
Linking small pelagic dietary shifts with ecosystem changes in the Gulf of Lions

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Abstract :

Since 2008, a severe decrease in size and body condition together with a demographic truncation has been observed in the sardine (secondarily in anchovy) population of the Gulf of Lions (NW Mediterranean Sea). In parallel, sprat biomass, which was negligible before, has increased tenfold. All of these changes have strongly affected the regional fisheries. Using trophic and isotopic data from contrasting periods of low versus high growth and condition, we investigated potential changes in diet and interspecific feeding interactions through time. Evidence of resource partitioning was found between sprat and both anchovy and sardine in 2004 and 2005. Since 2010, the isotopic niches of the 3 species have tended to overlap, suggesting higher risk of competition for food resources. Moreover, the wider trophic niche of sprat indicates higher variability in individual diets. Anchovy and sardine diet varied through time, with a high proportion of large copepods or cladocerans in periods of high growth and condition (1994 and 2007, respectively) versus a dominance of small copepods in the present (2011-2012). Furthermore, an important reduction in prey diversity was also identified in the diet of both anchovy and sardine during the most recent period. Our results support the hypothesis that changes in small pelagic fish growth, size and body condition and ultimately biomass could be due to bottom-up control characterized by changes in food availability and increasing potential trophic competition.

Keywords : Trophic ecology, Anchovy, Sardine, Sprat, Dietary overlap, NW Mediterranean

1. INTRODUCTION

Small pelagic fish species are characterized worldwide by important temporal fluctuations of their abundance and biomass, generally ruled by environmental changes in marine ecosystems (Schwartzlose et al. 1999, Alheit & Niquen 2004). Bottom-up control, driven by changing ocean conditions was therefore often argued as the main hypothesis to explain these regime shifts (Cury & Shannon 2004), but changes in plankton quantity and quality is difficult to confirm due to a lack of sufficient observations of the planktonic community in both time and space.

In the Gulf of Lions, sardine (*Sardina pilchardus*, W. 1792), anchovy (*Engraulis encrasicolus*, L. 1758) and sprat (*Sprattus sprattus*, L. 1758) the three main small pelagic species, act as a critical link between planktonic production and top predators (Bănaru et al. 2013). Additionally, anchovy and sardine support pelagic trawling and purse seine fisheries (between 30 and 50% of the total landings in this area, Bănaru et al., 2013), making them both ecologically and economically essential (Palomera et al. 2007). During the last decade, a decrease in size and body condition was observed for anchovy and sardine while at the same time, sprat biomass which had been negligible before, increased tenfold (Van Beveren et al. 2014). These changes made sardine and anchovy commercially less interesting, so that landings dropped dramatically, reaching their lowest values in 150 years for sardines (Van Beveren et al. 2016). Surprisingly, the recruitment has remained high and these modifications primarily affected the adults, with a disappearance of older age classes, especially for sardine (Van Beveren et al. 2014, Brosset et al. 2015).

Such changes in the small pelagic fish community are far less common than changes in recruitment and might result from selective pressure from fishing or natural predation or modifications in prey availability and/or quality. Yet, fishing pressure does not appear to be the main driver of these changes, as these populations were/are not overfished (GFCM 2014) and exploitation rates have remained low over the last 2 decades (i.e. at around 10 to 20% in average without exceeding 40%, see Van Beveren et al. 2016). Predation pressure from Atlantic Bluefin tunas, the main top predator

of those small pelagic fish in this area, has been recently evaluated to be < 2% (Van Beveren et al. *submitted*), indicating that a top-down control is unlikely. While predation due to natural predator or fishing remained at low levels for these species, body condition in sardine and anchovy has been shown to be strongly affected by mesozooplankton abundance (Brosset et al. 2015), advocating for a bottom-up control as the most probable source of small pelagic fish changes in the NW Mediterranean. Unfortunately, plankton records are scarce in the Gulf of Lions, and no time series is currently available to test for such a bottom-up control.

Stomach content analyses and stable isotope analyses (SIA) are two of the main approaches for investigating feeding habits and trophic interactions (Darnaude et al. 2004, Post et al. 2007). Stomach content analyses document recently consumed food items and permit a quantitative and qualitative snapshot of the diet (Hyslop 1980). SIA are complementary to stomach content analyses and allow obtaining an integrated measure of the assimilated food over the previous months depending on the variability of prey and their stable isotope ratios, the fractioning and the isotopic turnover. Values of $\delta^{15}\text{N}$ may be related to the trophic level of an individual, while the $\delta^{13}\text{C}$ ratio indicates the primary production sources, that is, the different feeding environments (coastal/oceanic, pelagic/benthic) used by consumers (Vander Zanden & Rasmussen 1999, 2001). Combining stomach content analyses and SIA has become an effective tool to investigate changes in trophic structure. Hence, their joint use contributes to the further understanding of how an ecosystem may be affected by changes in interspecific interactions (Caut et al. 2006).

Several studies have provided important information on feeding habits and diets of these 3 species in the Gulf of Lions (Plounevez & Champalbert 2000; Costalago et al 2012; Costalago and Palomera 2014; Pethybridge et al. 2014; Le Bourg et al 2015). However, they were usually limited to one species or a given period, so that the investigation of potential temporal changes along the last 15 to 20 years is still missing. The aim of this study was to investigate the hypothesis that recent changes observed in anchovy, sardine and sprat populations from the Gulf of Lions might result from diet

changes. In this study, we propose to investigate changes in the feeding habits between periods of contrasted growth and condition (before and after 2008) defined by Van Beveren et al. (2014). In particular, isotopic interspecific overlap, trophic niche width and prey type were examined through time. Indeed, knowing that sardines, sprats and anchovies strongly co-occur in terms of spatial distribution in the Gulf of Lions (Saraux et al. 2014), trophic overlap between species might result in food competition if resources become limited (Hardin 1960). Moreover, the niche width, i.e. an index of prey diversity estimated through the range of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values or Shannon's diversity may be used to determine how generalist a population might be in terms of diet and feeding areas (Newsome et al. 2007). Finally, prey species composition might have a strong effect on the energy intake of predators (Beaugrand et al. 2003, Blanchard et al. 2012).

2. MATERIAL AND METHODS

2.1 Study area

The Gulf of Lions (42°26'-43°40'N and 3°00'-5°27'E; Fig. 1) is located in the North Western Mediterranean Sea and is characterized by a large continental shelf (Millot 1990). Shallow waters between 0 and 200 meters associated with Rhône river discharge and coastal upwelling due to Northern winds support high productivity, making it one of the most productive areas of the Mediterranean Sea (Minas & Minas 1989, Lefevre et al. 1997). A decreasing trend in the concentration of nutrients exists from East to West and from coastal to deeper waters (Bănaru *et al.*, 2013). The particulate organic matter and phyto- and zooplankton communities at the base of the food webs show inter annual, seasonal and spatial variations in terms of composition and stable isotope ratios inside this area (Darnaude et al. 2004, Bănaru et al. 2014, Espinasse et al. 2014). These variations may be related to the terrestrial and anthropogenic river inputs, to currents and wind forcing influencing the hydrography of the area, as well as to changes in the phyto- and zooplankton

communities in terms of species composition and size classes (Rau et al. 1990, Harmelin-Vivien et al. 2008, Bănaru et al. 2014).

