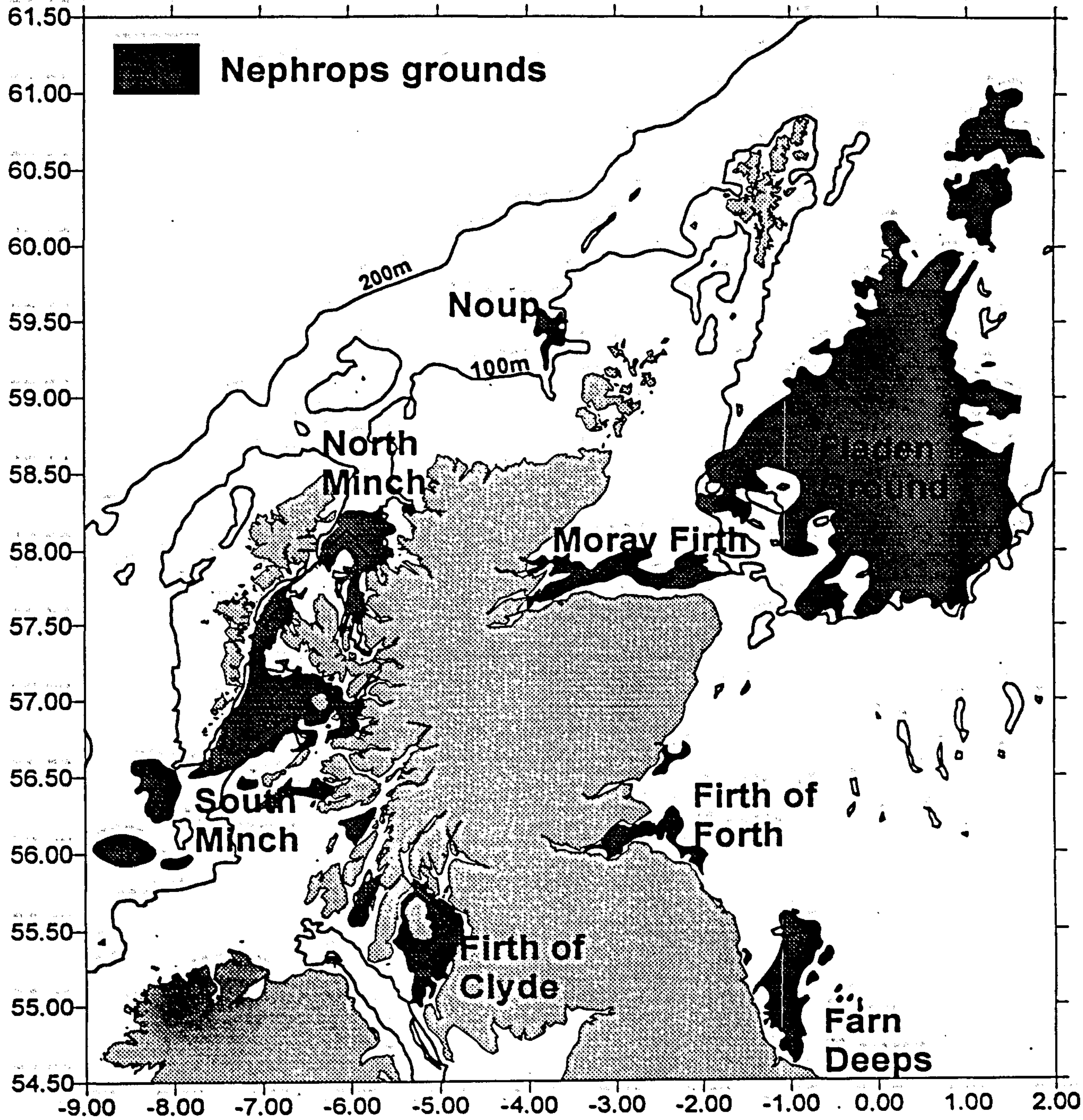

Figure 1

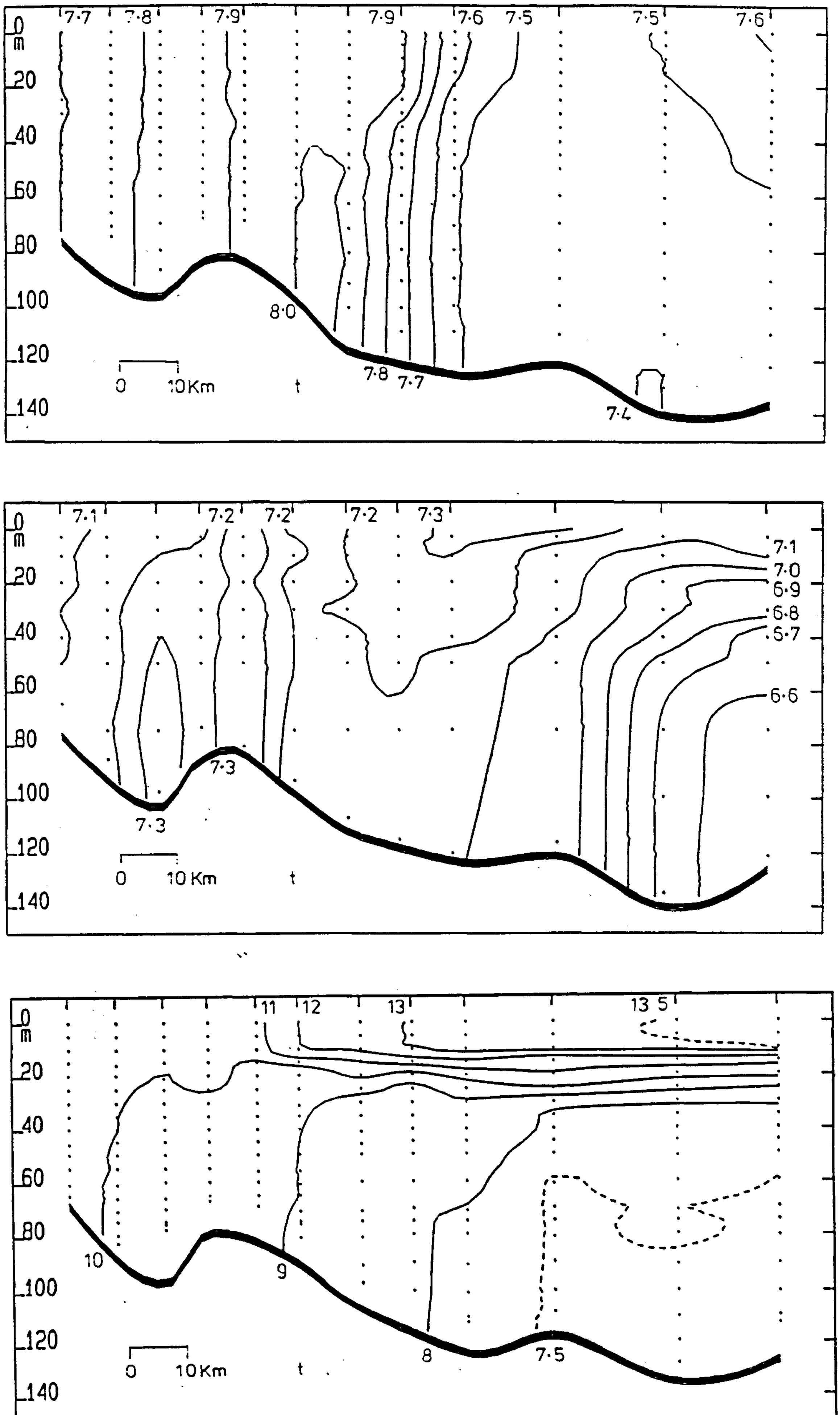
