ICES CM 2005/O:02

Environmentally caused variability in the fluctuations of the European lobster, Homarus gammarus, fishery in Scottish coasts

[1,2]Lizárraga-Cubedo, H.A., [1]Tuck, I., [1]Bailey, N., [2]Pierce, G.J., [3]Zuur, A. F. and [1]Bova, D.

halizarraga@yahoo.com; I.Tuck@marlab.ac.uk

Address: [1]FRS Marine Laboratory, Aberdeen. PO Box 101 Victoria Road, Aberdeen AB11 9DB, UK. Tel. +44 (0)1224 295693, Fax +44 (0)1224 295511; [2]School of Biological Sciences, University of Aberdeen. Tillydrone Ave. ABERDEEN AB24 2TZ, UK; [3]Highland Statistics Ltd. 6 Laverock road, AB41 6FN Newburgh, United Kingdom Phone: +44 (0)1358 788177

Abstract

Variability in the fluctuations of two Scottish lobster populations, the Hebrides and Southeast, was investigated from available long data series of fishery and environmental variables. In a multivariate context, relationships between selected environmental variables and the fishery data were studied at different spatial and temporal (annual, spring and autumn) scales and from individual and overall sampled fleet. Multivariate techniques such as cross correlation function (CCF), principal components analysis (PCA) and redundancy analysis (RDA) confirmed that the capture of lobsters was strongly influenced by sea surface temperature (SST), wind speed (WS), and sea level pressure (SLP) throughout the year, and this dependence affected the duration of the fishery. In the Hebrides, the total variation (42%) of the interaction fishery-environmental variables for the spring and autumn fisheries could be attributed to the environmental variables in an 89%. For the Southeast, the spring fishery was more affected by changes in the environment, with a total variation of 34%, from which 85% could be explained by the environmental variables tested, than the autumn fishery where density-dependent processes were more important. From the analyses, it is deduced that the Hebrides lobster population is strongly influenced by density-independence processes at large and small spatial scales. Density-dependent processes at all spatial scales mainly drive the Southeast lobster population and environmental variables are important in spring.

Keywords: Homarus gammarus fisheries, redundancy analysis, environmental factors.

Introduction

Fluctuations in lobster abundance may occur as a consequence of the combination of environmental and fishery-related processes. This study attempts to account for sources of variation and highlight the most influential factors that might allow fishery managers to acquire the best tools for achieving a sustainable fishery. The mechanisms involved in any fishery have implications for the whole population under exploitation. For example, the success of trap-based fisheries strongly depends on the behaviour of the target species, trap efficiency and oceanographic conditions of the region (Miller, 1990; Addison, 1995; Fogarty and Addison, 1997; Tremblay and Smith, 2001). In homarid lobster fisheries, temperature is an important factor influencing lobster behaviour and availability to traps over the short term (McCleese and Wildner, 1958). For the American lobster fishery in Canadian waters, sea surface temperature is strongly correlated with long term catch rates (more than 50 years of data) at the largest spatial scales, with lags of 0-3 yrs. In addition, wind-driven temperature variability can directly affect catch rates in offshore localities (Comeau and Drinkwater, 1997; Drinkwater 1994).

Wind speed and direction is important for the transport of larvae directly affecting recruitment processes in pelagic (Borges et al, 2003) and benthic (Wegner et al, 2003) fish in eastern Atlantic waters. Investigation on the importance of wind on fluctuations of crustacean populations is desired. Furthermore, comparative studies of this environmental variable and catch rates of the European lobster, Homarus gammarus, in Scottish waters are lacking. For Scottish lobster fisheries, Shelton et al. (1978) demonstrated differences between spring and autumn in the Southeast of Scotland, related to moulting and recruitment, but the effects of this process on fisheries may differ between areas at different geographic scales. Differences in lobster size at maturity and fecundity have been identified between the Hebrides and Southeast (Lizárraga-Cubedo et al., 2003), and it is suggested such discrepancies may occur as a response to the local conditions and fishing strategies. From this information some questions can be addressed; are wind and sea temperature the most important environmental factors affecting the fluctuations of lobster abundance, if so how do they contribute to the total variation in catch rates, and are there any temporal and spatial differences? The environmental influences on the fishery will be investigated by addressing these questions.

It is acknowledged that catches alone may not necessarily reflect lobster abundance at the intermediate and small spatial scales (Koeller, 1999). Therefore, the relative abundance index (CPUE) may not be truly representative of the abundance of the population under exploitation (Addison, 1995; 1997; Fogarty and Addison, 1997; Jury et al, 2001) suggesting that more work on this field should be done. This leads us to inspect how all the fishery components respond to environmental conditions and also what elements of the fishery are more relevant for stock assessment purposes.

In a fishery context, knowledge of the pre-recruit and recruit components is of great importance. These components are seldom compared with environmental conditions hence it would be important to assess: 1) how the pre-recruit (undersized lobsters) and post-recruit (legal size lobsters) components relate to fishing effort and environmental elements at different temporal and spatial scales; and 2) how do these components relate to catch rates.

Individual series of fishery and environmental data may not necessarily present significant correlation owing to time lags, which may discourage further statistical analysis. However, a more careful analysis of long time series or short time series at different spatial scales may reveal the underlying relationships.

In this paper, we explore the relationships between the elements involved in the European lobster fishery (fishing effort, catch, and catch rates of undersized and legal size lobsters) and environmental data for two Scottish stocks, the Hebrides and Southeast, between 1983-1997. We also analyse the relationships between variables at smaller (data from individual vessel) and larger (overall sampled fleet) spatial scales (Table 1). The auto-correlation function (ACF) and cross-correlation function (CCF) are used to analyse individual data series and to explore relationships between two pairs of variables, respectively. In addition, two dimension reduction techniques, principal components analysis (PCA) and redundancy analysis (RDA), are applied to investigate the data in a multivariate context. As well as analyses on an annual basis, the data were partitioned into two seasonal (spring and autumn) components to investigate changes of the variables studied on three different temporal bases.

Materials and Methods

Fisheries

Fisheries data were obtained from FRS, Marine laboratory Aberdeen, in the form of voluntary logbooks completed by selected fishermen. Data from the overall sampled fleet ($_{sf}$), aggregated on a weekly basis, include a discontinuous series of catch in numbers of legal size lobsters (L_{sf}) and discarded (undersized, S_{sf}) lobsters, and fishing effort (creels lifted, f_{sf}), for the period 1970-1996 for the Hebrides and 1963-97 for the Southeast of Scotland (Fig. 1). From these data, two abundance indices or catch rates were calculated: the legal lobster catch rate, $U\,L_{sf}$ (legal lobsters per 100 creels lifted), and the undersized lobster catch rate, $U\,S_{sf}$ (undersized lobsters per 100 creels lifted). Total weight of annual, spring and autumn commercial landings data (TL) were obtained from Scottish Sea Fisheries Statistical Tables for the longest period available of 1981-97. The number of vessels contributing to the data varied between years and areas. Therefore, for a better understanding of the fishery data structure, the vessel with the longest continuous series available was chosen from each area (from 1983-93 for the Hebrides and from 1985-97 for the Southeast). The individual vessel information ($_{iv}$), included catch in numbers of legal lobsters (L_{iv}), discarded lobsters (S_{iv}), fishing effort (f_{iv}), legal lobster catch rate ($U\,L_{iv}$), and undersized lobster catch rate ($U\,S_{iv}$). For comparative purposes, fishery data from all the sampled vessels, individual vessels and total landings were confined to the periods 1983-93 for the Hebrides and 1985-97 for the Southeast.

The Hebrides lobster fishery extends over an area of 26,500 km² (56.5-59°N and 6-9°W), containing 8 ICES rectangles. The fishery in the Southeast covers an area of approximately 11,500 km² (55.5-56.5°N and 1-4°W) and contains about 3.5 ICES rectangles. Although all the sampled vessels contributed with fishery statistics for the area specified for each region (Hebrides and Southeast), individual vessels fished in a more reduced range. The individual vessel in the Southeast fished in an area of about 370 km² per year, mainly along the coastline, and activity was focused on very confined fishing grounds (Fig. 1a). The individual vessel in the Hebrides covered an average area of approximately 740 km² per year, specifically performing its fishing in two ICES rectangles of the Outer Hebrides (data from 1990-93, Fig. 1b). It is assumed that data from overall sampled fleet represent processes at larger spatial scale than information from individual vessels.

Regulation in the fishery during the study period has been limited to specification of a minimum landing size (MLS). During this time there have been three different MLSs. Prior to 1984 the MLS was 80mm carapace length (CL), 83mm CL from 1984-92 and 85mm CL from 1993-97. There has been no effort limit, closed season or protection of berried females (although in the Hebrides a programme of V-notching started in

September 2000, after the period considered in this study). In the Hebrides, the duration (length) of the fishing season is dictated by the local weather conditions. Normally, the fishery starts from April or May, and ends in October-November. In the Southeast, the conditions are more favourable for fishing for the whole year. This fishery can be divided into two components, the spring or pre-moult season and the summer or post-moult season. From March-May the sea temperature starts increasing and lobsters feed actively, and this is reflected in increasing catch rates. Fishing declines and lobster activity decreases from June-July (Shelton et al., 1978). In the summer (August-October) recruits join the fishable stock after moulting and catch rates increase to their highest levels (Thomas, 1958, Shelton et al., 1978). Based on this seasonal pattern, analysis of the fishery data from each area has been carried out for annual, spring (March-May) and autumn (August-October) time series.