2.2 Sample collection

Fish and zooplankton samples were collected during MERLUMED and Pelagic Mediterranean (PELMED) scientific surveys during the summer under a similar protocol. Fish were sampled with a pelagic trawl with a small-mesh cod-end (mesh length 5 mm, ISO 1107) and towed at an approximate speed of 4 knots over 30 min periods. All specimens were selected randomly from hauls and their standard length was determined to the nearest mm, as well as their mass (to the nearest g) and sex. Numerous stations were sampled each year in the Gulf of Lions (*i.e.* inshore/offshore, West and East) to cover the complete area (Fig 1.) and to avoid bias of interannual differences due to spatial heterogeneity. In 2004, 2005 and 2014, zooplankton was sampled using a vertical WP2 net (200 µm mesh size) at each trawl station (4 stations in 2004 and 2005 and 10 in 2014, respectively). Zooplankton samples were stored in frozen sea water to be used for SIA as bulk. Using a combination of previously published data (Costalago et al. 2012, Le Bourg et al. 2015) and new samples that were analyzed for this study, stable isotope values were available for June and July of 2004, 2005, 2008, and 2010-2014 (except for sprat in 2008 which was not sampled). Stomach content data were available in 2011-2012 for both anchovy and sardine (previously published data; n = 118 & 104 for sardine and anchovy respectively; Le Bourg et al 2015) as well as prior to population changes: in 2007 for sardine (n=156; Costalago et al. 2014) and in 1994 for anchovy (n=50, unpublished).

2.3 Stable isotope analyses

Fish isotope analyses were conducted on a piece of ~1 cm³ of white muscle that had been kept frozen at -80°C (Sweeting et al. 2005).

Both fish white muscle and zooplankton samples were freeze-dried during 48h and grounded into a fine powder before being encapsulated in a tin cup and sent for SIA analysis to the LIENSs laboratory

(La Rochelle, France). An acidification step was necessary for zooplankton samples to remove any ^{13}C -enriched carbonates (DeNiro & Epstein 1978). A subsample was acidified with 1% of HCl, rinsed with distilled water and dried to determine the $\delta^{13}\text{C}$ ratio while an untreated subsample was used for $\delta^{15}\text{N}$ analysis. Three zooplankton replicates were performed from each sampled site for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. A continuous-flow isotope ratio mass spectrometer (Delta V Advantage, Thermo Scientific) coupled to an elemental analyzer (Flash EA1112, Thermo Scientific) was used to perform stable isotope measurements. Results were expressed in parts per thousand (‰) relative to Vienna PeeDee Belemnite and atmospheric N_2 for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively, using the equation:

$$\delta X = ((R_{\text{sample}}/R_{\text{standard}}) - 1) \times 10^3$$

where X is ^{13}C or ^{15}N and R is the isotope ratio $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$, respectively. Replicate measurements of internal laboratory standards (acetanilide) indicated a precision of 0.2‰ for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values.

Variation in lipid content among fish species can introduce a bias in carbon stable isotope analyses (Post et al. 2007). Therefore, the potential effect of lipids on $\delta^{13}\text{C}$ values of fish samples was corrected by applying the procedure of (Post et al. 2007) when the C/N ratio was >3.5 (which was mainly the case for sprat). Thus, the time and uncertainty due to lipid extraction were reduced. For all years, fish length ranges were kept similar (from 10 to 15 cm, Table 1.) to avoid any bias due to ontogenetic changes.

2.4 Stomach content analyses

A similar protocol was applied on all analyses of stomach contents regardless of the year (see details in Costalago and Palomera, 2014; Le Bourg *et al.*, 2015). Briefly, fish were frozen at -20°C immediately after being caught to stop digestive processes. Then, the gut was removed and stored into alcohol (95%) at the laboratory. Each stomach was carefully opened and all prey species were placed in a Petri dish and identified and quantified under a stereo microscope to the lowest possible taxonomic level, depending on the digestion state. Unidentified preys were excluded from the

statistical analyses. A single difference in protocol occurred, as fish were analysed individually in all years except for sardines in 2007, for which fish of a given station were pooled together, i.e. between 16 and 20 stomachs were pooled together. In that case the associated sardine length corresponded to the mean length of all individuals from a given sample. Prey dry weight was derived from literature (see Le Bourg *et al.*, 2015).

Prey importance was assessed using the percentage of occurrence (%O, proportion of stomachs where the prey species was found), percentage in number (%N, ratio between the number of one prey species and the total number of prey), percentage in dry weight (%DW, ratio between the weight of one prey species and the total weight of prey). These percentages were then combined to calculate the Index of Relative Importance (IRI, Pinkas *et al.* 1971), necessary to compute the %IRI, which allows an integrated comparison between dietary items of the same species (Hyslop 1980, Cortés 1997):

$$\%IRI = \frac{IRI}{\sum_{a=1}^n IRI} \times 100$$

where $IRI = \%O \times (\%N + \%DW)$ and n is the number of prey species. Because of potential disparities in species or groups of species names between 1994 and 2011-2012, we carefully linked all prey names to current species name. Due to a lack of correspondence between periods, few species were not retained. However these species/groups of species, all had very low %IRI (< 0.2%), so that their absence could not significantly affect the computation of %IRI and trophic niche width (see below).

The trophic niche width was measured for each period, using the exponential of Shannon's entropy, $N_1 = \exp(H)$, where H is the Shannon-Wiener diversity index: $-\sum_{i=1}^q p_i \ln(p_i)$ and p_i is the proportion of IRI (Hill 1973, Medina *et al.* 2015).

2.5 Data analyses

Determinants of isotopic values

To investigate the potential effect of species, year, fish length, latitude, longitude and coastal/offshore gradient on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, we used the Classification And Regression Tree (CART) approach of Breiman et al. (1984). Decision trees were built by recursively partitioning our dataset into increasingly homogeneous subgroups of isotope values. Each split is defined by a simple rule based on a single explanatory variable, and each final group is characterized by its mean isotope values. Two separate CARTs were applied for fish $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. As less stations and years were sampled for zooplankton, we only tested annual differences in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ to look for interannual variability (2004, 2005 and 2014) using one-way analyses of variance (ANOVA).

