Scottish lobster fisheries and environmental variability

[1,2,3]LIZÁRRAGA-CUBEDO, H.A., [2,4,6]TUCK, I., [2]BAILEY, N., [7, 8]PIERCE, G.J., [5]ZUUR, A. F. AND [3]BOVA, D.

Petcacab L-19, Mza 191, Chetumal, Quintana Roo, Mexico, 77086.

e-mail address: halizarraga@yahoo.com; hector.lizarraga@inapesca.gob.mx

[1]Instituto Nacional de Pesca, Centro Regional de Investigación Pesquera, Ciudad del Carmen, Mexico; [2] Marine Scotland Science, Marine Laboratory PO Box 101 Victoria Road, Aberdeen AB11 9DB, Aberdeenshire, UK. [3]School of Biological Sciences, Department of Zoology, University of Aberdeen, Tillydrone Avenue, Aberdeen AB24 2TZ, UK. [4]National Institute of Water and Atmospheric Research (NIWA), Fisheries and Marine Ecololgy, Auckland, New Zealand; [5]Highland Statistics Ltd. 6 Laverock Road, AB41 6FN Newburgh, United Kingdom; [6]Department of Statistics, University of Auckland, Private Bag 92019, Auckland 1149, New Zealand; [7]Oceanlab, University of Aberdeen, Main Street, Newburgh, Aberdeenshire, AB41 6AA, UK; [8]CESAM & Departamento de Biologia, Universidade de Aveiro 3810-193 Aveiro, Portugal.

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. There were evident differences in the patterns of environmental variables for both regions. 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 catches and catch rates may be more affected by the way individual vessel and sampled fleet operate. Two elements were identified, Hebrides and Southeast spring and autumn fisheries. The Hebrides lobster population is strongly influenced by density-independence processes at all spatial scales. The Southeast fishery is also driven by environmental processes, with higher correlations for recruits with differences at small and large spatial scales

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, like the homarid lobster 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; Watson and Jury, 2013). In homarid lobsters, sea temperature influences behaviour and availability to traps over the short term (McCleese and Wildner, 1958). Researchers have found a strong correlation between long term catch rates of the American lobster (more than 50 years of data) and sea surface temperature at the largest spatial scales, with lags of 0-3 yrs, and it has also been suggested that wind-driven temperature variability can directly affect catch rates in offshore localities (Comeau and Drinkwater, 1997; Drinkwater 1994). Other results have found that temperature changes are due to alongshore winds forcing upwelling or downwelling (Drinkwater et al., 2006).

On the other hand, 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.

Comparative studies of wind and catch rates of the European lobster, *Homarus gammarus,* in Scottish waters are lacking. However, for Scottish lobster fisheries, authors (Shelton et al., 1978) have 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 (Lizárraga-Cubedo et al., 2003) and population size structure (Kinnear, 1988; Mill et al, 2009) have been identified between the Hebrides and Southeast, 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; Watson and Jury, 2013). 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 undertaken. 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 Marine Scotland Science, 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 relative 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 km^2 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 km^2 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, 85mm CL from 1993-97 (data for the studied period) and currently of 87mm CL. 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, Mill et al, 2009).

Other fishery management measures have been inspected recently by the Scottish Government (2012) such as a reduction of number of creels deployed by fishermen and the introduction of quotas. These measures could apply to a mix creel fishery composed by catches of velvet crabs, edible crabs and lobsters, from which lobsters have shown to be the most valuable resource reaching its maximum value of £13.2 million in 2011 and this trend has been increasing since 2002.

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 weather 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; Schmalenbach and Buchholdz 2013). 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; Tremblay and Drinkwater, 1997; Schmalenbach and Buchholdz 2013; Watson and Jury 2013; Green et al., 2014). 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 highlight differences between sites, 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

Patterns in individual exploratory variables were visually inspected, with further exploration of the temporal patterns of individual variables carried out with the auto-correlation function (ACF). The ACF was applied to the environmental data series (38 years, 1960-97) and 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 (2014, 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 (Blackith and Reyment, 1971; Kshirsagar, 1972; Gauch, 1982; ter Braak, 1987). PCA and RDA have been previously used to detect species-environmental relationships in ecological data (Depczynski et al., 2009) as well as for fisheries data (Hamon, 2009; Suprenand et al., 2014) and further technical descriptions can be found in Zuur (1999) and Ieno (2000).

Results

Data structure

Initial inspection of the environmental data highlighted differences in the environmental conditions between areas. Sea surface temperature and air temperature were warmer for the Hebrides, especially in spring. Autumn sea surface temperature was higher by about 6 ^{o}C at both sites. Wind speed was also higher in the Hebrides with an increasing trend over time for the period of 1960-97. In contrast, sea level pressure was higher for the Southeast (Fig. 2).

The results of the ACF analyses are given in the appendix (Tables i and ii). ACF analysis showed that the mean annual data of 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, were 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. Significant relationships were observed in the comparisons of the correlation between the different data series suggesting temporal changes. 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 catch rates and the tested environmental variables on annual, spring and autumn bases and these were more significant for the legal sized lobsters.

In spring, at large spatial scale SST and AT were positively correlated to total landings but negatively correlated with $U\ L_{sf}$ at lag time of 0 years.

In autumn, wind speed and sea level pressure presented the strongest correlations with catch rates of both legal and undersized lobsters for both the sampled fleet and individual vessel (Table iii).

Annual series of all environmental variables were highly correlated to the catch rates of all lobsters only at large spatial scale.

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.3-5).

The Hebrides fishery

In the Hebrides, significant correlations were obtained between the catches and catch rates and the tested environmental variables at any time of the year. In spring, sea surface temperature is the most significant variable and most noticeable at larger spatial scale (Fig. 3a). This is reflected in the high catches of undersized and legal lobsters obtained, corresponding to a high fishing effort, hence indicating a significant and negative relationship with catch rates.

In autumn, the short arrows of the triplot showed that environmental conditions have less significant impact (interaction) on the fishery. In contrast, fishery variables are highly correlated at large and small spatial scale (Fig. 3b).

Annually, total landings seemed to be strongly influenced by the environmental conditions, and this also coincided with the catches of legal sized lobsters of the sampled fleet. Annual data series of wind speed showed to be the most important variable at large spatial scale (Fig. 5a).

The Southeast fishery

The spring fishery varied spatially, with differences between the sampled fleet and the individual vessel selected. There were strong and positive relationships between fishing effort, pre-recruits and recruits at each spatial scale. Sea level pressure was highly correlated with the fishery data at large spatial scale, whereas wind speed was found to be correlated to fishery data at small spatial scale. (Fig. 4a).

In the autumn, wind speed was the environmental variable with the highest, and positive, correlation with fishery data, although the relationship between fishing effort, legal and undersized lobsters varied at small and large spatial scale (Fig. 4b).

The analysis of the annual data series showed that for this fishery both, air and sea surface temperature strongly correlate with the data series of catches of recruits and pre-recruits, at small and large spatial scale (Fig. 5b).

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 different between areas with marked differences in the trends of the three temporal components, spring, autumn and annual. Overall, sea surface temperature and air temperature were higher in the Hebrides and also stronger wind speed was observed. These long annual time series 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 be indicative of widely disperse data points or abrupt changes in the patterns over time as for the sea level pressure and wind speed (Fig. 2).