Environmental variables

Time series of sea surface temperature (SST), air temperature (AT), sea level pressure (SLP), and wind speed (WS), for the Hebrides and Southeast were acquired from the COADS (Comprehensive Ocean-Atmosphere Data Set) web site http://www.cdc.noaa.gov/coads/ for the period 1960-97. The spatial coverage of the data was the same as for the fishery data. These environmental variables were chosen as those likely to influence fisheries at a relatively small spatial scale (areas about 11,500 km² to 26,500 km²). Sea surface temperature may affect changes in lobster behaviour and catchability (McCleese and Wildner, 1958). Sea level pressure, the interaction between air and sea temperature, and wind speed may help to describe valuable meteorological information for the lobster fishery, and therefore they were selected as explanatory variables for this investigation.

To eliminate seasonal patterns in the data, the annual, spring and autumn arithmetic mean estimates of SST, AT, SLP and WS were obtained.

Interactions between variables

Exploration of the temporal patterns of individual variables was carried out with the auto-correlation function (AFC). The ACF was applied to the environmental data series (38 years, 1960-97). ACF was also used for preliminary investigation of the short fishery data series, as well as short environmental data series (Hebrides 11 years and Southeast 13 years). To detect relationships between the series, the cross-correlation function (CCF) was used.

Further data exploration was carried out with multivariate techniques as implemented in the statistical program Brodgar (2000, www.brodgar.com Highland Statistics Ltd.). Initial investigations suggested that the relationships were likely to be linear, and therefore Principal components analysis (PCA) and Redundancy Analysis (RDA), were applied to the fishery and environmental data from both areas to highlight the most important gradients (Kshirsagar, 1972; Gauch, 1982; Blackith and Reyment, 1971; ter Braak, 1987). PCA and RDA have been previously used to detect species-environmental relationships in ecological data and further technical descriptions can be found in Zuur (1999) and Ieno (2000).

Results

Data structure

The results of the ACF analyses are given in the appendix (Tables i and ii). ACF analysis showed that the mean annual data of only SST, AT and WS showed significant auto-correlation for over the period 1960-97, with time lags of +1 to +6 yrs. Annual data over the shorter time scales were mostly not significantly auto-correlated. In the Hebrides, the fishery variables were mostly positively auto-correlated at a lag time of +1 year, and only f_{sf} and $U\ L_{sf}$ were significantly auto-correlated in the three series (spring, autumn and annual). For the Southeast fishery variables, significant auto-correlation at time lags of between +1 and +5 years, was obtained only for the annual and autumn series. These results encouraged further investigation of interactions between individual series.

Investigating relationships between variables

The CCF analysis suggested possible relationships between environmental and fishery variables. Relationships between all fishery variables were also obtained, although emphasis was made to the most significant correlations. Comparisons of the correlation between the different data series suggested temporal changes in the significance of the relationships. Full details of the significant correlations are provided in Tables iii, iv and v of the appendix. For a better interpretation of the results, only the significant relationships between environmental and catch rates annual, spring and autumn data were included for both areas (Table iii and iv).

In the Hebrides, significant correlations were obtained between the tested environmental and fishery (TL and catch rates) variables at the larger spatial scale annually and in spring. Spring SST and AT were negatively correlated with U L_{sf}, while also being positively correlated with TL. In autumn, the variables showed significant correlation at all spatial scales (Table iii). TL and catch rate data were correlated with wind speed and sea level pressure. Annually, catch rates showed significant positive correlation with WS, AT and SST and negative correlation with SLP.

In the Southeast, catch rates and total landings were significantly correlated with the environmental variables at all spatial scales in spring and autumn, whilst annually, the relationships were significant at small spatial scale (Table iv). The spring time series showed negative correlations with SLP, WS and AT. In autumn, TL and catch rates were correlated with SST and AT (lagged between +2 to +4 yrs). Annually, U S_{iv} showed a positive correlation with SST and AT, whilst the U L_{iv} was negatively correlated with AT with a 3 year lag.

The correlation between fishery variables was highly significant for the Hebrides data series and moderately significant for the Southeast. For both areas, the CCF analysis identified fishing effort as a significant correlate with most of the other fishery variables.

Multivariate analysis: relationships between variables

Adopting a multivariate approach, RDA revealed the relationships between environmental and fishery variables for each of the time series (Figs.2-4).

In the Hebrides area, the triplots (various biplots overlapped) indicated strong relationships between environmental and fishery variables for each of the time series (Fig. 2a-b and Fig. 4a). In the spring the RDA triplots, three main groups of variables were identified with positive correlation between the variables: catch rates of legal ($_{sf}$ and $_{iv}$) with undersized ($_{iv}$) lobsters negatively related with SST, WS, fishing effort ($_{sf}$) and legal lobsters ($_{sf}$) and poorly related with TL, SLP and AT. A negative relationship between catch rates of legal lobsters with legal lobsters and fishing effort of the sampled fleet ($_{sf}$) was observed and this was similar in autumn where fishery and environmental series showed weaker relationships than in spring.

In the Southeast, spring time series, there were three main groups of correlated variables identified: the environmental variables AT, SST and WS, negatively correlated with catch rates of undersized lobsters ($_{sf}$); the individual vessel information (S, L an f); and sub-legal and legal lobsters of the sampled fleet with sea level pressure, all with high values in 1990. In the autumn time series, information of the individual vessel showed higher correlation with the environmental variable wind speed and poor correlation with AT and SLP. Two other groups of variables were observed: one referring to data of the sampled fleet (*f*, S, L and *U* L) poorly related to any environmental variable and TL and *U* S_{iv}, negatively related to SST.

For the Hebrides annual time series, catch rates were negatively related to effort. WS was negatively related to AT and SLP, but there was poor correlation between the fishery and environmental data.

For the annual time series in the Southeast, catch rates were generally positively correlated with AT and SST, but showed little correlation with fishing effort (Fig. 4a-b).

Multivariate analysis: quantifying variability

In the Hebrides, based on PCA, the proportion of variability explained by the interaction between fishery variables was greater (71.24%) for the autumn and annual (71.13%) time series than the spring (63.55%). In the Southeast, less variability was explained, and while the greatest proportion was also explained in the autumn (62.14%), the proportion explained for the spring series (57.47%) was greater than for the annual data (52.42%)(Table 2). From the redundancy analysis, in the Hebrides, the explanatory variables account for the 88.99% of the variance in autumn, and 84.77% in spring. For the Southeast, the environmental variables account for more of the variance in spring (84.81%) than in autumn (69.38%). The RDA analysis, with the four explanatory variables studied, best described the processes that contribute with most of the variation in the fisheries of both areas.

Discussion

The long annual time series (1960-97) of environmental variables were mostly auto-correlated, while the shorter series (1983-97) were generally not. The lack of auto-correlation of the short annual time series may indicate a change in the patterns over time, or may be related to the time series length. Auto-correlation was, however, identified in the short time series of fishery data. From the CCF analysis, the Hebrides pre-recruits and recruits are correlated with the ocean-atmospheric processes at large scale, assuming that sampled fleet data represent larger spatial scales than individual vessels data, such as temperature that is important for the lobster biology in spring, and in autumn wind speed is also important. Although catch and catch rates of pre-recruits present stronger significant correlation than the recruits on annual basis, in spring and autumn fisheries both, pre-recruits and recruits appear to respond to the fluctuations of environmental conditions in a similar way. In addition, the triplots showed in spring a more important role of sea and air temperature affecting the catches at all spatial scales (Fig. 2a). The Southeast area shows the opposite patterns to the Hebrides. CCF estimates of atmospheric pressure at sea level and wind have a highly significant positive correlation, lag 0 yrs, with catch and catch rates of pre-recruits, in spring at the small and large spatial scale. Similarly, air and sea temperature positively correlate to catches of sub-legal lobsters, in autumn, at small spatial scale and negatively to catches of legal lobsters at large spatial scale. The triplots corroborated this for spring but not in autumn (Fig. 3a and b). In fact, in autumn, the Hebrides and Southeast present high catches of legal and undersized lobsters at the smaller spatial scale (1986, Fig. 3b) when wind is high, and at the larger spatial scale when sea level pressure is low (Fig. 3b). On the other hand, in the Southeast the cross-correlations between catch rates of undersized lobsters of sampled fleet and catches of undersized lobsters of individual vessel with wind speed, in a lag of four yrs, may stress the importance of wind speed in the recruitment processes for the whole area (Tables iii-iv). It also indicates that catch of undersized lobsters, in spring, may be more susceptible to the environmental processes, in the short tem, than catch of legal lobsters. Sea level pressure also plays a very important role in the interaction with the Southeast and Hebrides fisheries. It correlates to catches of undersized and legal size lobsters at the large (Fig. 3a) and small (Fig. 2a) spatial scale, and indicates a special climatologic event in 1990. Although there was a lack of correlation between sea level pressure and wind speed there is close relation between them product of a wind formation on gradients of sea level pressure (Parker, 1989).