Isotopic niches

Standard ellipse areas corrected for small sample size (SEA_c , Jackson et al. 2011), which define the isotopic niche space of 40% of typical individuals within the group based on bivariate normal distributions, were calculated as a measure of the mean core population isotopic niche in order to analyze resource partitioning among species over time. However, because both the shape and size of the area filled by the points influence this estimate, we first scaled isotope values as recommended by Cucherousset & Villéger (2015) to obtain an informative assessment of isotopic overlap. Then, niche overlaps between the different species were determined using SEA_c . Niche overlap varied between 0 (no overlap) and 1 (one species is included in the other species stable isotope space). Additionally to niche overlap, the size of standard ellipses was also compared between species and between years for each species. To do that, bayesian standard ellipse areas (SEA_b) were calculated, which allowed for robust statistical comparisons. In addition, the probability of Bayesian ellipses, which were larger or smaller relative to the compared group was computed (e.g p , the proportion of ellipses in 2011 that were lower than 2012, see Jackson et al. (2011) for more details). We considered two SEA_b to be significantly different when more than 95% of the posterior estimates of one group

were smaller than those of another group (Turner et al. 2010). Estimation via Bayesian inference allowed to make robust comparisons among data sets comprising different sample sizes (Syväranta et al. 2013).

Temporal variation in stomach contents

To describe the temporal variations in stomach contents of anchovy and sardine, we applied a principal component analysis (PCA), which is a multivariate analysis of individuals' stomach contents in function of prey using a correlation matrix. For each predator species, only prey constituting > 2% of %IRI in at least one of our data subsets were considered for the analysis, except for non-identified copepods. Empty stomachs were excluded from this analysis. To deal with different sampling strategies for sardine stomach contents between 2007 and 2011/2012, the 8 stations of 2007 (representing each between 16 and 20 individuals) were weighted by the number of corresponding individuals in the PCA analysis. The PCAs were performed on the dry weight (%DW) of the different prey ingested for each individual. Similar results were obtained when PCAs were performed on the proportion of frequency (%N), showing the robustness of these results.

All statistical analyses were performed with R version 3.0.2. Values are indicated as mean \pm standard error (SE) and all statistical tests were performed at a significance level of 0.05. All data were tested for normality and heteroscedasticity using Kolmogorov-Smirnov and Levene's tests.

3. RESULTS

3.1 Factors influencing isotope values

Fish size, nitrogen and carbon stable isotope ratios were determined for 330 anchovies, 327 sardines and 236 sprats (Table 1. & Fig 2). Using a CART analysis, 85% of the variability in the $\delta^{13}\text{C}$ values were significantly explained by the variables year and species, whereas spatial locations of capture inside the Gulf of Lions (latitude and longitude), fish length and the coastal vs offshore gradient were not

retained (Fig 3a). The year variable had the greatest effect, and $\delta^{13}\text{C}$ values were mainly split accordingly (Fig 3a). First, the maxima for 2004 and 2005 were separated from all other years. In this small group, a secondary partition separated high $\delta^{13}\text{C}$ sprat values from anchovy and sardine values. From all remaining years (2008 to 2014), the years 2010 and 2011 showed the most negative values, especially for sprat (Fig 3a). Years 2008, 2012, 2013 and 2014 had intermediate $\delta^{13}\text{C}$ values, with no differences between the three species studied. Between 2004 and 2014, the $\delta^{13}\text{C}$ isotope values of all three species decreased progressively, but less for sardine and anchovy (-2‰) than for sprat (-3‰) (Fig 2).

According to the CART, 39% of the variability for the $\delta^{15}\text{N}$ signal was accounted for by year and species variables (Fig 3b). In 2005 and 2011 to 2013, $\delta^{15}\text{N}$ values were lower for anchovy and sprat in comparison to sardine (Fig 3b). In contrast, during all others years (2004, 2008, 2010 and 2014), sardine and sprat had more similar $\delta^{15}\text{N}$ values than anchovy. Only in anchovy in certain years did other variables affect isotope values. Indeed, anchovy values in 2004, 2008, 2010 and 2014 also depended on the sampling location, in particular the longitude, with lower values in the East. Moreover, in the Western part during those years, anchovy $\delta^{15}\text{N}$ values increased with size (Fig 3b). However, even if year was significant in the CART analysis (Fig 3b), during our study period only a slight difference in trophic levels was observed for any species ($\delta^{15}\text{N}$ range), with no clear temporal trend (Fig 2).

Similarly to fish, the $\delta^{13}\text{C}$ values of the bulk of zooplankton were higher in 2004 and 2005 in comparison to 2014 (ANOVA, $p < 0.001$) while $\delta^{15}\text{N}$ values remained stable over time (ANOVA, $p > 0.05$; Fig.A.1).

3.2 Temporal changes in isotopic niche overlap

Figure 4 displays the bayesian ellipse areas (SEA_c) that represent the isotopic niche of the three small pelagic species in a scaled isotopic niche space. Two patterns were observed: firstly, sprat was segregated from sardine and anchovy during the two earliest years (2004 and 2005, Fig 4); second,

the overlap of sprat isotopic niche on sardine's was present until 2014 (Table 2.). Sprat also overlapped strongly with anchovy in 2012 and 2013, but no clear temporal trend was evidenced (Table 2.). In contrast, the trophic niche overlap of sardine and anchovy was high in 2004 and 2005 (Table 2.). In 2008, the total anchovy niche even fell within the one from sardine. However, during the subsequent years (2010-2014), overlap was much lower except for 2013 (at least halved compared to before 2010, Table 2.). For each species, the isotopic location of the SEA_c differed among years (Fig 4).

3.3 Temporal changes in isotopic niche width

The niche width of the three species varied notably between years (Fig 2.). The anchovy isotopic niche width decreased between 2004 and 2008 (SEA_B: $P < 0.001$) and then increased to remain steady at middle values (SEA_B: $P > 0.05$, Fig 2.). The sardine isotopic niche width also decreased between 2004 and 2005 (SEA_B: $P < 0.001$), but increased between 2005 and 2008 (SEA_B: $P < 0.01$) to then decrease again in 2010 (SEA_B: $P < 0.01$) and finally remain steady until 2014 (SEA_B: $P > 0.05$, Fig 2.). The isotopic niche width of sprat decreased between 2004 and 2010 (SEA_B: $P < 0.01$) and subsequently increased and stabilized from 2011 to 2014 (SEA_B: $P > 0.05$, Fig 2.). In 2010 and 2013, the SEA_B width was similar between all three species (SEA_B: $P > 0.05$, Fig 2.). On the contrary, during years 2004, 2005, 2011, 2012 and 2014, sprat always had a larger SEA_B than sardine and anchovy (SEA_B: $P < 0.05$, Fig 2.). Thus, sprat always had a larger or equivalent isotopic niche width when compared to anchovy or sardine. In 2008, when only two species were available, sardine SEA_B was significantly larger than the anchovy one (SEA_B: $P < 0.001$).