The analysis of the fishery data indicated that fishery processes are markedly different between geographic areas and at different spatial scales. Both fisheries are strongly influenced by the oceanographic conditions with wind speed, sea surface temperature and air temperature contributing with relevant information in the interactions.

Data series of exploratory and explanatory variables at three temporal scales revealed that fisheries of the Hebrides and Southeast can be divided into two component fisheries, spring and autumn and this was supported by the CCF, PCA and RDA analyses.

For the Hebrides fishery, the information obtained from the sampled fleet represented the fishery processes at larger spatial scale whilst the individual vessel fished over a reduced area (Table v). The analysis of the spring fishery indicated sea surface temperature as a highly relevant variable with significant correlation with the catch rates over the whole area. High catch rates were inversely correlated to high fishing effort and high catches.

In autumn, although there were weaker relationships between the environmental conditions and catch rates, wind speed was significant. Catch rates were highly correlated at small and large spatial scales (*f*, L and S), as depicted by the arrows of the triplots (Fig. 4b). Annually, wind speed seemed to be important for this fishery for legal lobsters at larger spatial scale. The PCA indicated the proportion of variability explained by the interaction between fishery variables was greater for the autumn time series and the RDA also accounted for a higher variance in autumn.

Similar to the Hebrides fishery, in the Southeast the information obtained from the sampled fleet represented the fishery processes at larger spatial scale whilst the individual vessel fished over a reduced area but there were marked differences between data series (Table v). In spring, all the environmental variables tested were correlated with the fishery data at both spatial scales (Fig. 4a). However, pre-recruits were found to be more correlated to environmental variables than legal lobsters as this was shown in the triplots with longer and positively correlated closer arrows (Fig. 4a).

In contrast, in autumn wind speed was highly correlated to the fishery data at both spatial scales but this was only revealed by the RDA analysis (Fig. 4b). For the autumn fishery the triplots showed undersized lobsters to be more correlated to environmental variables at the small spatial scale than legal lobsters.

The analysis of the annual data series showed that for this fishery both, air and sea surface temperature, are the prevailing conditions that strongly correlate with the data series of catches of recruits and pre-recruits, at small and large spatial scale (Fig. 5a-b).

As a comparison, and derived from the RDA analysis, less variability could be explained by the interaction between the environmental and fisheries variables for the Southeast, with the greatest variation being explained in the autumn but environmental variables explained greater variance of the relationships in spring (84.81%).

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.

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). Stronger winds were observed in the Hebrides in spring and autumn whilst sea level pressure was higher for the Southeast, suggesting weather conditions vary between areas.

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.

In spring, however, pre-recruits were found to be more correlated to environmental variables than legal lobsters. For the autumn fishery undersized lobsters, the triplots showed stronger correlation to environmental variables at the small spatial scale than legal lobsters.

Studies by Green et al (2014) stressed the need for cautious interpretation when assessing relationship between environmental variables and the interaction with lobsters and crabs. Independent assessment may show clearer trends relating temperature to increasing growth rates of all life stages whereas an assessment of a combination of variables would often magnify the resulting relationships.

In this study, we corroborated the role water temperature and wind have on the lobster biology and fishery at all spatial-geographic scales. Similar observations have been made 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; Drinkwater et al., 2006). 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.

Homarus gammarus in some lobster reserves in Norwegian waters experienced sea temperatures ranging from 2°C during late winter (February to March) to 18°C during late summer (August to September) with seasonal variations in lobster activity levels being correlated to water temperature (Moland et al., 2011). Lobster juvenile moulting and locomotory activity is optimal at temperatures of between 12-14 ºC (Schmalenbach and Buchholz, 2013) and a similar range of temperatures was observed in this study for the Hebrides and Southeast in autumn throughout the studied period.

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.

Wiig et al (2013) studied the behaviour of individual acoustic tagged European lobsters in Norwegian Skagerrak coasts in relation to home-range and fishing practices. They found that behaviour and exposure to coastal fishery varied a small geographical scale of less than 1km. They also observed fishermen´s knowledge and selection on fishing grounds may reflect a high rate of lobster removal. This may cause a clear displacement of big lobsters that move from high quality habitats (where most of the fishing effort concentrates) to low quality habitats where fishing effort is low.

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. 3a-b and 5a). This may indicate the representativeness of the data highlighting fishermen´s knowledge and preferences of fishing grounds as well as stressing differences in fishing practices at small and large spatial scale. In the Hebrides lobsters are caught mostly in individual creels whereas for the Southeast creels are arranged in strings of up to 10. Catch per unit effort is standardised for all areas as lobster catches per hundred creels. Therefore care must be taken when interpreting a combination of fishery variables, such as catch rates, and lobster abundance on different 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).

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 which affected the studied areas. These findings may be corroborated by the work of Nunn et al. (2010) who found possible evidences of shift in fish growth and recruitment success linked to changes in the North Atlantic Ocean for the mid 1990s. In addition, Hannesson (2007) also analysed variation in catches of several species of fish in relation to ocean temperature recorded along the coasts of the North Sea, Norwegian Sea and Barents Sea for a period of more than 50 years (mid 1940´s to early 2000´s). In an attempt to detect past changes he found differences in the correlations between temperature and catches and recruitment between sites, suggesting that some species need to past certain thresholds of temperature in order to show changes, other factors may also influence those variations and that study at big spatial scales may not necessarily show displacements of stocks.

Most recently, a study by Mills et al (2013) found that for the American lobster fisheries in American coasts, a strong heat wave in 2012 strongly affected the lobster populations by altering the moulting processes as well as evidencing a shift in temporal landings that matched a shift in temperatures. These authors also highlighted these type of changes are likely to occur and caution must be taken.

In a climate change context, there is need for a better estimate of the predicted long-term increases in water temperatures and its effects on the lobster size at maturity, possible implications in the abundance decline and increase in lobster diseases and shifts in the increase in catches. Monitoring of the recruitment components becomes relevant and this leads to consider downscale climate change models to a spatial and temporal scale relevant to lobster stocks as well as considering the uncertainties in the climate change projections and their effect on the ecosystem (Caputi et al., 2013).

In conclusion, based on our statistical analyses, the CCF analysis and RDA triplots showed similarities in their results. The former indicated the presence of a relationship between two variables. In contrast, the later 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 to interpret the fishery-environmental interactions. 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.

In the fishery context, our findings confirm that the fisheries of the Hebrides and Southeast can be divided into two component fisheries, spring and autumn and this was supported by the CCF, PCA and RDA analyses.

The results also suggested that fishery processes are markedly different between geographic areas and at different spatial scales.

For the Hebrides, fishery data were highly correlated to environmental variables with high catch rates inversely correlated to high fishing effort and high catches in spring and autumn.

For the Southeast fishery pre-recruits were found to be more correlated to environmental variables than legal lobsters in spring and autumn emphasising at the small spatial scale. This may be an indicative of the importance of recruitment processes affecting the lobster catches.

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.