In the Hebrides the influence of more regional scale events of temperature in spring, including the incursion of air masses to the area seems to affect directly the lobster fishery. For the Southeast in autumn, local events of wind speed have repercussions on the fishery success, specially affecting the deployment of creels. These events could also produce strong vertical mixing of the water column which enhance and/or inhibit the growth of some species of phytoplankton that are the main source of food for the early stages of crustacean larvae (Zheng and Kruse, 2000). In addition, turbid or dull conditions can enhance adult lobster activity (Smith et al., 1999) and strong water flow near the seabed can weakened juvenile lobster mobility (Howard and Nunny, 1983).

Previous to this investigation, Shelton et al. (1978) demonstrated the importance of partitioning the fishery elements into two main fisheries, spring and autumn. The biological interpretation relies on the fact that lobsters increase their activity, hence increase catchability and availability to traps, in spring as a response to increasing temperature. When lobsters start moulting, from June-July (Thomas, 1958), the fishery ceases or stops only to start again in August when all the recruits have incorporated to the exploitable stock. Although the autumn fishery component is important, the influence of environmental variables decreases. The role water temperature and wind have on the lobster biology and fishery at all spatial-geographic scales was corroborated in this study. Authors made similar observations for the Homarus americanus fishery in Canadian waters on the interaction of wind, temperature and catch rates (Koeller, 1999; Comeau and Drinkwater, 1997; Comeau et al., 1997; Tremblay and Drinkwater, 1997). Results obtained by Koeller (1999) showed differences in the correlation between variables and between adjacent localities (landing districts or ports), at the smallest temporal and spatial scales. This author found that at the largest spatial and temporal scale (Atlantic coast of Nova Scotia, 50 yr), these variables were significantly correlated at short lags (0-3 yr) prior to 1974. He also suggested that lobster activity or changes in growth were temperature induced, and as a consequence affected catch rates. Koeller (1999) argued that at intermediate scales, catches alone do not accurately reflect changes in lobster abundance. At smaller spatial and temporal scales changes in fishing effort were driven by wind and wind event affected water temperature. In addition, he concluded that fishing effort must be considered as an important variable at the smallest temporal and spatial scales for stock assessment. In the present investigation, fishing effort of the sampled fleet and individual vessels from both areas was one of the most significant response variables (appendix Tables v-vi and Figs. 2a-b and 4a). Other fishery variables, catch rates used in this study could reflect, with reserved conclusions, lobster abundance depending on the temporal-spatial-geographic scales (Addison, 1995). Catch rates of undersized lobsters is strongly correlated to the environmental variables, at any temporal and spatial-geographic scale, and do not necessarily reflects direct changes in fishing effort. The opposite response was detected in the catch rates of legal lobsters, where it may validate relative abundance of legal lobsters depending on temporal changes in effort (increase in deployment of creels) and fishing strategies (differences between individual vessel and overall sampled fleet).

At the largest spatial scale describing other environmental processes such as currents or water circulation patterns may also be important for any commercial fishery. Although little specific information of the Hebrides and Southeast water circulation patters is available, it is believed that the extent and strength of the shelf edge current and its counter flow, and of the re-circulation cell in the northern North Sea, are dependent on the prevailing wind direction (Hainbucher and Backhaus, 1999). The warm North Atlantic Water surface (NAW) that flows to the Northwest of the Scottish slope inshore from the 400m-depth contour (Turrell et al., 1999) influences both areas. In a broader spatial scale, Welch et al., (2000) suggested that recruitment and survival of the steelhead trout (Oncorhynchus mykkis) populations of British Columbia were possibly affected by an oceanographic regime shift around 1989-90. Changes in atmospheric circulation patterns throughout the Northern Hemisphere around winter of 1989 were not ruled out (Watanabe and Nitta, 1999 in Welch et al., 2000). Recruitment patterns in the Alaskan crabs appear to be related to decadal climate shifts with periods of strong Aleutian Lows coinciding with periods of weak recruitment (Zheng and Kruse, 2000). In addition, in the North Sea, ecosystem pulses in the eastern margin current and warmer water off the Northwest European shelf have, possibly caused an alteration of the whole ecosystem (Reid et al., 2001). Evidence of dramatic changes have been observed in a wide variety of life forms from algae to birds, in particular the abundance of phytoplankton and benthos, as part of a regime shift after 1987 (Reid et al., 2001). This regime shift has occurred as consequence of pulses of oceanic incursion into the North Sea, which may have been developed from strong positive temperature anomalies which extended from off Gibraltar, in 1987, to the north and south of Europe with a higher intensity in 1990, making the North Sea more productive since 1987 (Reid et al., 2001). These authors observed a peak in zooplankton in 1989 a year later than a peak in phytoplankton, reflecting a trophic lag. Although trophic and ecological interactions within and between species were not analysed in this study, we must not rule out any influence that food supply and species interactions have on the total variations of the lobster fishery. In this investigation, we found that the years 1986, 1990 and 1996 presented peak values in some of the environmental and fisheries variables. The spring of 1990 was a period of extremely high wind speed, sea surface and air temperature in both studied areas, and sea level pressure only in the Southeast.

The fishery data showed similar extraordinary values with catches of legal and undersized lobsters, fishing effort for the Hebrides and catches of legal and undersized lobsters for the Southeast. For the autumn fishery in 1990, catches of both, discarded and landed lobsters, and fishing effort were also high in the Hebrides while in the Southeast only sea surface temperature was greater than normal. This may suggest that the Hebrides fishery is highly susceptible to environmental conditions at any time of year, which were favourable in 1990, while it is the Southeast spring fishery which is susceptible to the changes in the environment, where catches of undersized lobsters highly contribute to the total output of the fishery. In addition, the fact that sea level pressure, wind speed and sea surface temperature were high in 1990 may indicate that there was a possible oceanographic regime shift (as mentioned above) which affected the studied areas as it possibly affected most of the Northern Hemisphere waters.

On the other hand, the CCF analysis and RDA triplots showed similarities in their results. The CCF indicated the presence of a relationship between two variables. In contrast, the RDA analysis allowed comparisons of multiple variables at the same time. In the triplots, the length of the arrows graphically highlighted the importance of the relationships tested.

The percentage of variation obtained with the use of multivariate analysis techniques (PCA and RDA), helped in the biological interpretation of the interactions studied. Studying the data structure in all its components proved to be necessary and a valid approach to explain most of the variation occurring between and within the interactions of all the variables tested. The PCA analysis gave account of the cumulative percentage of variation obtained from the fishery variables in two main dimensions. This variation differed between areas, data series, and axes where the leading eigenvalue contributed most (Table 2). The cumulative percentage of variance of fishery data proved to be higher for the Hebrides on an annual and autumn basis and for the Southeast on a spring and autumn basis (Table 2). However, with the RDA analysis, the variance of the fishery data was generally lower than in the PCA. In the Hebrides the highest variance was obtained on annual basis and lowest in spring. For the Southeast, spring variance was highest and autumn lowest (Table 3). Redundancy analysis showed that the variables used represented a reasonable amount of variation. In the Hebrides the environmental variables represented about 88.99% of the total 42.33% variance obtained from all environmental-fishery variables in autumn (Table 3). In the Southeast, the percentage of variance of environmental-fishery relationships was higher in spring (84.81%). The low percentage of variance obtained in this analysis may indicate that there are other biological and environmental factors contributing with the total variation that were not considered in this study. The difference in estimates between PCA and RDA indicate that redundancy analysis helped in explaining the source of the variation obtained specifically from the environmental variables chosen for this study.

The fact that for the Hebrides the cumulative eigenvalues of total variance on annual basis was higher than in spring may be caused by the irregularity and scarce data, in spring, which are directly affected by the starting period of the fishery as well as the number of fishing vessels contributing with the information.

The results obtained suggest that the oceanographic conditions are more important to the Hebrides fishery in autumn, and the Southeast fishery in spring. In the fishery context, fishing effort is the most commonly significantly correlated component of all the fisheries elements and its implications should be considered for better stock assessment purposes. The importance of pre-recruits in the fishery was accounted as a good response variable, which was affected by the explanatory variables at the immediate effect (lag 0). Finally, care must be taken when considering the abundance index as a valid tool for stock assessment purposes, it may bias or misrepresent the abundance of undersized and legal size lobsters at any temporal and spatial-geographic scale.

Acknowledgements

The authors are indebted to CONACYT (Mexican National Council for Science and Technology) and staff of the FRS Marine laboratory, Aberdeen, Inshore Fisheries Group; J. A. M Kinnear, J. Drewery, A. Weetman and D. Beare.