3.4 Size, area and temporal variations in diet composition

The diet of sardine and anchovy was mainly zooplanktivorous, with some traces of phytoplankton consumption (diatoms) in 2011-2012 for both species (see Tables 3 and 4). The anchovy diet in 1994 was characterized by the dominance of *Acartia clausi* (18.23 %IRI), *Microsetella* spp (13.52 %IRI), Clauso/Paracalanidae (13.22 %IRI), *Oncaea* spp. (12.67 %IRI) and Euphausiacea larvae (7.31 %IRI)

(Table 3). Copepods also dominated the anchovy diet in 2011-2012, but anchovy fed almost only on two species: *Microsetella* spp (34.78 %IRI) and *Oncaea* spp. (27.52 %IRI). In 2007, sardine diet was composed of copepods (60.31 %IRI, mainly *Euterpina acutifrons*, *Microsetella* spp. and *Temora stylifera*) and cladocerans (31.48 %IRI). In contrast, cladocerans were almost absent in 2011-2012, while *Microsetella* spp. (29.34 %IRI), *Oncaea* spp. (24.55 %IRI) and *Corycaeus* spp. (21.64 %IRI) dominated the sardine diet (Table 4). For both sardine and anchovy, we also found a strong increase in the proportion of Corycaeidae during years 2011 and 2012.

The trophic niche width, measured with the exponential of Shannon's entropy was highest in the earliest period studied for both species (10.84 in 1994 versus 5.57 in 2011-2012 for anchovy (Table 3), and 8.54 in 2007 versus 6.46 in 2011-2012 for sardine, see Table 4).

In the PCA performed on the dry weight (%DW) of the different prey of anchovy, the first (F1) and second (F2) component represented respectively 35% and 25% of the total variance (Fig 5). F1 represented a gradient whereby *Oncaea* spp was opposed mainly to *Acartia clausi* and Clauso/Paracalanidae species. F2 represented a gradient opposing *Microsetella* spp to *Acartia clausi* and Clauso/Paracalanidae species in anchovy diet. The majority of anchovy from 1994 had negative values on both axes while the majority of anchovy from 2011-2012 had positive values. Thus, we deduced an increasing proportion in dry weight of *Microsetella* spp and *Oncaea* spp and a decreasing proportion of *Acartia clausi* and Clauso/Paracalanidae species in the anchovy diet from 1994 to 2011-2012 (Fig. 5). In the PCA carried out on the sardine data, F1 and F2 represented 44% and 18% of the total variance respectively (Fig 6.). *Microsetella* spp was opposed to *Oncaea* spp, *Corycaeus* spp and cladocerans on F1 axis, while the second axis showed a clear separation between the cladocerans and other prey species. The two time periods were opposed on the second axis reflecting a decreasing gradient of cladocerans and an increasing proportion of *Oncaea* spp, *Corycaeus* spp and *Microsetella* spp in the sardine diet from 2007 to 2011-2012. Fish length (4 length classes of 1.5 cm

from 10 to 16 cm) as well as sampling area (3 areas; West, Central and East) were plotted on the PCA, but both factors displayed no trend.

4. DISCUSSION

Data availability does not allow us to describe the trophic ecology along the last 20 years, but we can contrast the present situation to data collected before the drastic changes in demography occurred. The comparison of small pelagic trophic data: (i) showed wider isotopic niche in sprat compared to sardine and anchovy; (ii) tended to confirm the hypothesis of changes in the anchovy and sardine diets and (iii) suggested a recent increase in the trophic overlap between the different small pelagic fish species of the Gulf of Lions.

Using SIA and isotope-derived metrics to study interspecific trophic differences, we showed that sprat had a larger isotopic niche width (in 2004, 2005, 2011, 2012 and 2014) than sardine and anchovy or at least equivalent (in 2010 and 2013), mainly due to the broad range of $\delta^{13}\text{C}$. Assuming that wider sprat isotopic niche reflects higher variability in individual diets (Matthews & Mazumder 2004), sprat intraspecific trophic competition may be lower than those of other species. Additionally, stomach content analyses tended to indicate a slightly more diversified sprat diet (Le Bourg et al. 2015). These results are particularly interesting from a population dynamics viewpoint. Indeed, sprat biomass has considerably increased since 2008, while the ratio biomass/abundance of both sardine and anchovy has considerably declined (GFCM 2015). Previous studies have shown that those changes were mainly driven by reduced growth, age truncation and condition and bottom-up processes were the most likely drivers (Van Beveren et al. 2014). Being a generalist feeder with low intraspecific food competition might thus have conferred important advantages to sprat over sardine and anchovy, especially to adapt to environmental changes. This might also explain why sprat body condition was more stable, while sardine and anchovy condition exhibited stronger ups and downs, possibly in reaction to prey variability (Van Beveren et al. 2014).

This study also depicts a considerable reduction in both sardine and anchovy isotopic niche through time. The carbon isotopic composition of fish muscle is mainly related to the ingested preys (Hobson 1999). As previously stated, strong changes in $\delta^{13}\text{C}$ values of small pelagic fish and zooplankton were observed along years. Differences between years in fish stable isotope values may be due to inter-annual differences in the planktonic community and/or the organic matter, the latter being at the basis of the food web. The Gulf of Lions is further known as a highly variable area in water circulation, productivity and stable isotope ratios of plankton community (André et al. 2005, Espinasse et al. 2014), which could add variability in fish isotopic signature. Yet, similarly to previous findings obtained with a different methodology (e.g fatty acid profiles, Pethybridge et al. 2014), we showed that isotopic values did not differ between sampling areas except for $\delta^{15}\text{N}$ in anchovy during some years, underlining the weak influence of the sampling area on the isotopic values at the scale of the present study. This allows us to reasonably assume that differences were not due to sampling bias, even if the sampling locations varied from year-to-year. A reduction of the anchovy isotopic niche was observed between 2004 and 2013, although the largest shrinkage occurred between 2004 and 2005. Nevertheless, this considerable change in isotopic niche area between the two years has to be considered with caution, due to the lower sampling size in 2005 in comparison to 2004 which reduces the precision of the estimated mean of niche width (see Syväranta et al. 2013). The largest reduction in sardine isotopic niche was observed between 2008 and 2013, concomitantly with the decrease in sardine size, condition and biomass.