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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

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	$U\,\mathrm{L}_{iv}$	Air temperature	-0.64	+3	+3
	$U\,\mathrm{S}_{iv}$	Air temperature	0.73	0	0
	$U\,\mathrm{S}_{iv}$	Sea surface temperature	0.64	0	0
Spring	$U\,\mathrm{S}_{sf}$	Wind speed	-0.50	0	0
	$U\,\mathrm{S}_{sf}$	Sea level Pressure	-0.50	+1	+1
	$U\,\mathrm{S}_{sf}$	Air temperature	-0.59	+2	+2
	$U\,\mathrm{S}_{iv}$	Sea level Pressure	-0.72	0	0,+1
	$U\,\mathrm{S}_{iv}$	Air temperature	-0.56	+2	+2
	$U\,\mathrm{S}_{iv}$	Sea surface temperature	-0.50	0	0
Autumn	TL	Sea surface temperature	-0.62	+2	+2
	$U\,\mathrm{L}_{sf}$	Sea surface temperature	-0.52	+2	+2
	$U\,\mathrm{L}_{sf}$	Air temperature	-0.53	+2	+2
	$U\,\mathrm{S}_{iv}$	Sea surface temperature	-0.52	0	0
	$U\,\mathrm{L}_{iv}$	Air temperature	0.65	+4	+4,+5
	$U\,\mathrm{L}_{iv}$	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

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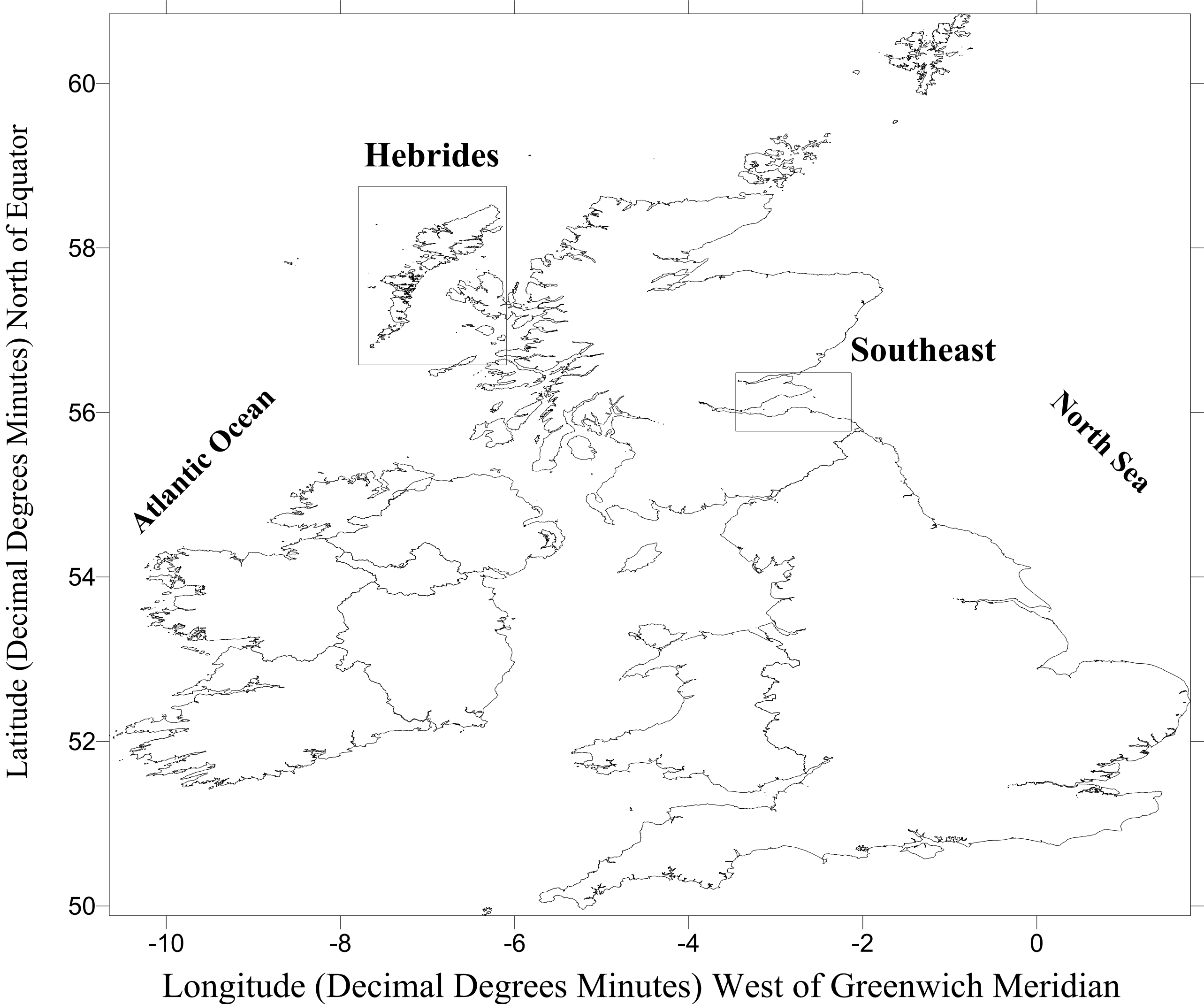
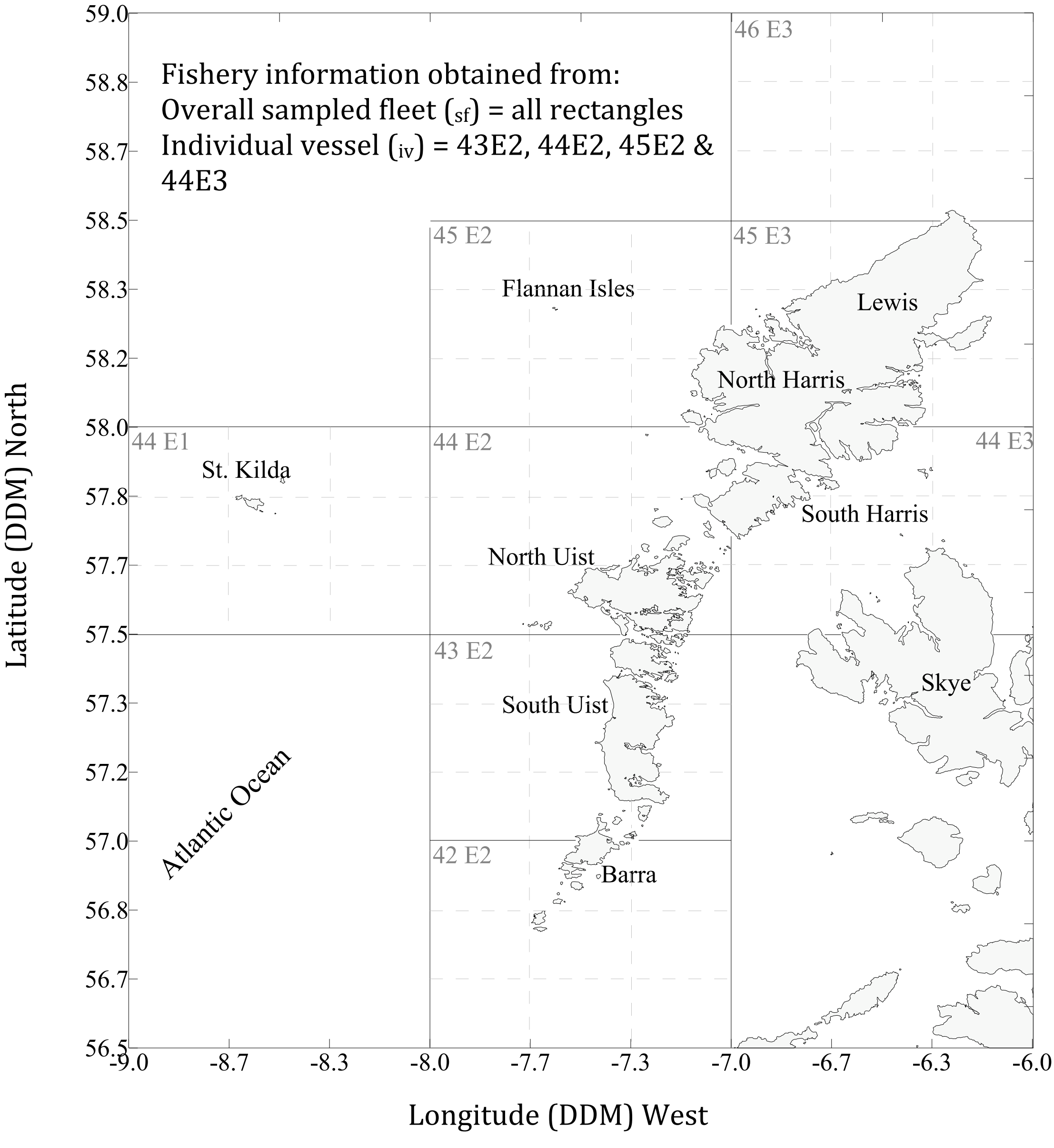
indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