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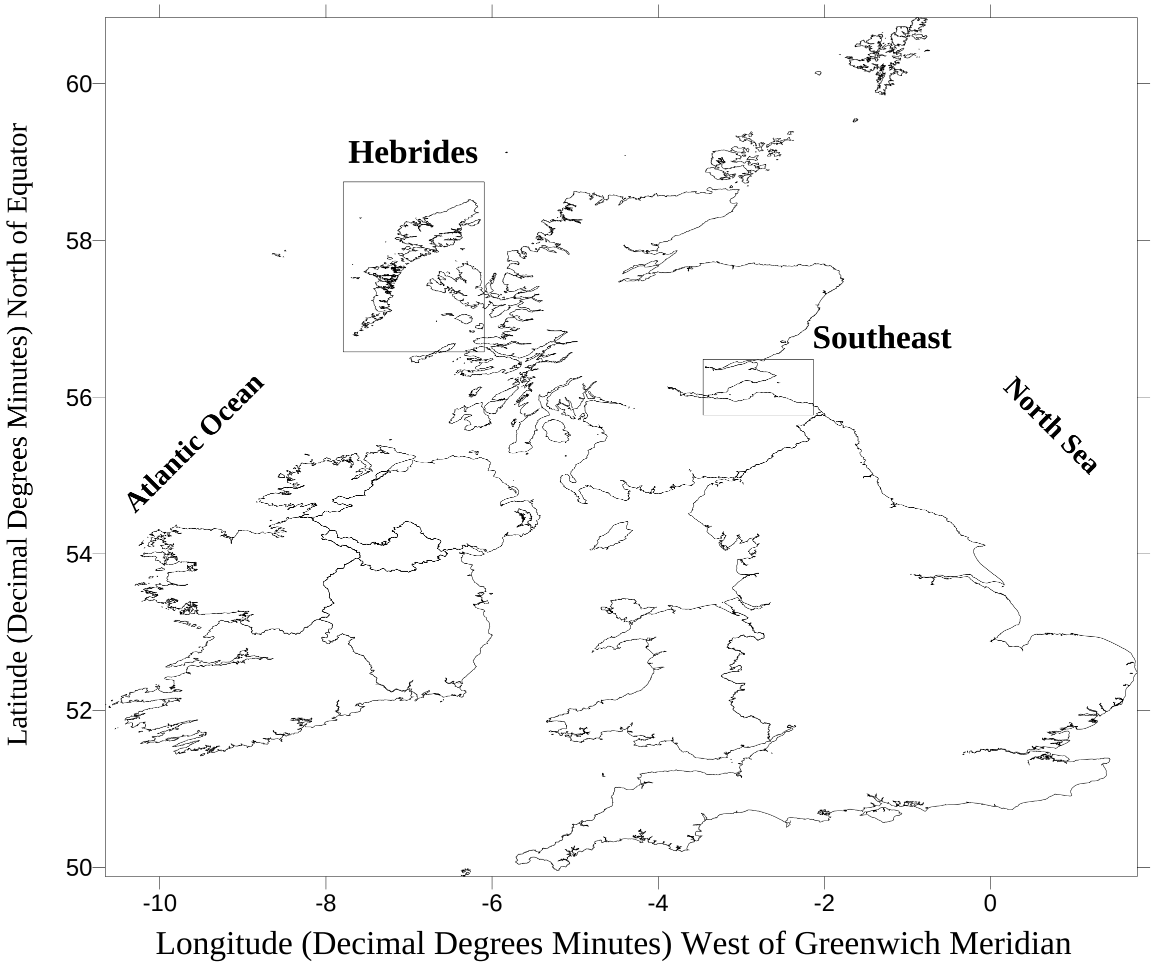

Fig. 1a. Map of the area of study for the Scottish Homarus gammarus fishery in the Hebrides and Southeast.

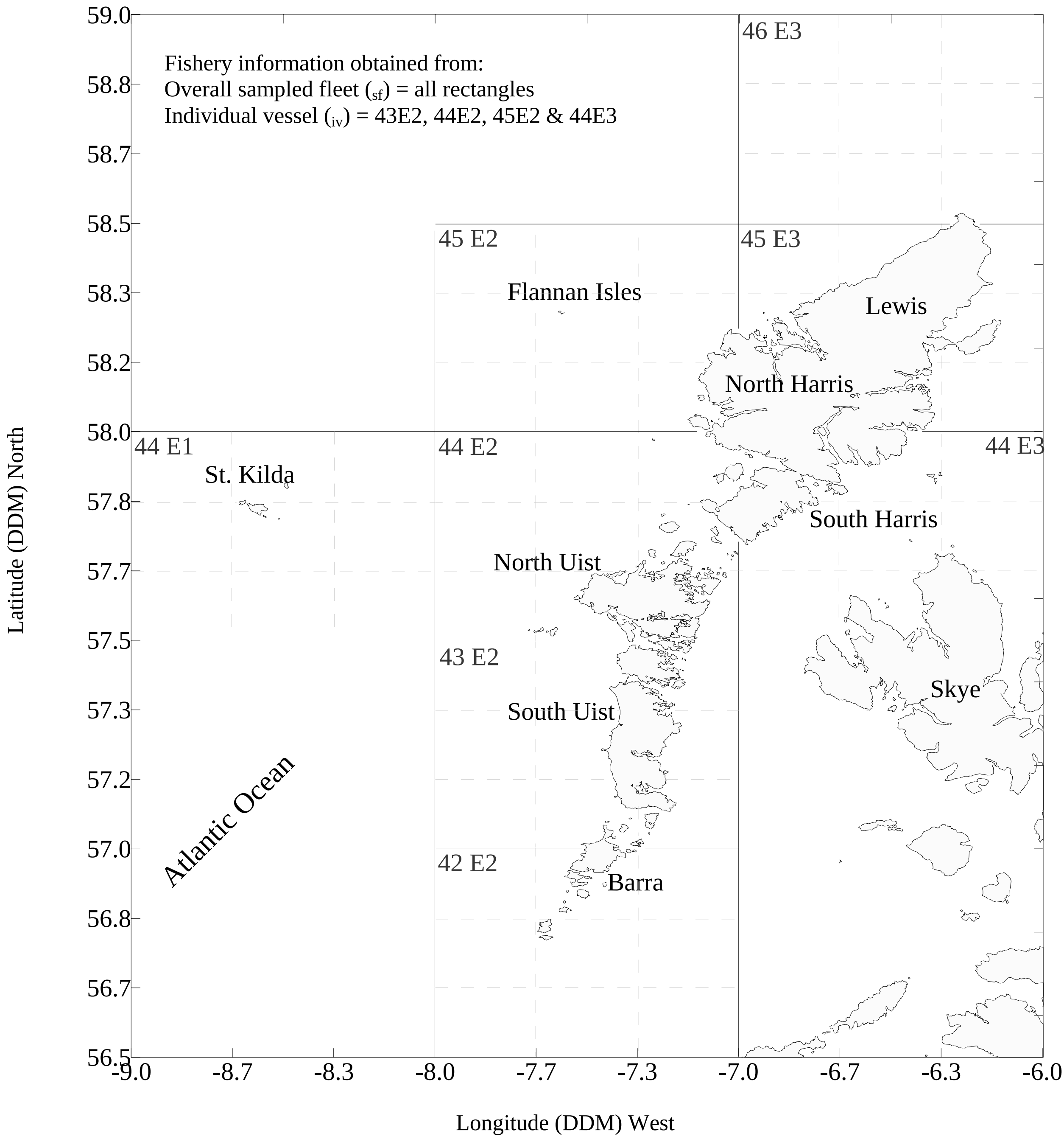

Fig. 1b. Map of the study area according to ICES rectangles, the Hebrides, where fishery data of overall sampled fleet ($_{sf}$) and an individual vessel ($_{iv}$) where obtained for the period 1983-93.