Moreover, stomach contents also confirmed a significant reduction in the trophic niche width of both anchovy and sardine (25% and almost 50%, respectively). Specifically, both species displayed a much narrower diet during recent years (2011-2012) compared to previous time periods (1994 or 2007). This might have resulted from a decrease in the availability of certain prey species, downplaying their role in the diet of the small pelagics, as indicated by temporal differences in composition and size range of consumed prey. The sampling methodology has been kept as consistent as possible during the study, especially in terms of season, fishing gear and daylight time. Hence, changes could only be

related to variables such as year, area and fish size. However, no size class or sampling area effects were detected during analyses, so that observed changes are likely to be due to a year effect. For adult anchovy and sardine, copepods were, as in most other studies in the Mediterranean (see Tudela & Palomera 1997, Borme et al. 2009, Nikolioudakis et al. 2012), by far the most important prey item, regardless of the year. However, there was a prey size reduction between both periods. In 1994, large copepods (size >1 mm, *Acartia* spp., *Candacia* spp., *Clauso/Paracalanus* spp. and *Centropages typicus*), attained almost 50% of the relative importance index (%IRI) and 65% in relative dry weight (%DW). This contrasted with 2011-2012 years when they represented barely more than 5% of the relative importance index and 15% in relative dry weight (Le Bourg et al., 2015). Large copepods in the anchovy diet were replaced in 2011-2012 by small copepods species (size <1 mm, such as Coryceidae, *Microsetella* spp. and *Oncaea* spp.), which increased threefold. The proportion of small and large copepods in 1994 was in agreement with another study from 1995 and 1996, performed in the same area and during the same period (Plounevez & Champalbert 2000). Marked changes between 1994 and 2011/2012 in the anchovy diet also concerned other prey groups, such as cladocerans that became practically absent in recent years, larvae (mainly Euphausiacea) that also decreased while diatoms appeared. The decrease of large Euphausiacea larvae, recognized as important anchovy prey in other areas such as the Humboldt current (Ayón et al. 2011), might have accentuated the deficiency in large prey species.

Similarly, small copepods dominated sardine diet in recent years, while cladocerans were the dominant prey in 2007. Assuming that larger copepods have a higher energy content (Dumont et al. 1975, Vijverberg & Frank 1976, Zarubin et al. 2014), current nutritional conditions of anchovy and sardine might have thus strongly decreased compared to pre-2008, potentially explaining the strong demographic changes observed in both species after 2008. Furthermore, fish were sampled in July, when adults need to accumulate their fat supply to survive the next winter (Wiegand 1996, Sánchez-Gómez 2013). Therefore, the lack of large copepods in their stomachs could reflect difficulties to build a sufficient fat to survive an energetically demanding winter, especially so for sardines which

reproduce at that moment. This might thus explain the apparent adult overmortality detected for sardine (less pronounced for anchovy, Van Beveren et al. 2014). However, in order to better understand the impact of the changes in sardine and anchovy diet, a detailed investigation of zooplankton variations in terms of quantity/quality and fish energetics would be required.

Nonetheless, considering the usual importance of large copepods in the diet of anchovy and sardine, these changes probably reflect a potential decrease in their availability, which might result either from an increase in competition between fish species or a decrease in abundance of large copepods. First, the increase in sprat abundance and biomass might have drawn more intensive interspecific competition. Indeed, all three species have been shown to inhabit the same areas and to spatially co-occur in the Gulf of Lions, except for some deeper grounds where only anchovy occurs (Saraux et al. 2014).

The hypothesis of an increased interspecific competition during the last decade is supported by the changes in the degree of overlap and segregation in the isotopic niches of the fish species. Indeed, there was clear isotopic niche segregation between sprat and the two other species in 2004 and 2005, indicating that sprat could have exploited different species groups from anchovy and sardine during these still prosperous years. On the contrary, sprat diet has overlapped significantly with anchovy and/or sardine diet since 2010. Conversely, the overlap between anchovy and sardine was strong in 2004, 2005 and 2008, but was nearly inexistent in 2010, 2011, 2012 and 2014. These stable isotope analyses are in accordance with stomach content analyses, which also provided evidence for potential strong competition between sprat, sardine and anchovy (Le Bourg et al. 2015). So, this study underlined the importance of new food sharing in the context of the recent increase of the sprat population. The special case of 2013 might be caused by very limited food resources (quantitatively or/and qualitatively), forcing the three species to highly exploit prey species with similar stable isotope ratios (possibly similar prey species).

Second, beyond prey size spectrum changes, we also showed the decreasing richness of small pelagic fish diet with time. This result was in agreement with observed and modeled changes in the composition and the phenology of zooplankton in Mediterranean areas surrounding the Gulf of Lions (Balearic Sea: Auger et al., 2014; Puelles and Molinero, 2008; Ligurian Sea: Molinero et al., 2008, 2005). Recent low prey diversity and small prey sizes suggest that recent environmental changes affected the planktonic production. This study, despite some missing values in some years, showed a decreasing trend in $\delta^{13}\text{C}$ values for zooplankton. This is also in agreement with other studies, which underlined similar isotopic values in 2010 and in 2014, and most importantly strictly lower values in 2010 than in 2004 and 2005 (Bănaru et al., 2013; Espinasse et al., 2014; Strady et al., 2015). Although isotopic variations may result from a multitude of drivers, strong differences documented in this study could support important changes in the planktonic community and/or in the organic matter sources. Auger et al., (2014) showed that climatic and environmental variations may induce changes in size structure of the plankton community, while Rau et al., (1990) showed that small phytoplankton (pico and nano phytoplankton) had lower $\delta^{13}\text{C}$ values than micro phytoplankton. Interestingly, possible reduction in $\delta^{13}\text{C}$ values for zooplankton between 2004/2005 and 2010 correspond to the period of the drastic changes in small pelagic fish populations (Van Beveren et al. 2014). As already observed in the Benguela ecosystem, where shifts between anchovy and sardine regimes were caused by changes in the availability of mesozooplankton prey mediated through changes in environmental conditions (Shannon et al. 2004), growth and condition of sardine and secondarily anchovy in the Gulf of Lions are also likely to be mediated by a bottom-up control.

CONCLUSION

This study supports the hypothesis that changes in small pelagic fish growth, size and body condition could be due to a bottom-up control characterized by changes in food availability or/and increasing potential trophic competition, two other factors that might influence the feeding success and the energy allocation. Our results illustrate the utility of comparing feeding habits between periods using

a combination of short (stomach content) and longer term (SIA) indicators. This not only helps to understand the current ecosystem fluctuations in the Gulf of Lions, but also provides an insight in the trophic dynamics of the pelagic ecosystem, possibly allowing a more efficient monitoring of marine food-web evolution.

Acknowledgements

The authors are grateful to the captain and the crew of RV “L’Europe”, as well as all the scientists onboard for their assistance during PELMED surveys. PELMED surveys are co financed by Europe through the Data Collection Framework. The authors express their thanks to Isabel Palomera for providing Spanish data, Mireille Harmelin-Vivien for comments on previous works, Gaël Guillou for performing stable isotope analyses and Virginie Marques for artwork help. This research was partly funded through the EcoPelGol project (Study of the Pelagic ecosystem in the Gulf of Lions), financed by France Filière Pêche (FFP) and partly funded through PERSEUS (Policy-oriented marine Environmental Research for the Southern EUropean Seas) financed by FP7 EU project, EMIBIOS (End-to-end Modelling and Indicators for BIOdiversity Scenarios) financed by FRB (Fondation pour la Recherche et la Biodiversité) and IPP (Intéractions plankton – planctonophages) financed by WP2 MERMEX (Marine Ecosystems Réponse dans l'Expérience de la Méditerranée). PB acknowledges doctoral fellowship support from the French Ministère de l’Education Nationale, de la Recherche et de la Technologie.