Fig. 5a. 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.

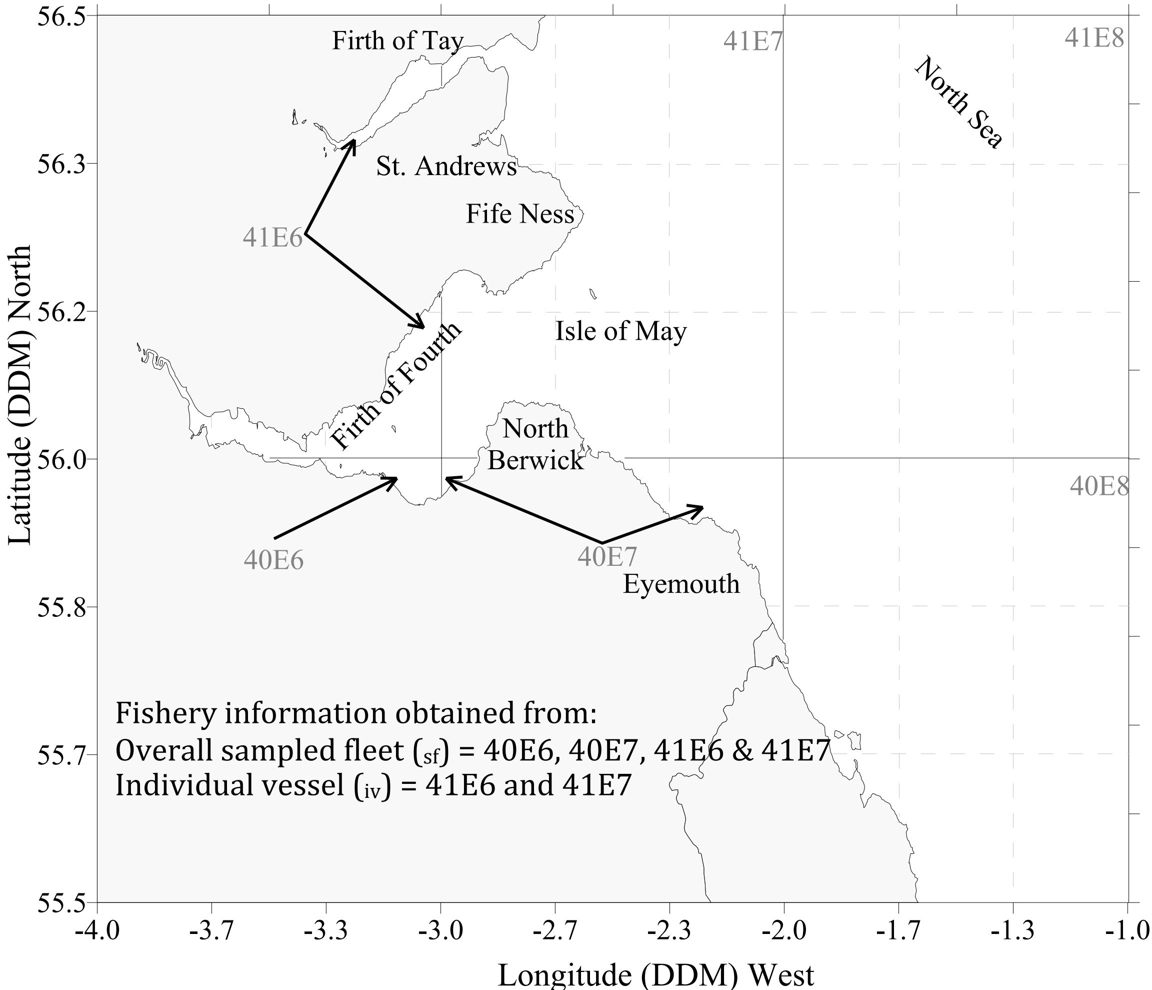
Fig. 5b. Triplot of the redundancy analysis for the annual Southeast data series from 1985-97. Long arrows indicate strong relationship. Arrows in the same direction indicate positive correlation, whilst arrows in opposite direction indicate negative correlation. An angle of 90º between arrows refers to not significant correlated variables. The acronyms of the variables are included in Table 1.