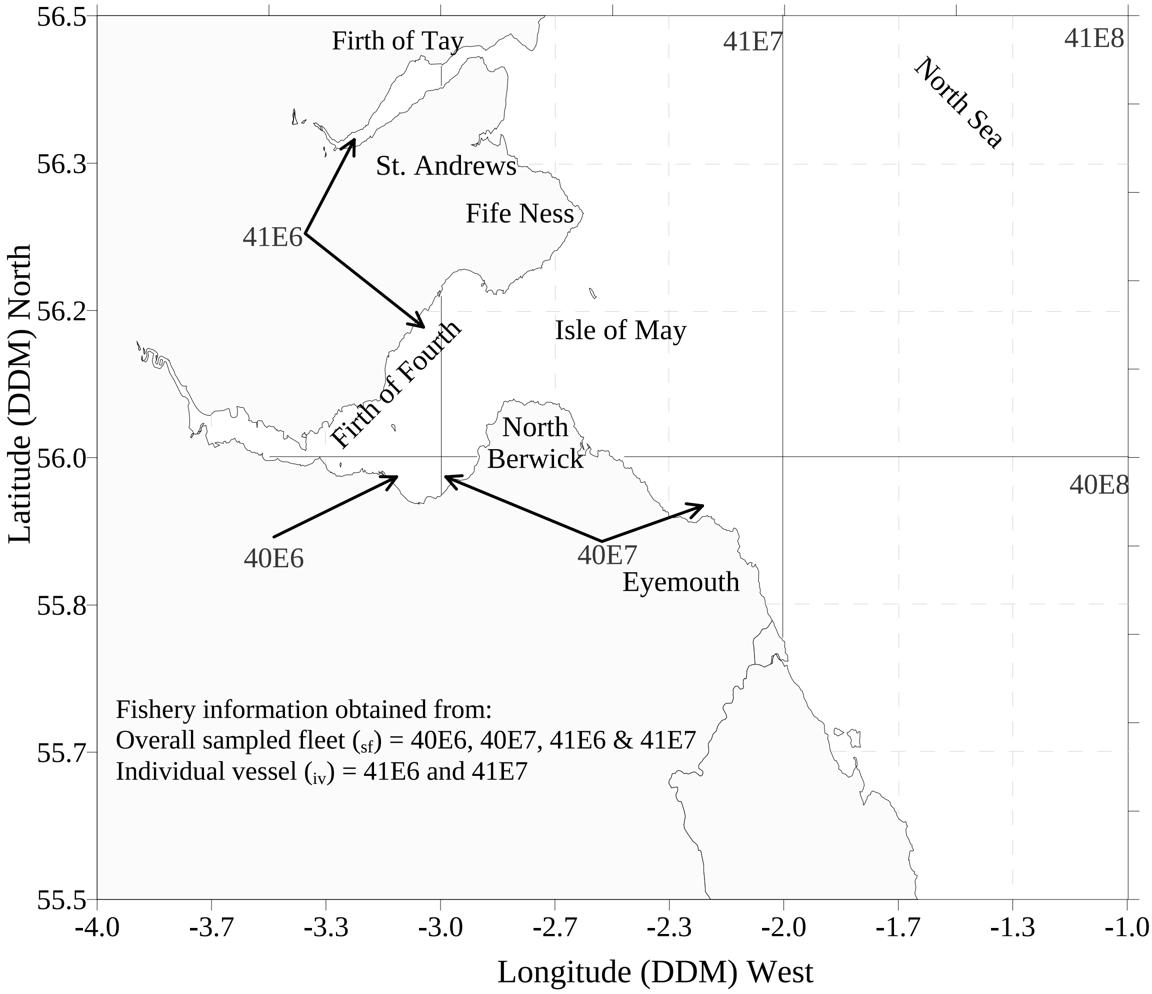

Fig. 1c. Map of the study area according to ICES rectangles, the Southeast, where fishery data of overall sampled fleet ($_{sf}$) and an individual vessel ($_{iv}$) where obtained for the period 1985-97.

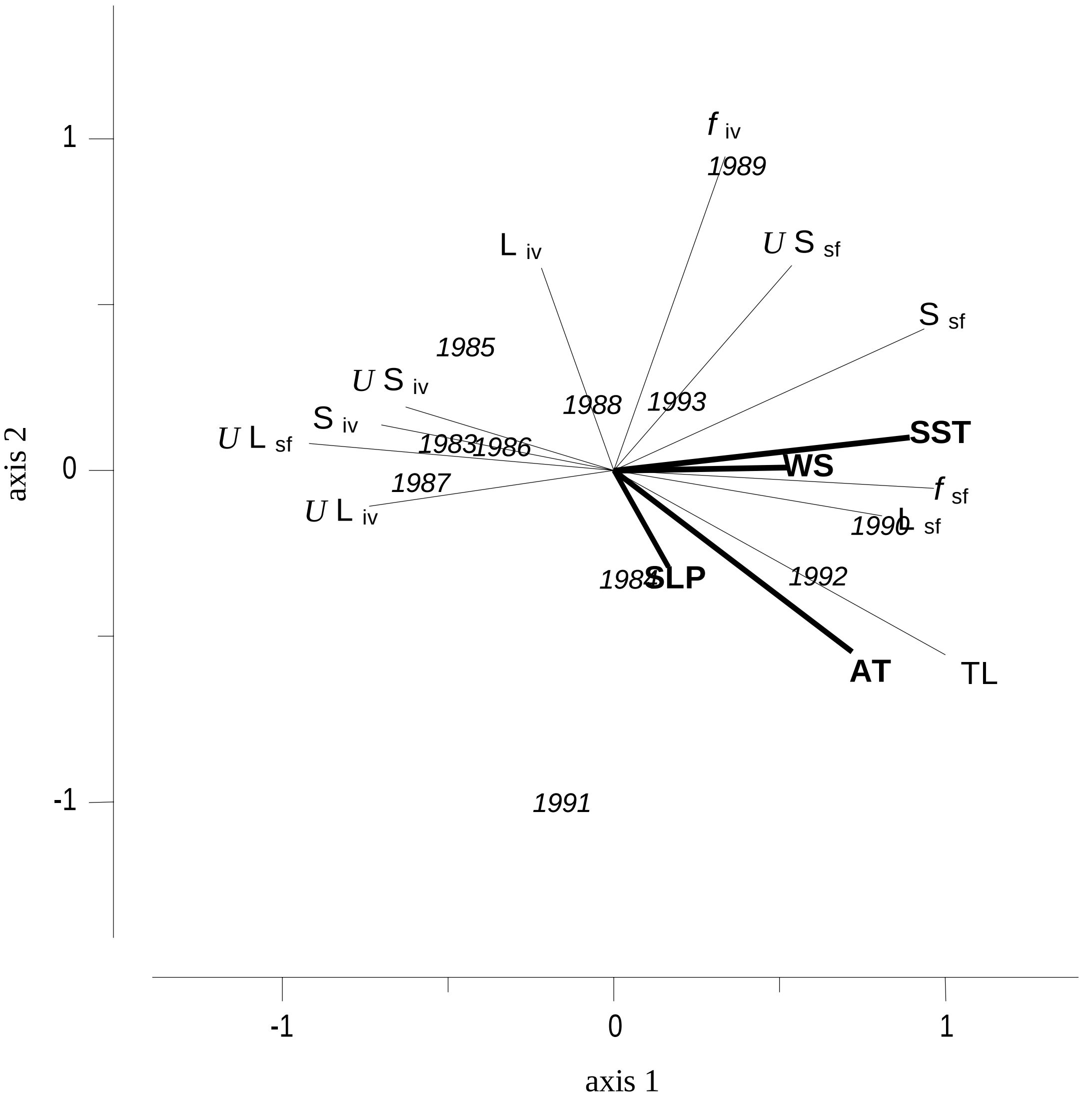

Fig. 2a. Triplot of the redundancy analysis for the spring Hebrides data series during 1983-93. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

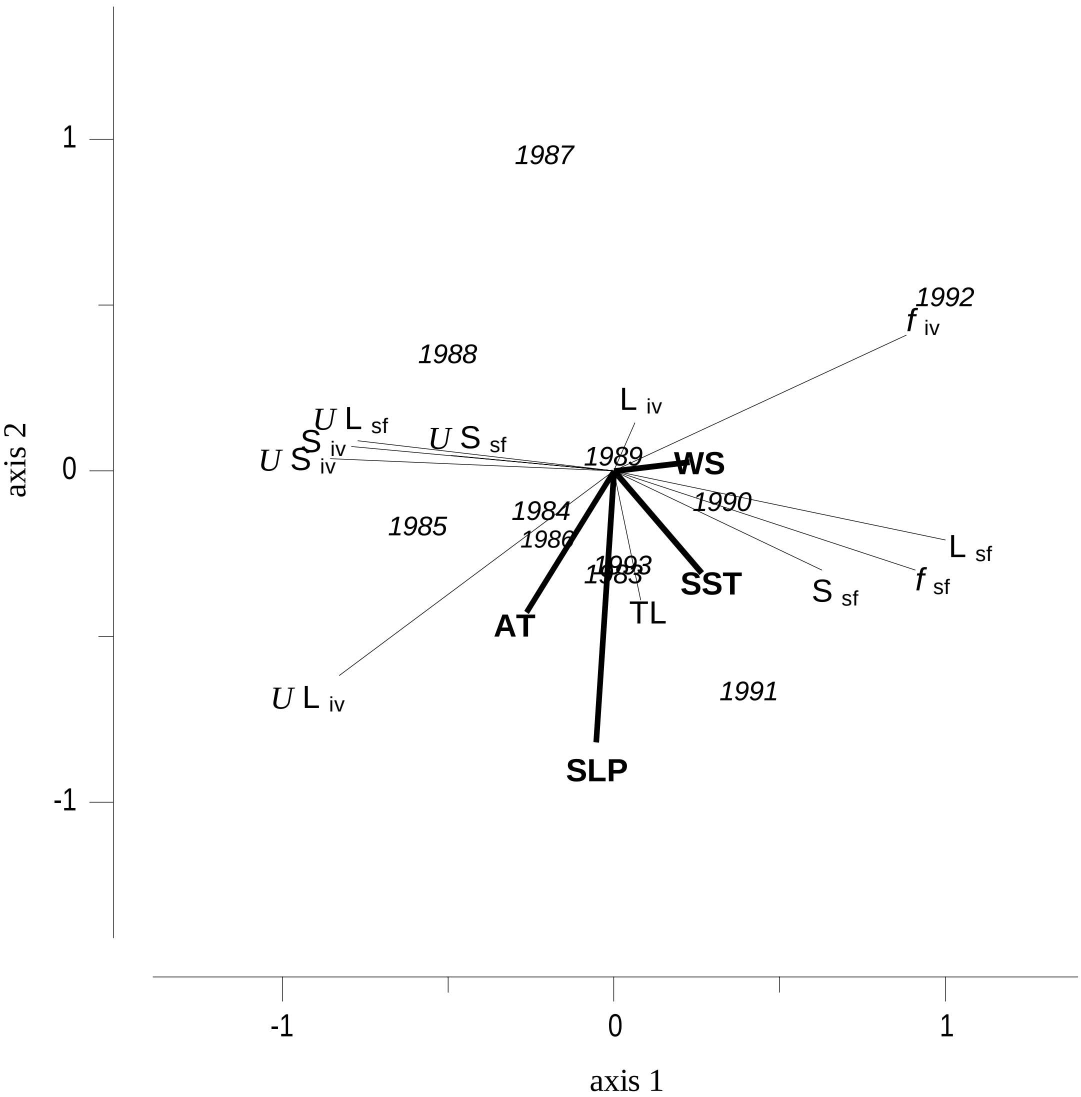

Fig. 2b. Triplot of the redundancy analysis for the autumn Hebrides data series from 1983-93. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