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Table 1. Mean standard length (in mm \pm standard deviation, sd) and number of samples analysed (n) for stable isotopes of *Engraulis encrasicolus*, *Sardina pilchardus* and *Sprattus sprattus*.

Year	<i>Engraulis encrasicolus</i>		<i>Sardina pilchardus</i>		<i>Sprattus sprattus</i>	
	Standard length (mm)		Standard length (mm)		Standard length (mm)	
	Mean \pm sd	n	Mean \pm sd	n	Mean \pm sd	n
2004	113 \pm 16	65	131 \pm 22	83	106 \pm 6	14
2005	121 \pm 15	29	129 \pm 18	25	114 \pm 8	8
2008	115 \pm 4	15	136 \pm 4	17	NA	NA
2010	110 \pm 4	32	100 \pm 5	33	87 \pm 8	32
2011	103 \pm 19	61	117 \pm 14	51	96 \pm 8	57
2012	97 \pm 5	36	111 \pm 13	38	95 \pm 8	50
2013	108 \pm 17	43	104 \pm 18	38	103 \pm 8	39
2014	111 \pm 14	49	121 \pm 15	42	94 \pm 9	36

Table 2. Standard ellipse overlaps for each combination of species. The values represent the percentage of overlap between the standard ellipse areas in the scaled stable isotope space. Each number in the cell refers to the percentage of overlap of the area of the species indicated first (e.g 68% is the percentage of ellipses of sardine that are overlapped with the ellipses of the anchovy while 52% is the percentage of the ellipses of anchovy that are overlapped with sardine).

Year	Sardine Anchovy	Anchovy Sardine	Anchovy Sprat	Sprat Anchovy	Sardine Sprat	Sprat Sardine
2004	68	52	0	0	0	0
2005	58	89	0	0	0	0
2008	100	15	NA	NA	NA	NA
2010	0	0	0	0	50	41
2011	12	14	8	6	41	35
2012	14	13	69	52	43	30
2013	69	63	65	65	54	49
2014	32	27	9	5	70	32

Table 3. Summary of stomach content analysis for *E. encrasicolus*. %N: Percent number; %W: percent estimated dry weight; %O: percent frequency of occurrence; %IRI: percent Index of Relative Importance; $\text{Exp}(H)$: trophic niche width determinate with stomach content.

Prey type	1994				2011 and 2012				
	%N	%W	%O	%IRI	%N	%W	%O	%IRI	
Crustacea									
Copepods									
	<i>Acartia clausi</i>	6.60	30.36	57.90	18.23	2.64	7.98	18.27	2.29
	Clauso-Paracalanidae	13.54	19.49	52.63	13.22	6.36	3.68	15.38	1.83
	<i>Centropages typicus</i>	9.76	4.82	50	6.21	3.60	3.64	21.15	1.81
	<i>Corycaeus</i> spp.	1.72	2.05	55.26	1.78	4.45	23.81	43.27	14.46
	<i>Clytemnestra</i>	0.02	<0.01	2.63	<0.01	0.08	<0.01	1.92	<0.01
	<i>Candacia</i> spp.	4.00	8.15	44.74	4.63	0.90	1.10	10.58	0.25
	<i>Oithona</i> spp.	1.48	0.07	42.11	0.55	0.12	<0.01	5.77	<0.01
	<i>Oncaea</i> spp.	15.30	0.39	94.74	12.67	20.15	15.43	65.38	27.52
	<i>Microsetella</i> spp.	16.08	0.22	97.37	13.52	26.38	13.34	74.04	34.78
	<i>Euterpina acutifrons</i>	1.25	0.36	94.74	1.30	2.01	0.13	36.54	0.89
	<i>Temora stylifera</i>	1.22	0.41	42.11	0.59	0.02	<0.01	0.96	<0.01
	Unidentified Copepods	23.26	0.78	71.05	14.55	15.36	18.69	32.69	13.16
	Cladoceran	2.79	5.36	73.68	3.37	0.33	<0.01	9.62	0.04
	Ostracod	0.29	0.03	44.73	0.08	1.29	0.29	22.12	0.41
Tunicata									
	Appendicularia	-	-	-	-	0.12	<0.01	0.96	<0.01
Protists									
	Diatoms	-	-	-	-	9.21	9.60	3.85	0.86
Chaetognatha									
	Chaetognatha	0.05	0.01	2.63	<0.01	-	-	-	-
Larvae									
	Crustaceae								
	Euphausiidae	0.21	26.96	31.57	7.31	2.34	3.31	7.69	0.45
	Decapoda	0.35	0.19	34.21	0.16	1.89	1.47	11.54	0.46
	Mollusca								
	Gasteropoda	<0.01	0.03	5.26	<0.01	1.98	0.04	10.58	0.25
	Bivalve	0.02	0.30	42.11	0.11	1.68	0.29	23.08	0.54
Eggs									
	Anchovy egg's	0.15	0.09	47.37	0.10	1.1	0.49	16.35	0.31
	Other fish egg's	0.24	0.42	50	0.28	0.14	<0.01	2.88	<0.01
				$\text{Exp}(H) = 10.84$					$\text{Exp}(H) = 5.57$

Table 4. Summary of stomach content analysis for *S. pilchardus*. %N: Percent number; %W: percent estimated dry weight; %O: percent frequency of occurrence; %IRI: percent Index of Relative Importance; $Exp(H)$: trophic niche width determinate with stomach content.