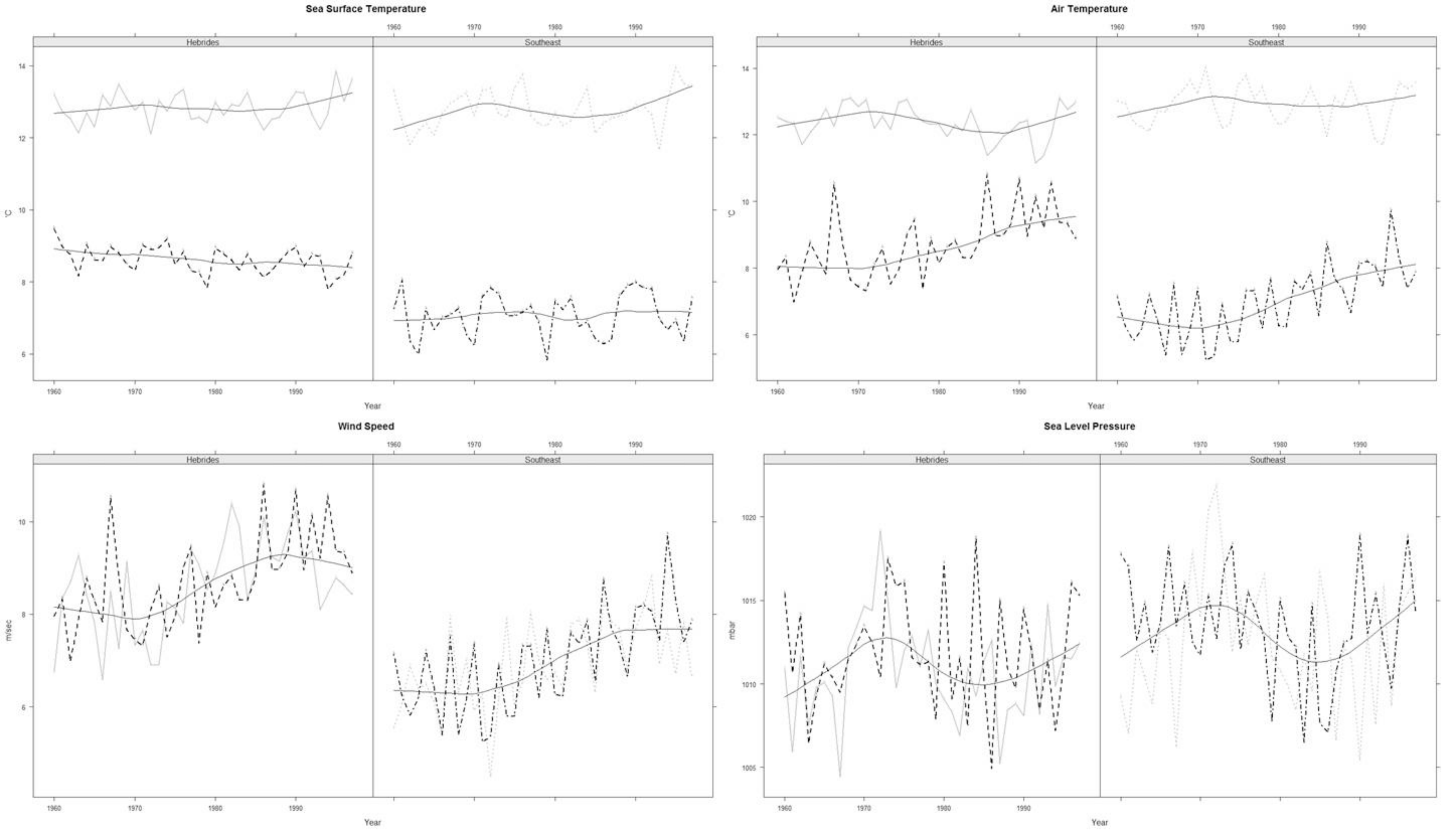


Hebrides
Southeast
Atlantic Ocean
North Sea
60
58
56
54
52
50
-10
-8
-6
-4
-2
0
Latitude (Decimal Degrees Minutes) North of Equator
Longitude (Decimal Degrees Minutes) West of Greenwich Meridian



Fishery information obtained from:
Overall sampled fleet (sf) = all rectangles
Individual vessel (iv) = 43E2, 44E2, 45E2 &
44E3
46 E3
45 E2
45 E3
44 E1
44 E2
44 E3
43 E2
42 E2
Flannan Isles
Lewis
North Harris
St. Kilda
South Harris
North Uist
South Uist
Skye
Barra
Atlantic Ocean
59.0
58.8
58.7
58.5
58.3
58.2
58.0
57.8
57.7
57.5
57.3
57.2
57.0
56.8
56.7
56.5
-9.0
-8.7
-8.3
-8.0
-7.7
-7.3
-7.0
-6.7
-6.3
-6.0
Latitude (DDM) North
Longitude (DDM) West


56.5
56.3
56.2
56.0
55.8
55.7
55.5
Latitude (DDM) North
-4.0
-3.7
-3.3
-3.0
-2.7
-2.3
-2.0
-1.7
-1.3
-1.0
Longitude (DDM) West
Firth of Tay
41E7
41E8
North Sea
St. Andrews
Fife Ness
41E6
Isle of May
Firth of Fourth
North
Berwick
40E8
40E6
40E7
Eyemouth
Fishery information obtained from:
Overall sampled fleet (sf) = 40E6, 40E7, 41E6 & 41E7
Individual vessel (iv) = 41E6 and 41E7