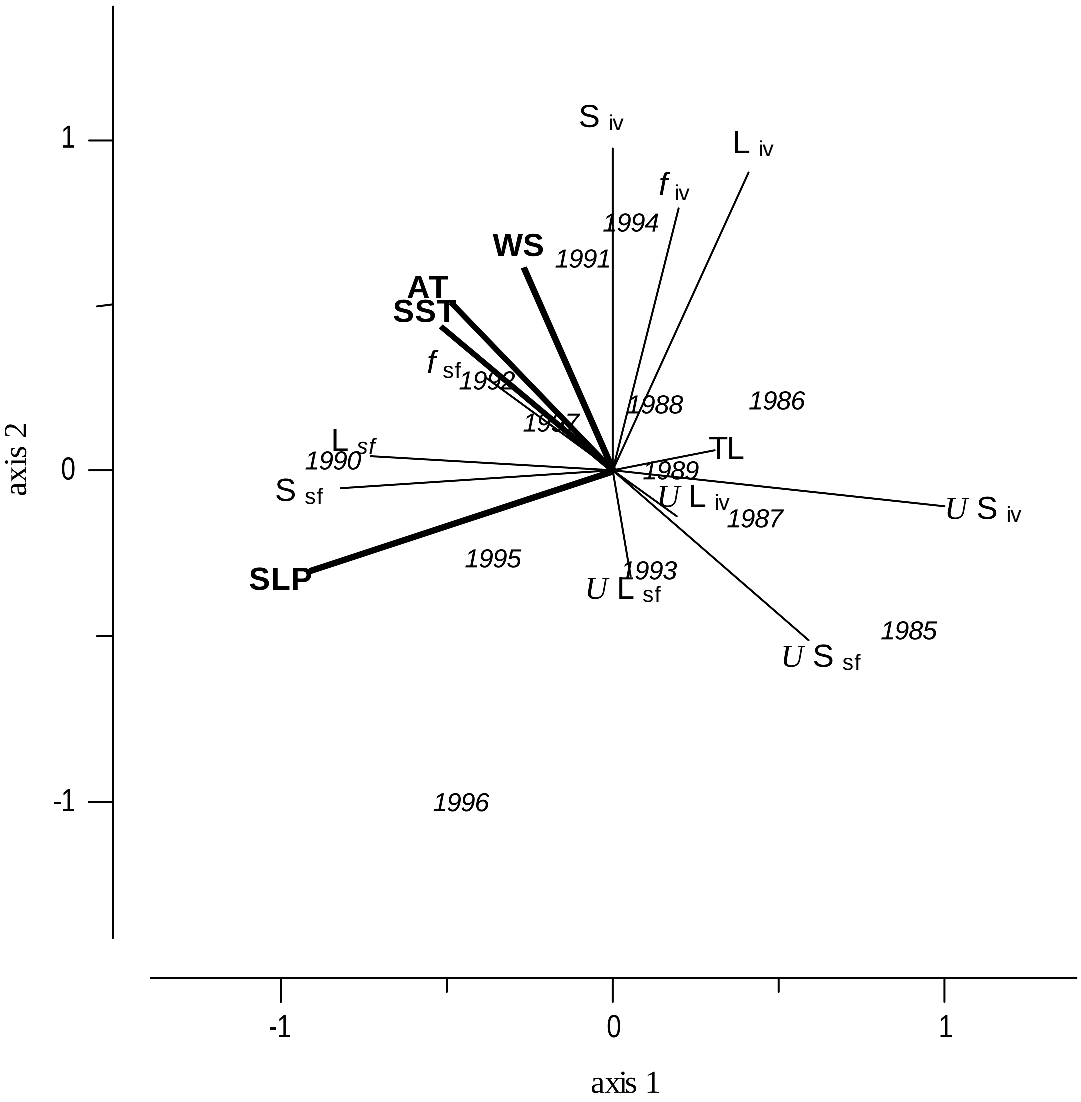

Fig. 3a. Triplot of the redundancy analysis for the spring Southeast data series from 1985-97. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

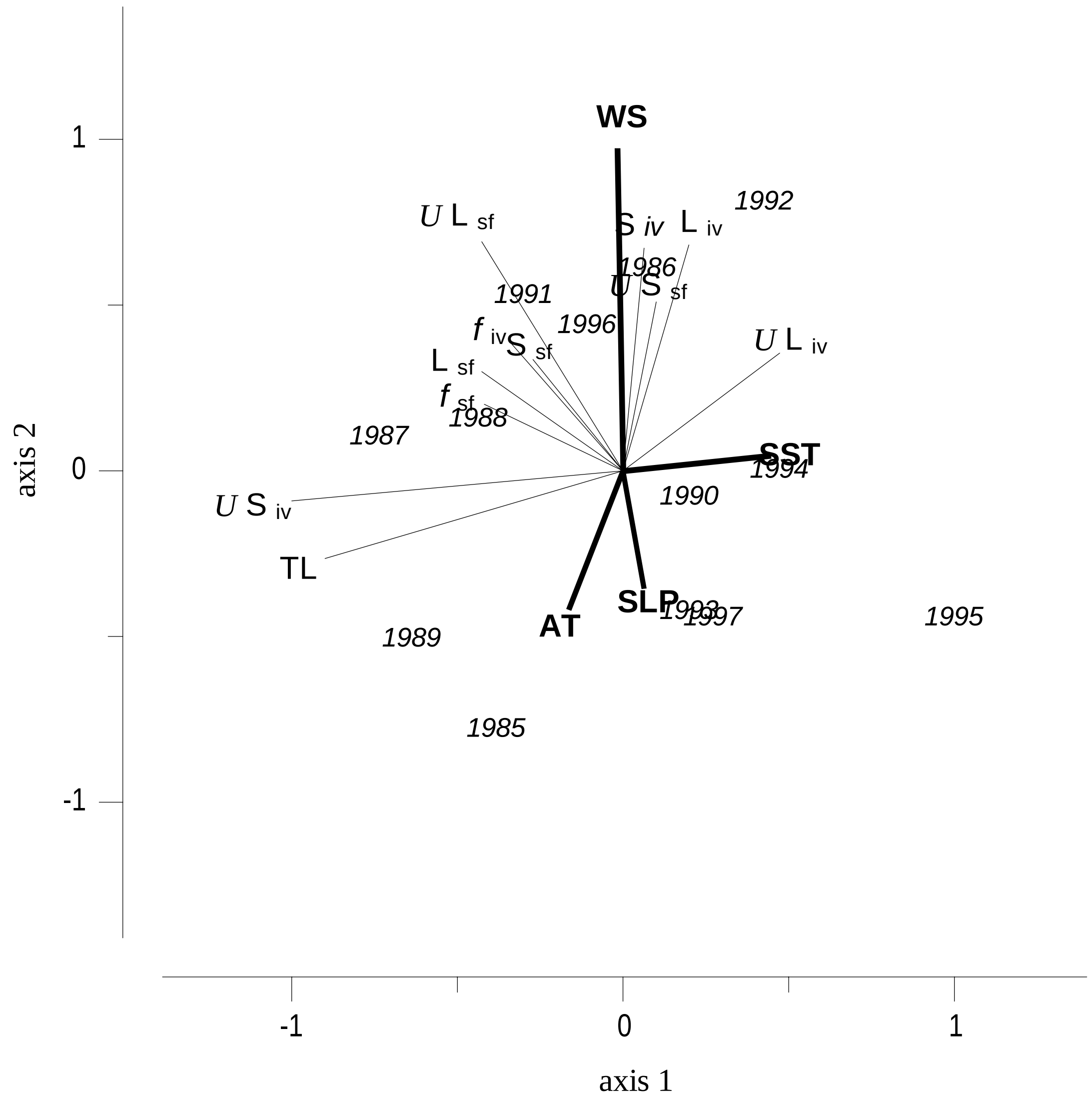

Fig. 3b. Triplot of the redundancy analysis for the autumn Southeast data series from 1985-97. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