Prey type	2007				2011 and 2012				
	%N	%W	%O	%IRI	%N	%W	%O	%IRI	
Crustacea									
Copepods									
	<i>Acartia clausi</i>	-	-	-	-	3.58	8.14	0.12	1.74
	Clauso-Paracalanidae	3.26	6.78	62.50	4.36	7.07	5.05	0.41	5.95
	<i>Centropages typicus</i>	-	-	-	-	1.51	1.55	0.13	0.49
	<i>Corycaeus</i> spp.	4.09	4.11	75.00	4.28	8.61	30.10	0.46	21.64
	<i>Clytemnestra</i>	-	-	-	-	0.43	0.16	0.03	0.02
	<i>Candacia</i> spp.	0.16	18.27	12.50	1.60	0.13	1.04	0.03	0.04
	<i>Oithona</i> spp.	-	-	-	-	0.16	0.04	0.04	<0.01
	<i>Oncaea</i> spp.	11.58	0.61	100	8.48	17.61	12.27	0.68	24.55
	<i>Microsetella</i> spp.	6.31	11.11	87.50	10.60	24.65	10.09	0.70	29.34
	<i>Euterpina acutifrons</i>	3.82	19.27	62.50	10.03	9.12	4.43	0.36	5.87
	<i>Temora stylifera</i>	2.01	30.95	50.00	11.46	-	-	-	-
	Unidentified Copepods	10.73	2.92	100.00	9.50	9.43	6.06	0.25	4.77
	Cladoceran	43.64	1.63	100	31.48	1.08	0.70	0.11	0.24
	Ostracod	-	-	-	-	1.09	1.55	0.12	0.39
Tunicata									
	Appendicularia	0.08	0.06	12.50	0.02	-	-	-	-
Protists									
	Diatoms	8.39	0.79	75.00	4.79	5.85	9.00	0.11	2.03
Chaetognatha									
	Chaetognatha	-	-	-	-	<0.01	<0.01	<0.01	<0.01
Larvae									
	Crustaceae								
	Euphausiacea	-	-	-	-	-	-	-	-
	Decapoda	0.54	2.63	37.5	0.83	0.09	0.76	0.05	0.05
	Mollusca								
	Gasteropoda	-	-	-	-	0.12	<0.01	0.02	<0.01
	Bivalve	1.29	0.19	50.00	0.51	1.09	1.04	0.09	0.24
Eggs									
	Anchovy egg's	-	-	-	-	5.40	6.87	0.11	1.68
	Other fish egg's	-	-	-	-	2.80	0.83	0.21	0.91
				$Exp(H) = 8.54$					$Exp(H) = 6.46$

Figure captions:

Figure 1. Sampling sites in the Gulf of Lions (Northwestern Mediterranean Sea). The left panel indicates isotope sampling locations and the right one stomach content sampling locations.

Figure 2. Summary of a) $\delta^{13}\text{C}$, b) $\delta^{15}\text{N}$ values (mean, s.d., in ‰) and c) trophic niche size of the 3 species over time in the Gulf of Lions. SEA_c (SEA_c : standard ellipse area) are indicated in ‰². The Bayesian area estimate of the standard ellipse metrics (SEA_B) that present differences between years for each species are indicated by superscripts.

Figure 3. Classification and regression tree assessing the importance of year, species, fish length, latitude, longitude and coastal/offshore gradient on (A) $\delta^{13}\text{C}$ values and (B) $\delta^{15}\text{N}$ values. Trees are split off on the values of one covariate at a time such that the overall variance in the dependent variable is minimized at each split. Terminal nodes indicate the value of assigned $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ to the node.

Figure 4. Species scaled isotopic niche space between 2004 and 2014, represented by solid bold lines based on the area of the standard ellipses corrected to small samples sizes (SEAc). Stable carbon and nitrogen isotope values are from the muscle of adult anchovy, sardine and sprat.

Figure 5. Principal component analysis of the dry weight percentage of the main anchovy prey in the Gulf of Lions. Cory: *Corycaeus* spp; Micr: *Microsetella* spp; Clpa: Clauso-Paracalanidae; Onca: *Oncaea* spp; Cand: *Candacia* spp; Acar: *Acartia clausi*; Euph: Euphausiacea; Cent: *Centropages typicus*. Barycenters of the years (Y) are added as supplementary variables.

Figure 6. Principal component analysis of the dry weight percentage of the main sardine prey in the Gulf of Lions. Clad: cladoceran; Temo: *Temora stylifera*; Cory: *Corycaeus* spp; Micr: *Microsetella* spp; Eute: *Euterpina acutifrons*; Diat: Diatoms; Clpa: Clauso-Paracalanidae; Onca: *Oncaea* spp. Barycenters of the years (Y) are added as supplementary variables.

Figure 1.

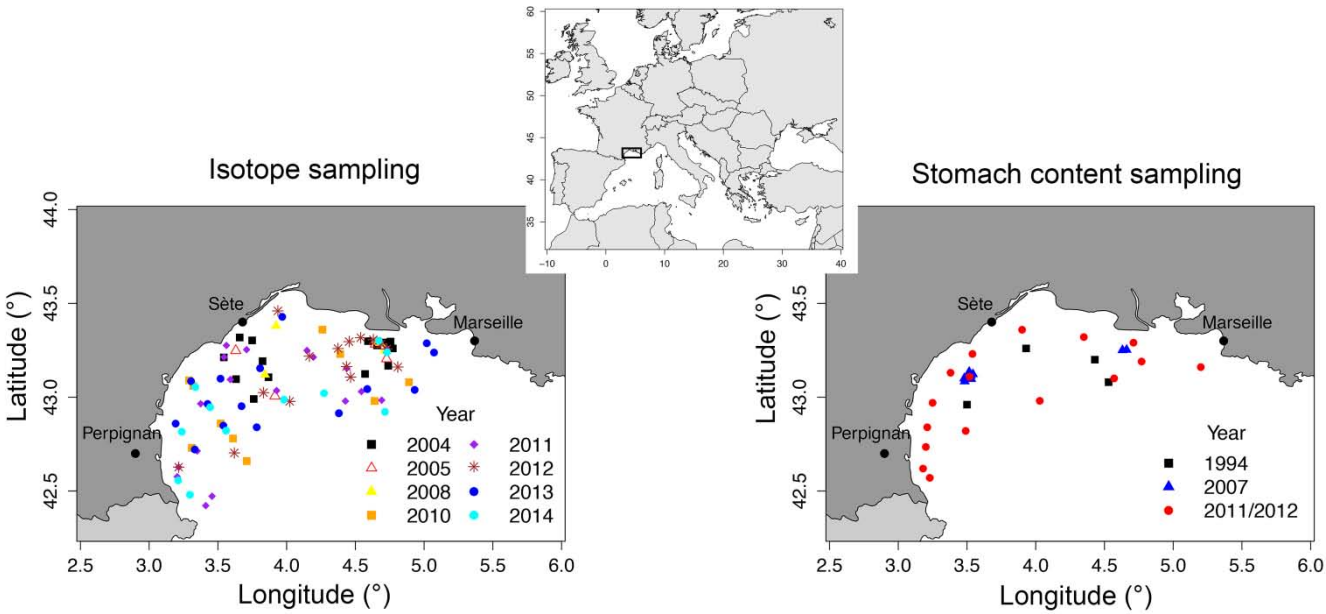


Figure 2.