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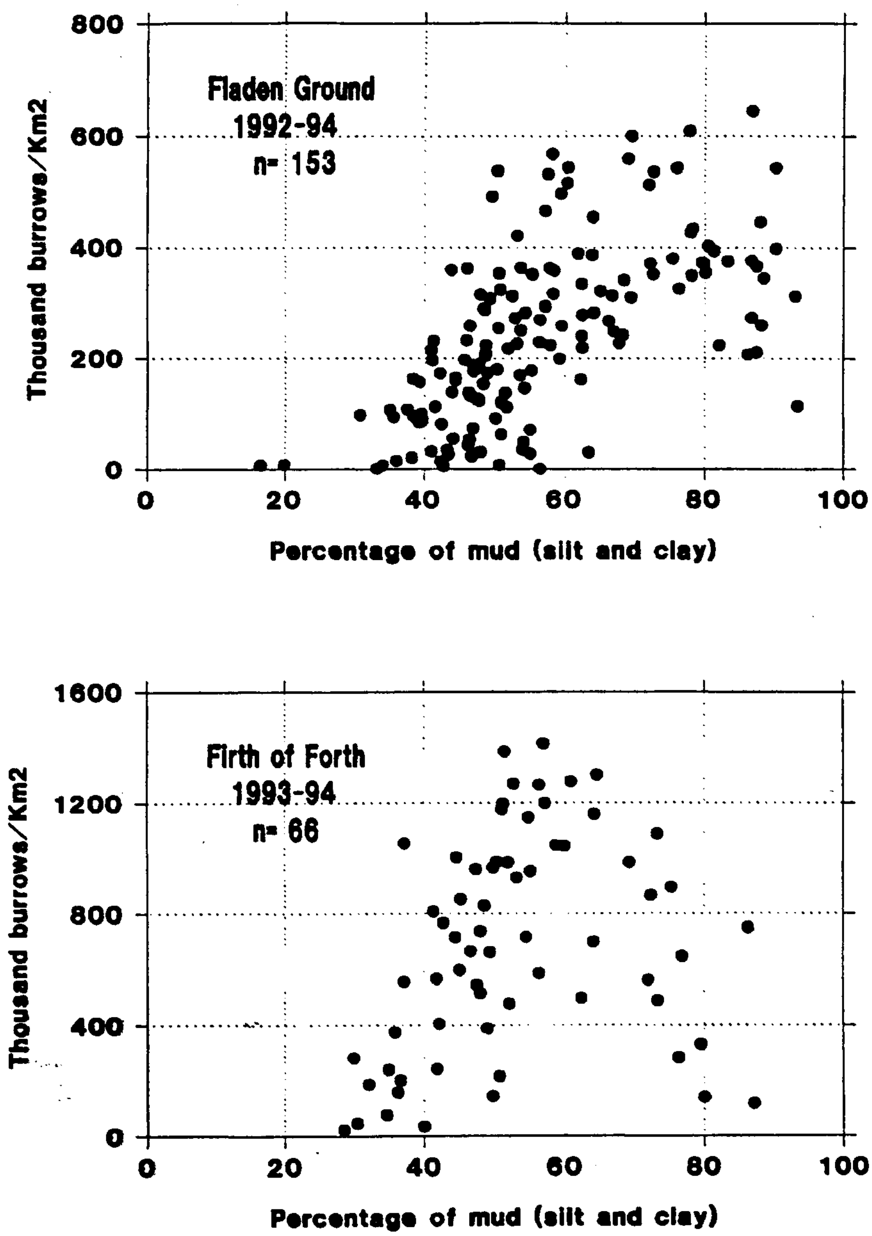
Figure 2



Fladen Ground