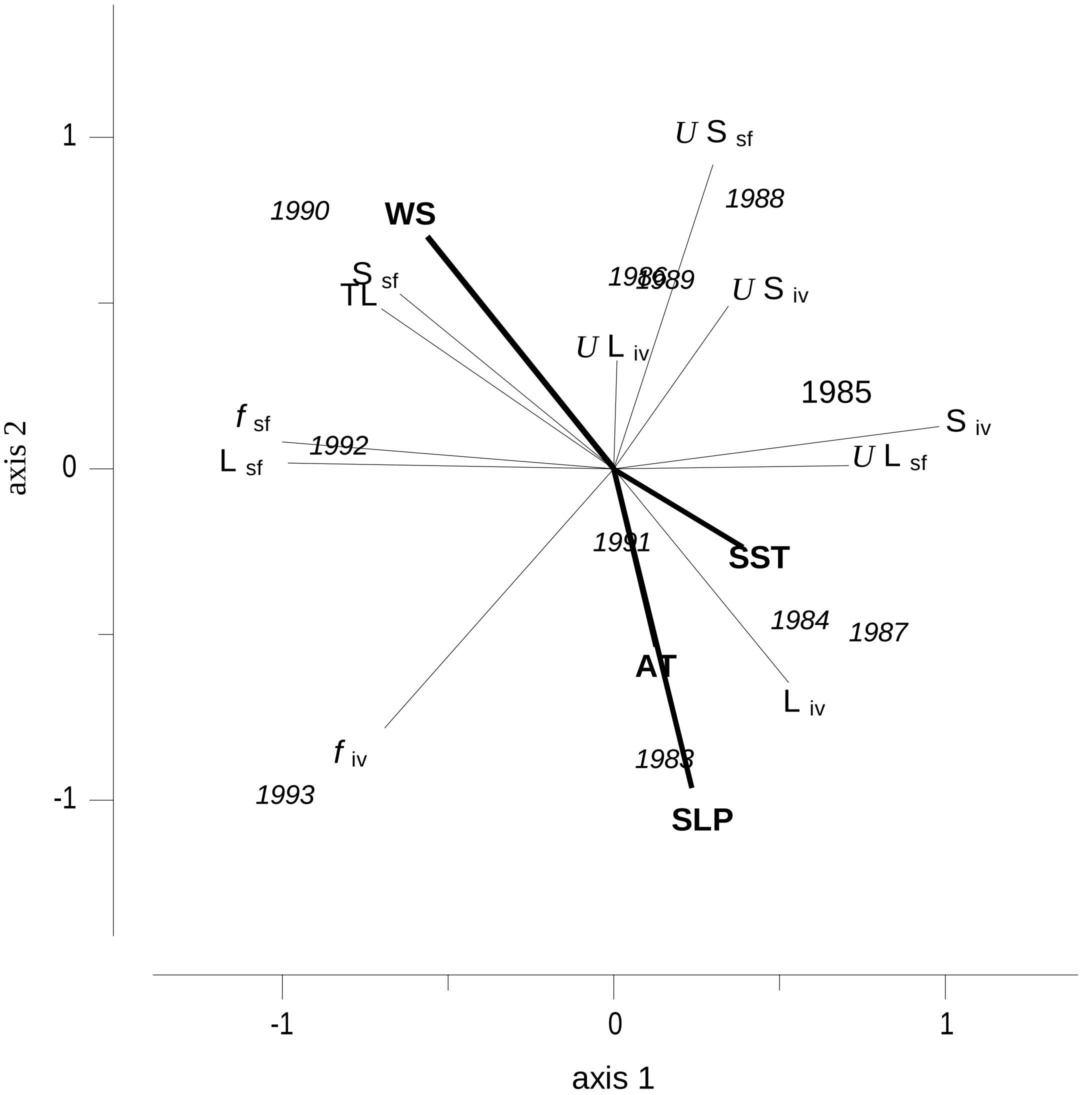

Fig. 4a. Triplot of the redundancy analysis for the annual Hebrides data series from 1983-93. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

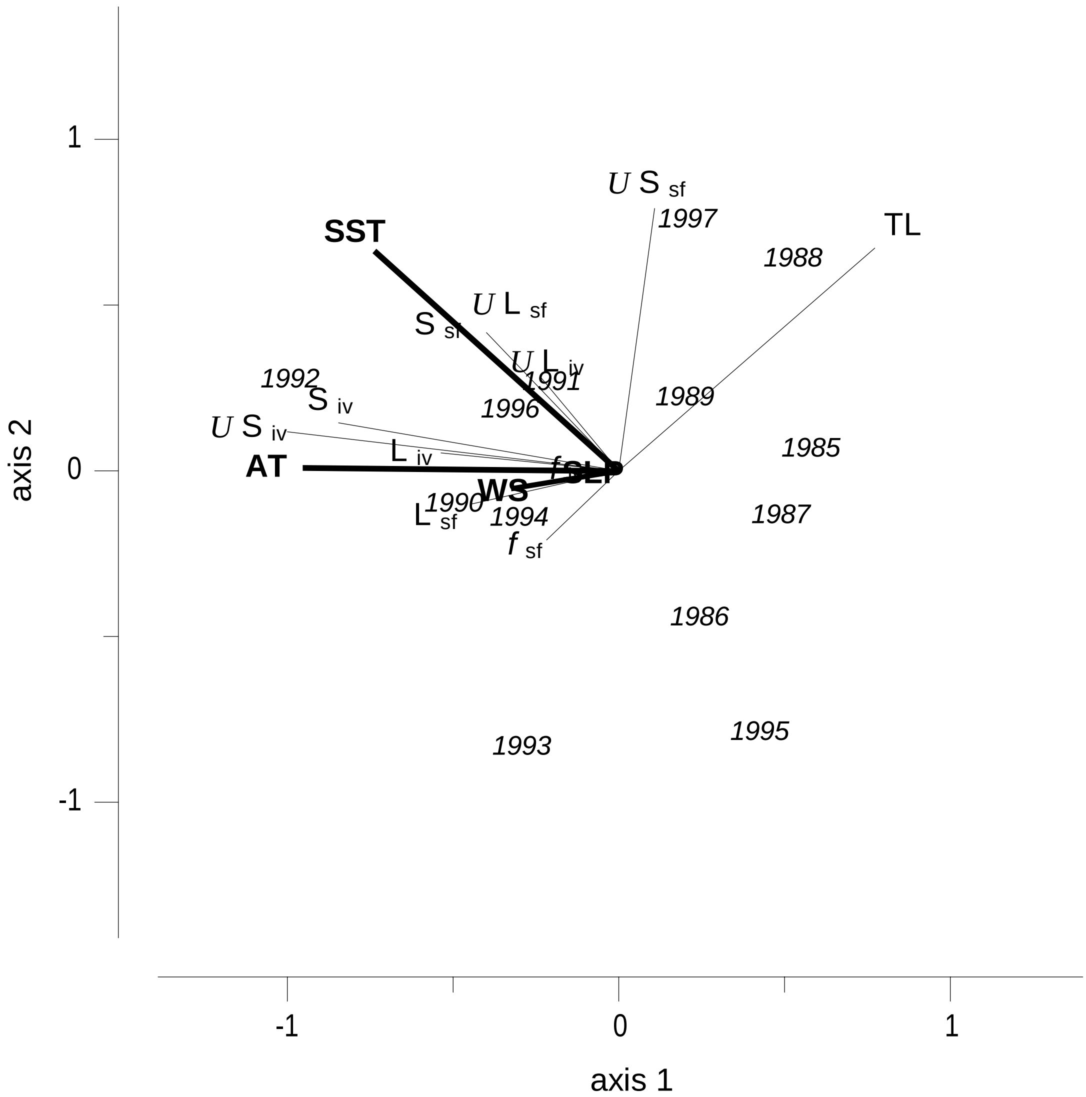

Fig. 4b. Triplot of the redundancy analysis for the annual Southeast data series from 1985-97. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

Table 1. Description of variables selected for this study. Environmental and fishery data series from overall sampled fleet ($_{sf}$) and individual vessel ($_{iv}$) for the Hebrides (1983-93) and Southeast (1985-97) areas.

Source	Acronym	Variable	Units of measurement
Environmental data	AT	Air temperature	°C
	SLP	Sea level Pressure	mb
	SST	Sea surface Temperature	°C
	WS	Wind Speed	m/sec
Overall sampled fleet	f_{sf}	Fishing Effort	Creels (thousands)
	L_{sf}	Catch of Legal size lobsters	Numbers (thousands)
	S_{sf}	Catch of Sub-legal lobsters	Numbers (thousands)
	TL	Total commercial landings	Kg (thousands)
	$U\,L_{sf}$	Catch rates of Legal size lobsters	# lobsters per 100 creels lifted
	$U\,S_{sf}$	Catch rates of Sub-legal lobsters	# lobsters per 100 creels lifted
Individual vessel	f_{iv}	Fishing Effort	Creels (thousands)
	L_{iv}	Catch of Legal size lobsters	Numbers (thousands)
	S_{iv}	Catch of Sub-legal lobsters	Numbers (thousands)
	$U\,L_{iv}$	Catch rates of Legal size lobsters	# lobsters per 100 creels lifted
	$U\,S_{iv}$	Catch rates of Sub-legal lobsters	# lobsters per 100 creels lifted

Table 2. Techniques applied to mean monthly (M), annual (An), spring (Sp) and autumn (Au) environmental and fishery time series for the Hebrides and Southeast of Scotland in different periods.