Sea Surface Temperature
Hebrides
Southeast
°C
Year
1960
1970
1980
1990
6
8
10
12
14
Air Temperature
Hebrides
Southeast
°C
Year
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Southeast
m/sec
Year
Sea Level Pressure
Hebrides
Southeast
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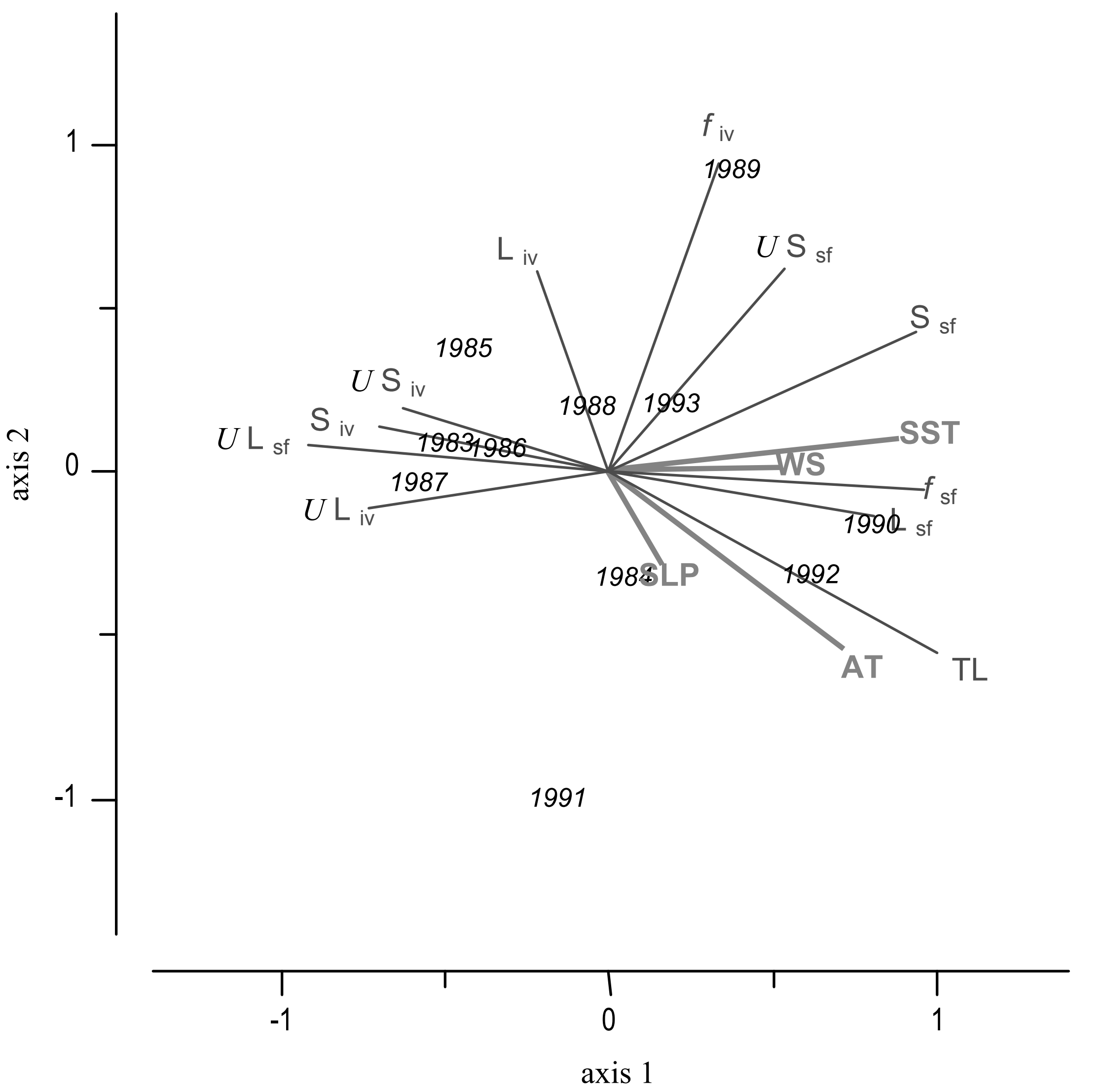
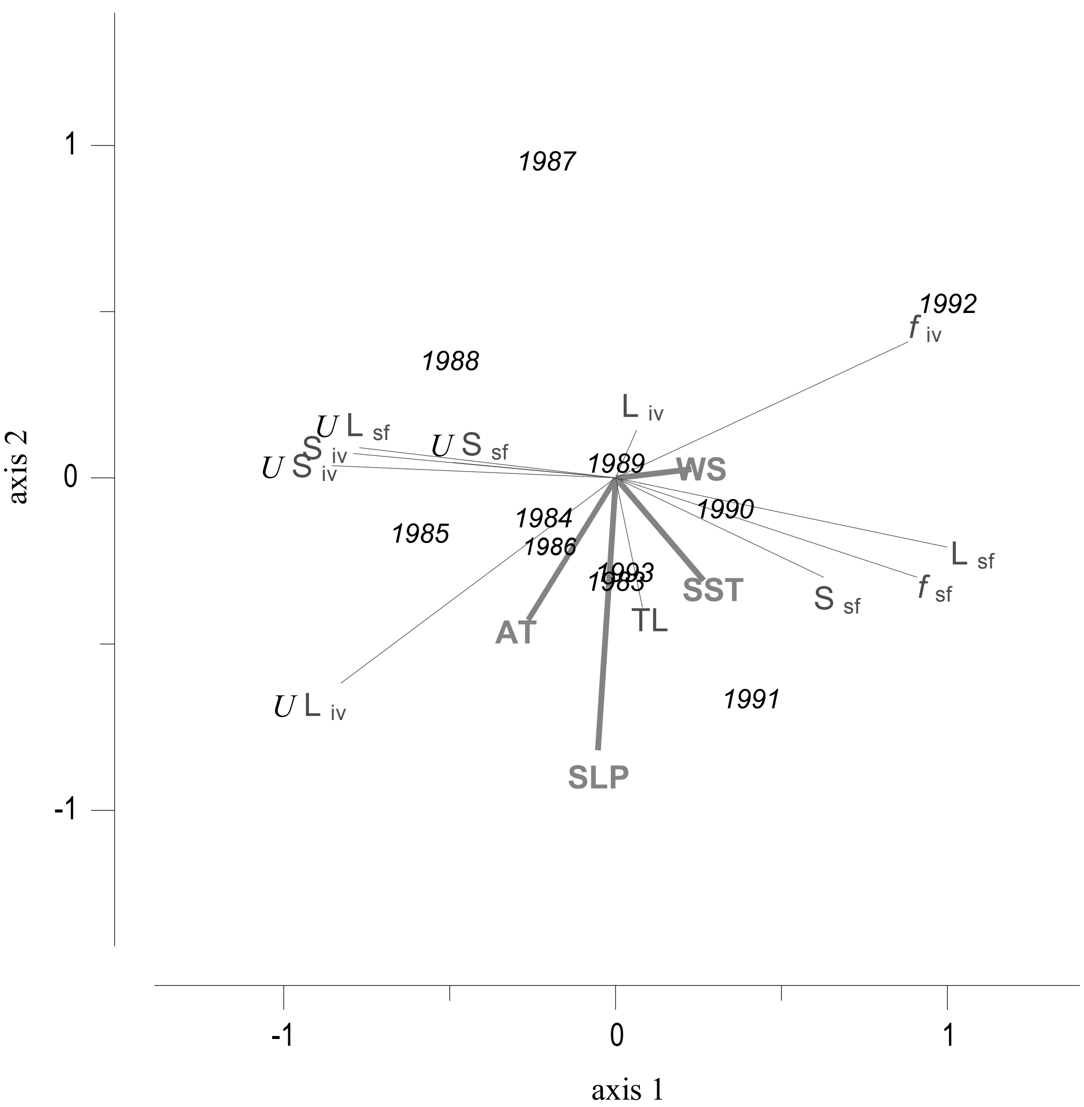
Year
1005
1010
1015
1020



axis 2
axis 1
1
0
-1
-1
0
1
f_{iv}
1989
$U\,S_{sf}$
L_{iv}
S_{sf}
1985
$U\,S_{iv}$
1988
1993
S_{iv}
SST
$U\,L_{sf}$
1983
1986
WS
1987
f_{sf}
$U\,L_{iv}$
1990
L_{sf}
1984
SLP
1992
AT
TL
1991