1992-94
n= 153
Thousand burrows/Km2
Percentage of mud (silt and clay)
Firth of Forth
1993-94
n= 66
Thousand burrows/Km2
Percentage of mud (silt and clay)

Figure 3

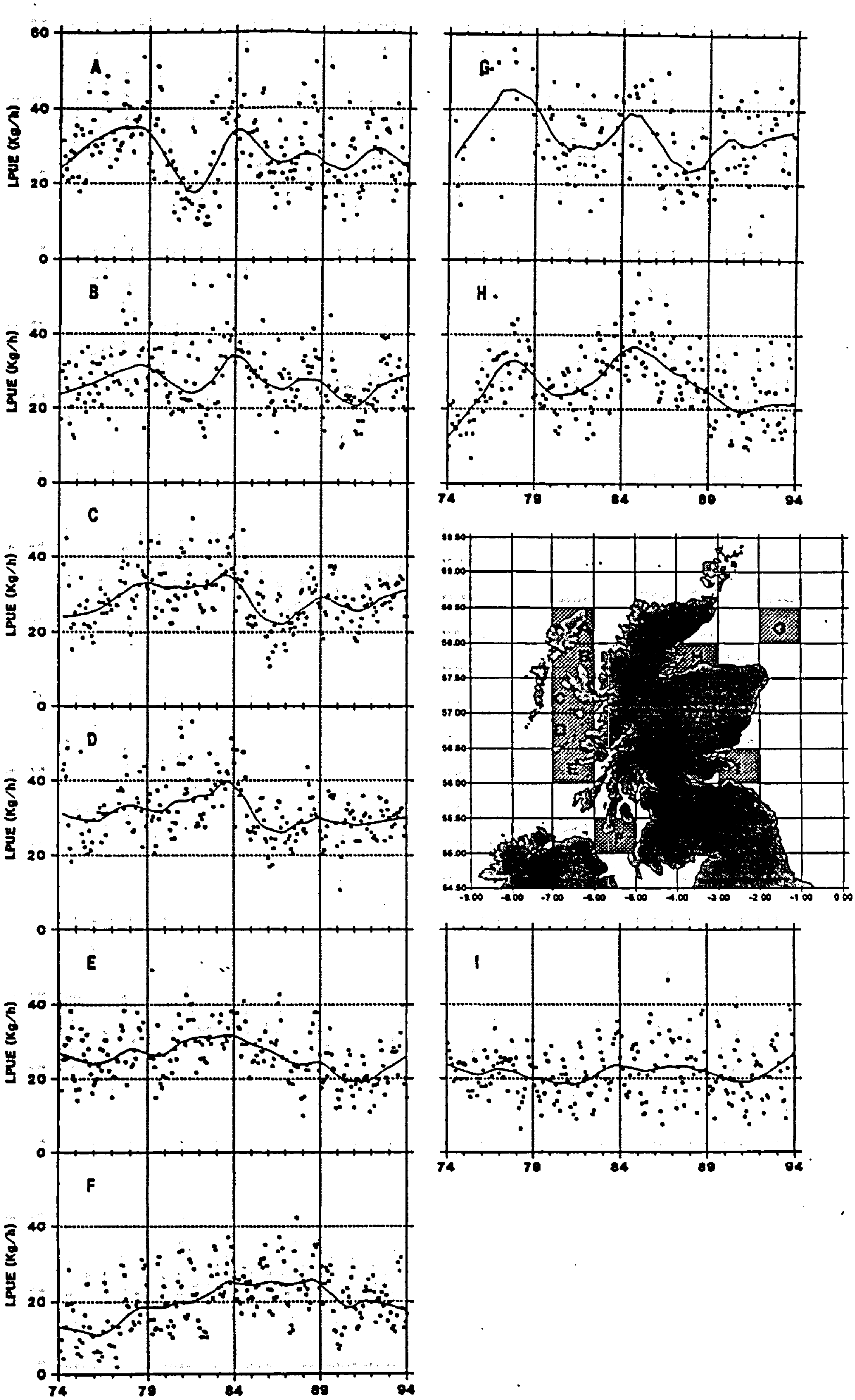


Figure 4