Data series	Period	Time basis	Uni or bi-variate	Multi-variate
Hebrides				
AT, SST, SLP & WS	1960-97	An	ACF	
AT, SST, SLP & WS	1983-93	An, Sp, Au	ACF	
All Fishery ($_{sf}$ and $_{iv}$)	1983-93	An, Sp, Au	ACF	PCA
Pairs of all fishery variables ($_{sf}$ & $_{iv}$)	1983-93	An	CCF	
Pairs of all environmental with all fishery variables ($_{sf}$ & $_{iv}$)	1983-93	An, Sp, Au	CCF	RDA
Southeast				
AT, SST, SLP & WS	1960-97	An	ACF	
AT, SST, SLP & WS	1985-97	An, Sp, Au	ACF	
All Fishery ($_{sf}$ & $_{iv}$)	1985-97	An, Sp, Au	ACF	PCA
Pairs of all fishery variables ($_{sf}$ & $_{iv}$)	1985-97	An	CCF	
Pairs of all environmental with all fishery variables ($_{sf}$ & $_{iv}$)	1985-97	An, Sp, Au	CCF	RDA

Note: fishery data are related to catch, CPUE, fishing effort and total landings for the overall sampled fleet and individual vessels; environmental data are those referred to air temperature, sea surface temperature, sea level pressure and wind speed, included in table 1.

Table 3. Variability of the factors involved in the PCA analysis with emphasis to the contribution of the response variables for mean annual, spring and autumn data series for the Hebrides (1983-93) and 1985-97 Southeast of Scotland.

Data series	Axis	Eigenvalue	Cumulative percentage of variance of fishery data
Hebrides			
Annual	1	48.61	48.61
	2	22.53	71.13
Spring	1	39.92	39.92
	2	23.63	63.55
Autumn	1	49.45	49.45
	2	21.80	71.24
Southeast			
Annual	1	26.88	26.88
	2	25.54	52.42
Spring	1	35.41	35.41
	2	22.05	57.47
Autumn	1	32.00	32.00
	2	30.14	62.14

Table 4. Variability of the factors involved in the RDA analysis with emphasis to the contribution of the explanatory variables for mean annual, spring and autumn data series for the Hebrides (1983-93) and Southeast (1985-97) of Scotland.

Data series	Axis	Eigenvalue	Cumulative percentage of variance of fishery data	Cumulative percentage of variance of fishery-environmental relationships
			Hebrides	
Annual	1	33.22	33.22	51.29
	2	17.05	50.27	77.62
Spring	1	28.29	28.29	62.32
	2	10.19	38.47	84.77
Autumn	1	36.41	36.41	76.55
	2	5.92	42.33	88.99
			Southeast	
Annual	1	17.85	17.85	55.87
	2	8.47	26.31	82.38
Spring	1	17.50	17.50	43.94
	2	16.27	33.77	84.81
Autumn	1	13.86	13.87	38.65
	2	11.02	24.89	69.38

APPENDIX

TABLES

Table i. Auto-correlation function analysis of time series of environmental data (mean annual estimates) for the Hebrides and Southeast of Scotland period 1960-97. For variables description refer to Table 1.

Variable	r	Lag time (yrs)	r	Lag time (yrs)
	Hebrides		Southeast	
Air temperature	>0.5	+1,+2,+3	>0.5	+1,+2
Sea surface temperature	>0.5	+1,+2	>0.5	+1 to +6
Wind speed	>0.5	+1 to +6	>0.5	+1,+2,+4,+5+6
Sea level pressure	n.s.	-	n.s.	-

n.s. is not significantly auto-correlated at the 5% significance level.

Table ii. Significant auto-correlated individual data series of the explanatory-fishery variables for the Hebrides, 1983-93 and Southeast, 1985-97. The auto-correlation function (ACF) analysis was set at the 5% level of significance. For variables description refer to Table 1.

Data series	Variable	r	Lag time (yrs)	Variable	r	Lag time (yrs)
	Hebrides			Southeast		
Annual	f_{sf}	0.70	1	TL	0.50	1
	L_{sf}	0.70	1	S_{sf}	-0.50	3
	S_{sf}	0.50	1	$U S_{sf}$	-0.50	2
	$U L_{sf}$	0.70	1	f_{iv}	0.60	1
	f_{iv}	0.50	1	L_{iv}	-0.50	3,4
	L_{iv}	0.70	1	S_{iv}	-0.50	4,5
	S_{iv}	0.70	1	$U S_{iv}$	-0.50	5
Spring	f_{sf}	0.65	1	SST	0.54	1
	SLP	0.54	3	-	-	-
	S_{sf}	0.53	1	-	-	-
	$U L_{sf}$	0.60	1	-	-	-
Autumn	f_{sf}	0.73	1	AT	-0.57	3
	L_{sf}	0.65	1	S_{sf}	-0.54	3
	TL	-0.61	2	$U L_{iv}$	0.52	1
	$U L_{sf}$	0.70	1	$U S_{iv}$	0.60	1,2
	L_{iv}	-0.64	1	-	-	-

Table iii. Significantly correlated interactions of the environmental-fishery relationships for the Hebrides, 1983-93. The cross-correlation function (CCF) analysis was set at the 5% level of significance. For variables description refer to Table 1.

Data series	Response Variable	Explanatory Variable	r max	Lag time at r max (years)	Lags of sig. correlation (years)
Annual	$U\,S_{sf}$	Wind speed	0.63	+1	+1
	$U\,S_{sf}$	Sea level pressure	-0.69	0	0,+1,+2
	$U\,L_{sf}$	Air temperature	0.75	+2	+2
	$U\,L_{sf}$	Sea surface temperature	0.64	+2	+2
Spring	$U\,L_{sf}$	Sea surface temperature	-0.60	0	0,+1,+2
	$U\,L_{sf}$	Air temperature	-0.77	+2	0,+2,+3
	TL	Sea surface temperature	0.57	0	0,+2
	TL	Air temperature	0.67	0	0,+2
Autumn	$U\,L_{sf}$	Sea level Pressure	-0.52	+3	+3
	$U\,S_{sf}$	Air temperature	0.54	0	0
	TL	Wind speed	-0.64	+3	+3
	$U\,S_{iv}$	Wind speed	0.51	+2	+2
	$U\,L_{iv}$	Sea level Pressure	0.52	0	0

Table iv. Significantly correlated interactions of the environmental-fishery relationships for the Southeast, 1985-97. The cross-correlation function (CCF) analysis was set at the 5% level of significance. For variables description refer to Table 1.

Data series	Response Variable	Explanatory Variable	r max	Lag time at r max (years)	Lags of sig. correlation (years)
Annual	$U\,L_{iv}$	Air temperature	-0.64	+3	+3
	$U\,S_{iv}$	Air temperature	0.73	0	0
	$U\,S_{iv}$	Sea surface temperature	0.64	0	0
Spring	$U\,S_{sf}$	Wind speed	-0.50	0	0
	$U\,S_{sf}$	Sea level Pressure	-0.50	+1	+1
	$U\,S_{sf}$	Air temperature	-0.59	+2	+2
	$U\,S_{iv}$	Sea level Pressure	-0.72	0	0,+1
	$U\,S_{iv}$	Air temperature	-0.56	+2	+2
	$U\,S_{iv}$	Sea surface temperature	-0.50	0	0
Autumn	TL	Sea surface temperature	-0.62	+2	+2
	$U\,L_{sf}$	Sea surface temperature	-0.52	+2	+2
	$U\,L_{sf}$	Air temperature	-0.53	+2	+2
	$U\,S_{iv}$	Sea surface temperature	-0.52	0	0
	$U\,L_{iv}$	Air temperature	0.65	+4	+4,+5
	$U\,L_{iv}$	Sea surface temperature	0.53	+4	+4

Table v. Significant correlated interactions of the fishery-fishery relationships for the Hebrides, 1983-93 and Southeast, 1985-97 on annual basis only. The cross-correlation function (CCF) analysis was set at the 5% level of significance. For variables description refer to Table 1.

Response Variable	Explanatory Variable	r max	Lag time at r max (yrs)	Lags of sig. correlation (yrs)
Hebrides				
L_{sf}	f_{sf}	0.90	0	-1,0,+1
S_{sf}	f_{sf}	0.82	0	0
TL	f_{sf}	-0.81	+1	0,+1
TL	L_{sf}	0.84	0	0,+1
TL	L_{iv}	-0.77	0	0,+1
TL	S_{sf}	0.71	0	0,+1
f_{sf}	f_{iv}	0.83	+2	+1,+2,+3
L_{iv}	f_{iv}	-0.80	+2	+2,+3
S_{iv}	f_{iv}	-0.70	+2	+1,+2
L_{sf}	L_{iv}	-0.80	+1	+1,+2
S_{sf}	S_{iv}	-0.78	+2	+1,+2
L_{sf}	S_{sf}	0.85	+1	0+,+1,+2
L_{iv}	S_{iv}	0.81	+2	+1,+2
$U\,L_{sf}$	$U\,S_{sf}$	0.68	+4	+4
$U\,L_{iv}$	$U\,S_{iv}$	0.66	0	0
Southeast				
L_{sf}	f_{sf}	0.77	0	0
S_{sf}	f_{sf}	0.63	0	0
S_{iv}	f_{iv}	0.58	0	0
L_{sf}	S_{sf}	0.78	0	0
L_{iv}	S_{iv}	0.67	0	0
$U\,L_{sf}$	$U\,L_{iv}$	0.78	0	0