1987
1992
f iv
1988
L iv
U L sf
U S sf
S iv
U S iv
1989
WS
1990
1984
1985
1986
L sf
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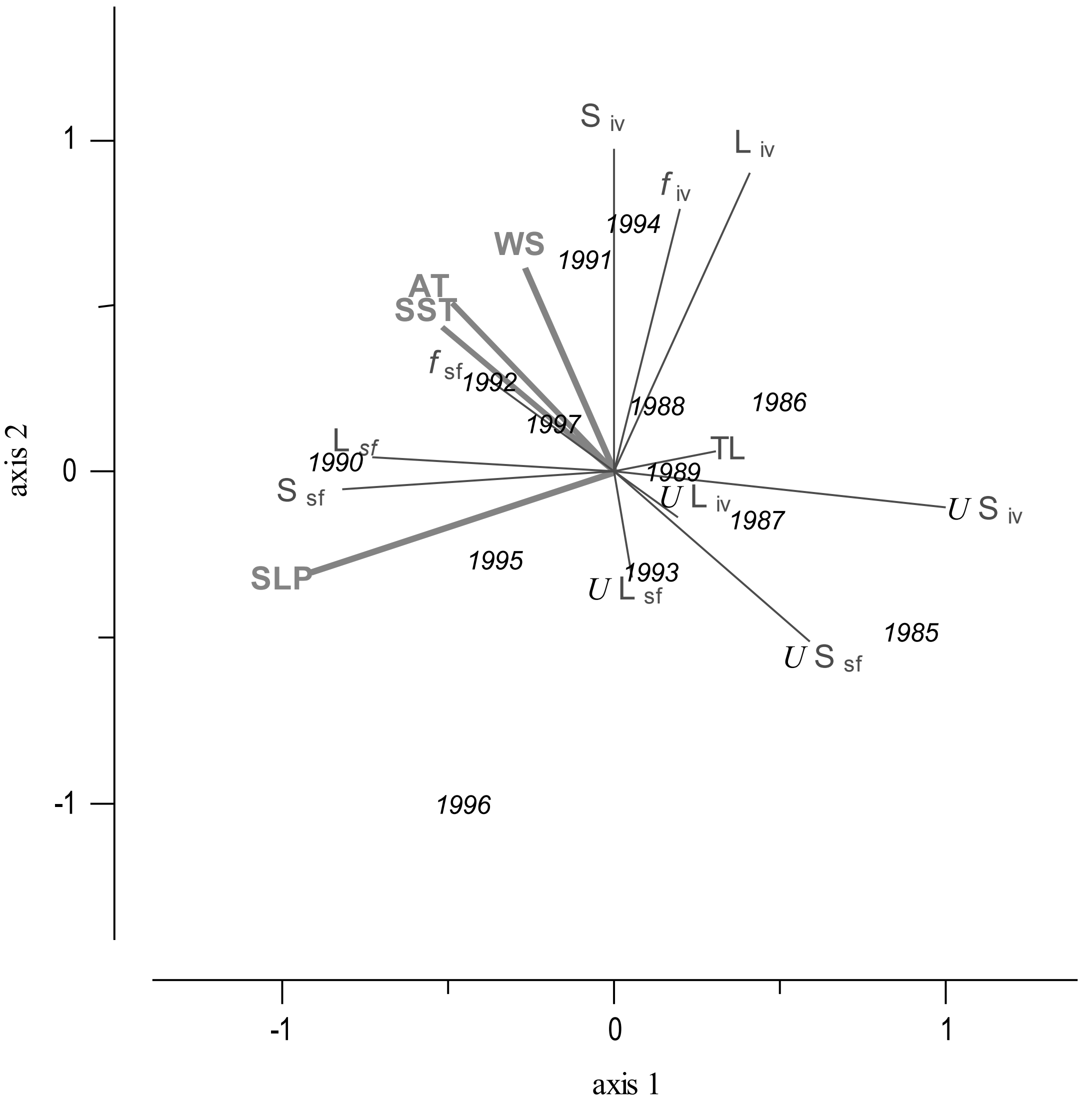
1983
SST
S sf
f sf
AT
TL
U L iv
1991
SLP
axis 2
axis 1
1
0
-1


S iv
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1994
WS
1991
AT
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1986
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L sf
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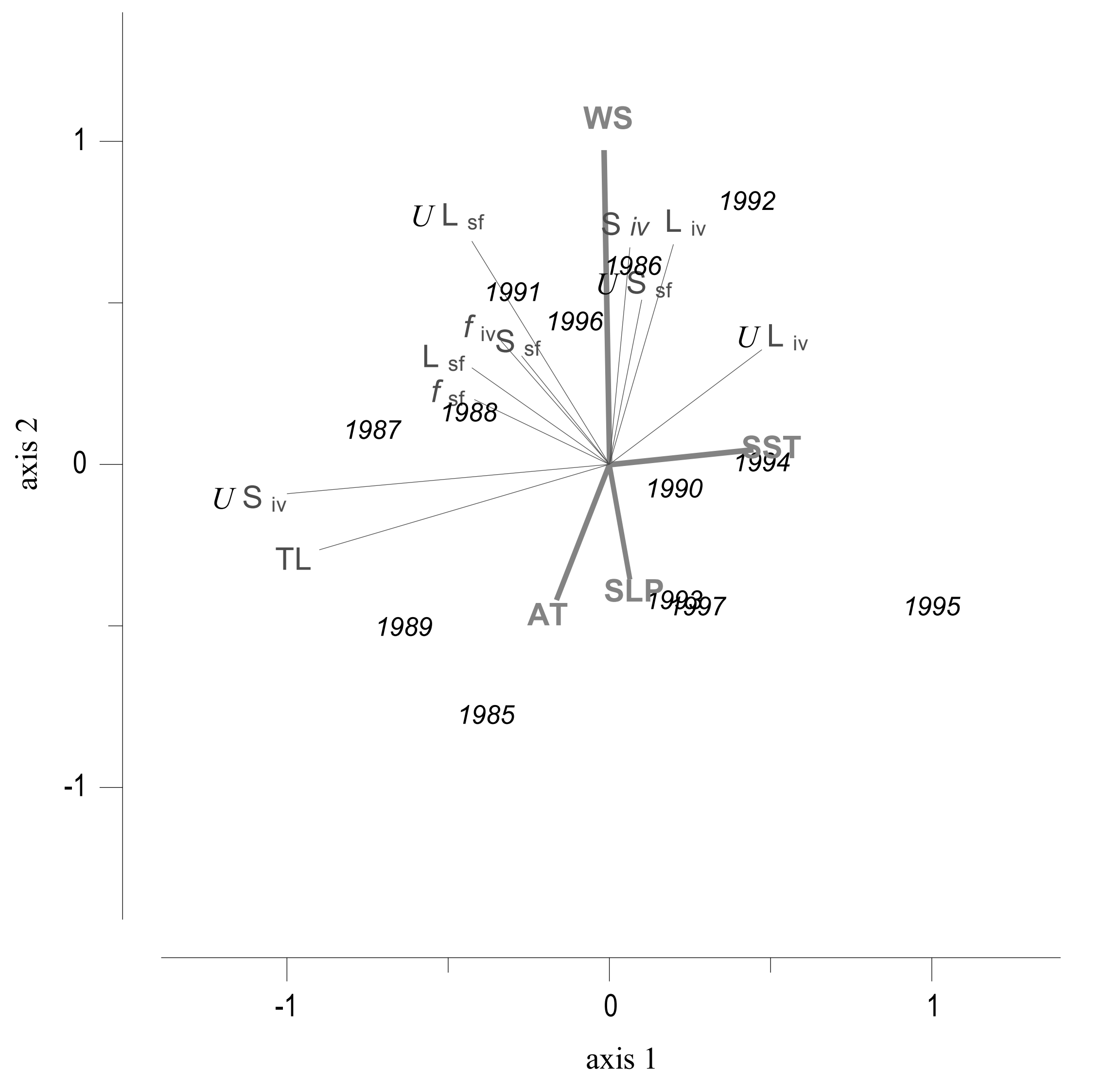
1989
S sf
U L iv
1987
U S iv
1995
SLP
1993
U L sf
1985
U S sf
1996
1
0
-1
axis 2
axis 1



WS
1992
U L sf
S iv
L iv
1986
U S sf
1991
1996
f iv
S sf
U L iv
L sf
f sf
1988
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SST
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U S iv
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1985
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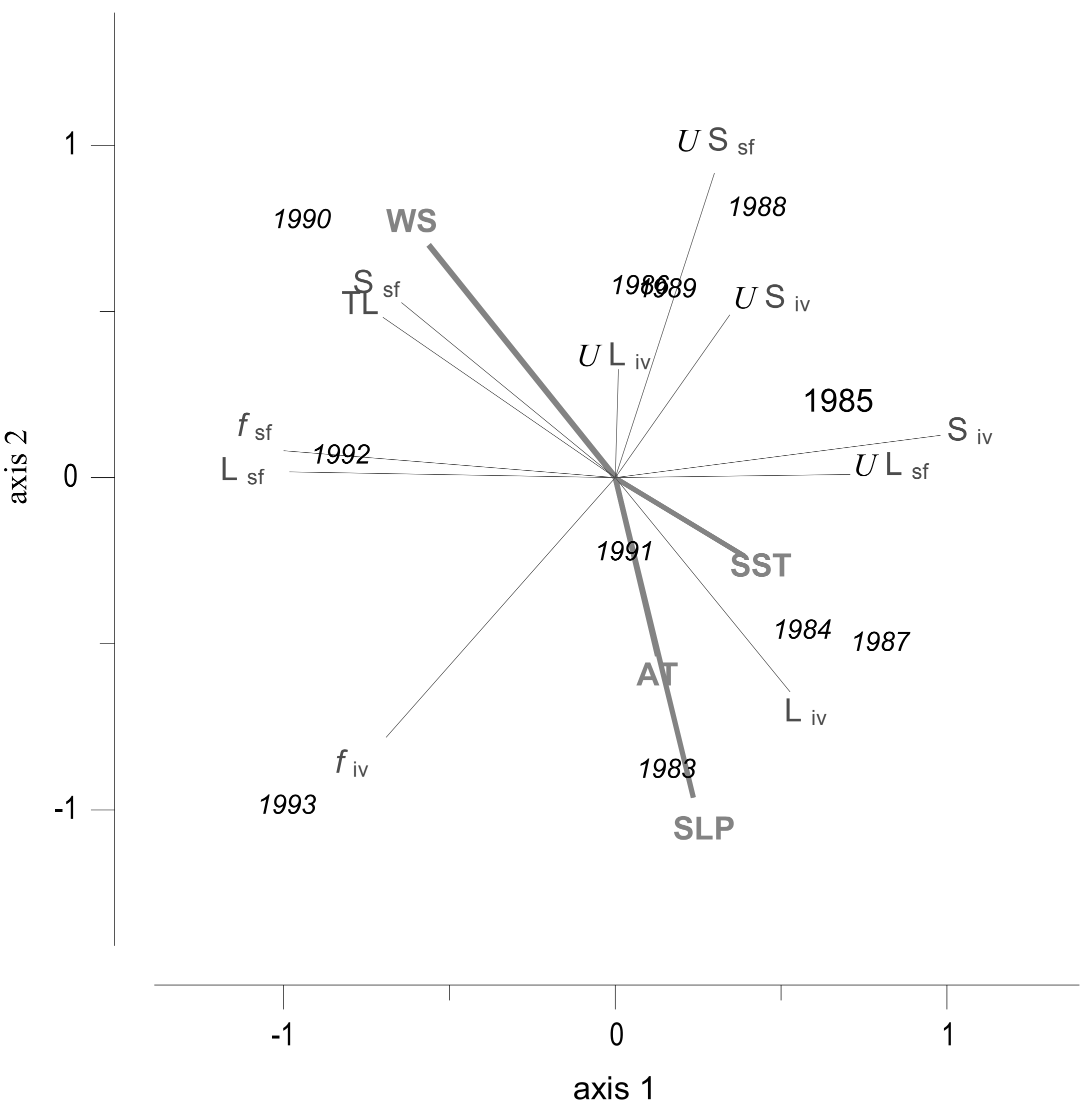
0
-1
-1
0
1
axis 2
axis 1



axis 2
axis 1
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0
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U S sf
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U S iv
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L iv
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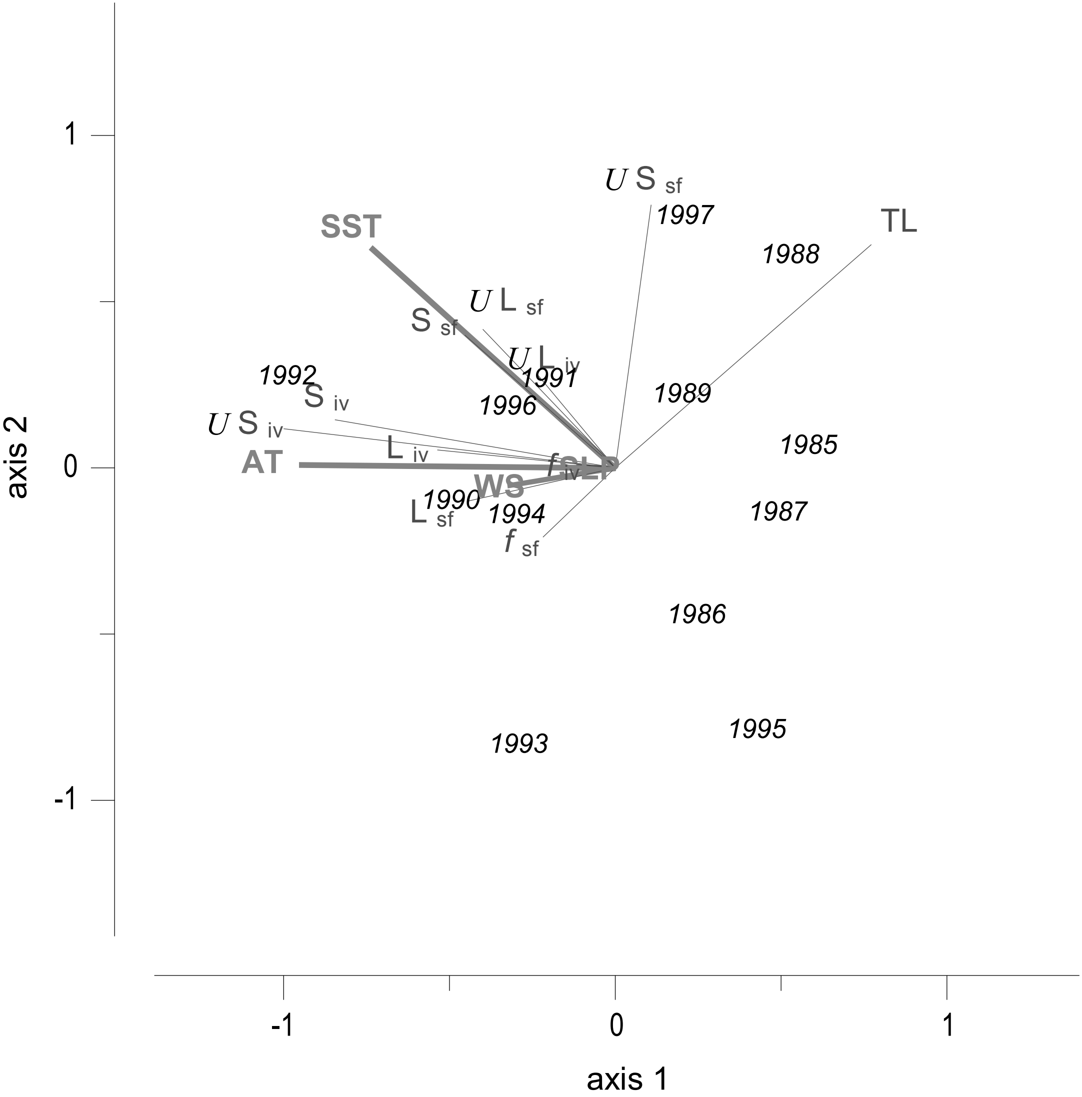

axis 2
axis 1
1
0
-1
-1
0
1
SST
AT
WS
SLP
TL
U S sf
U L sf
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U L iv
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U S iv
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