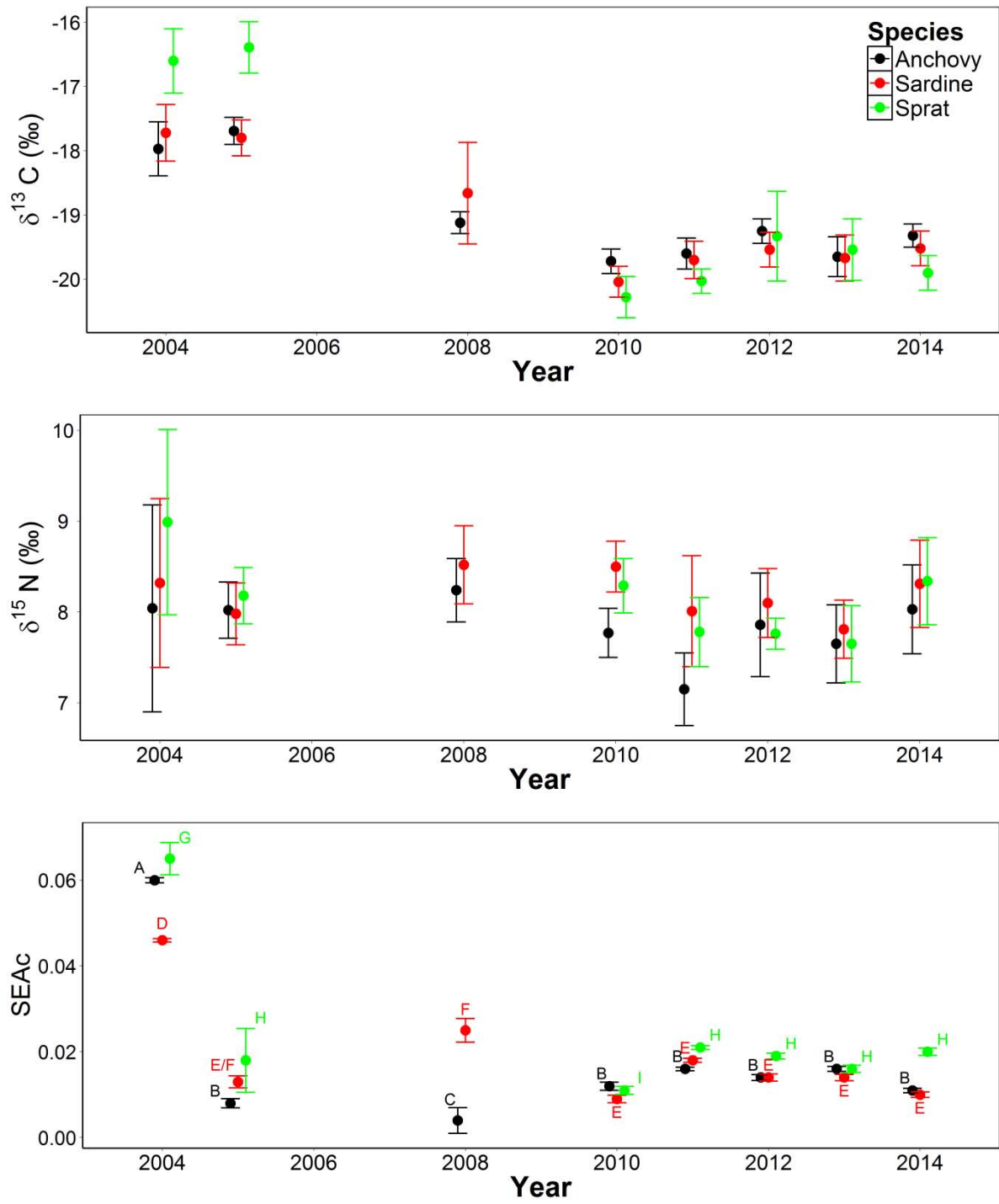
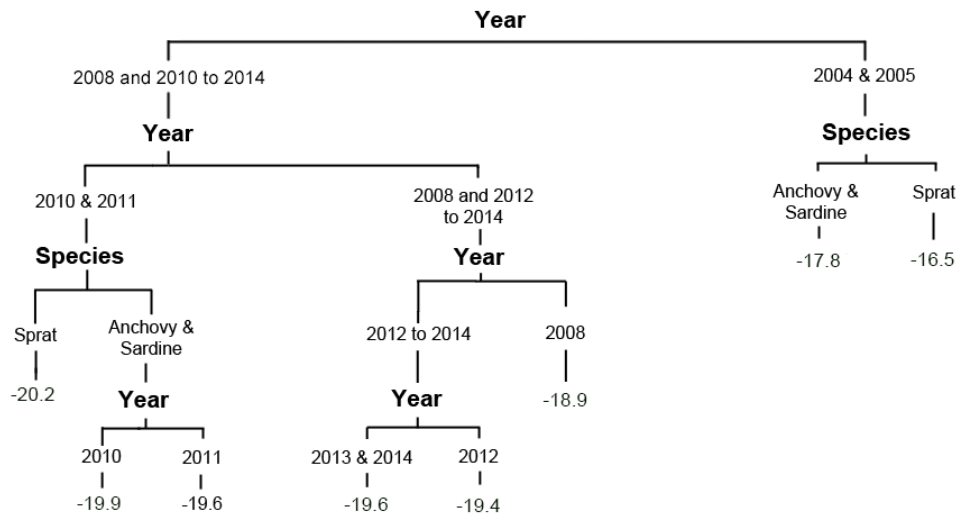


Figure 3.

(A) $\delta^{13}\text{C}$



(B) $\delta^{15}\text{N}$

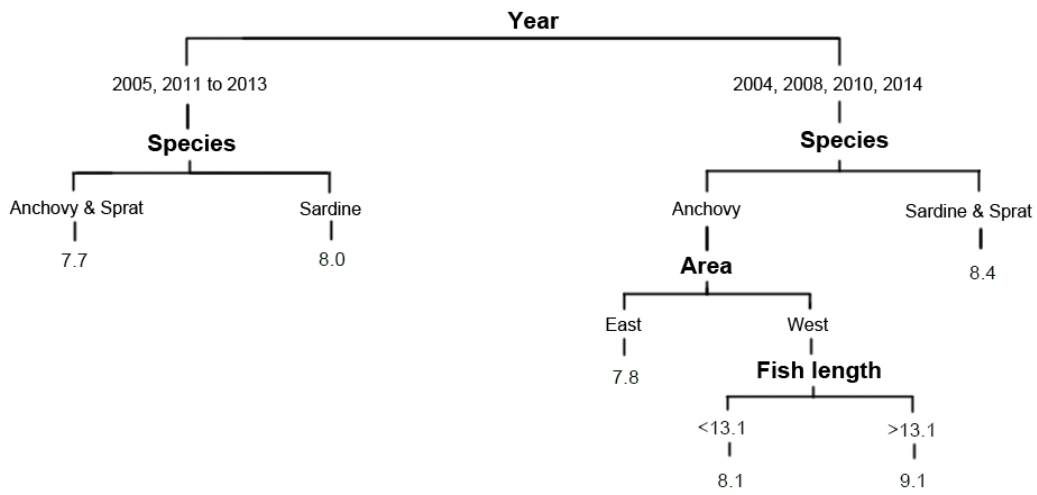


Figure 4.

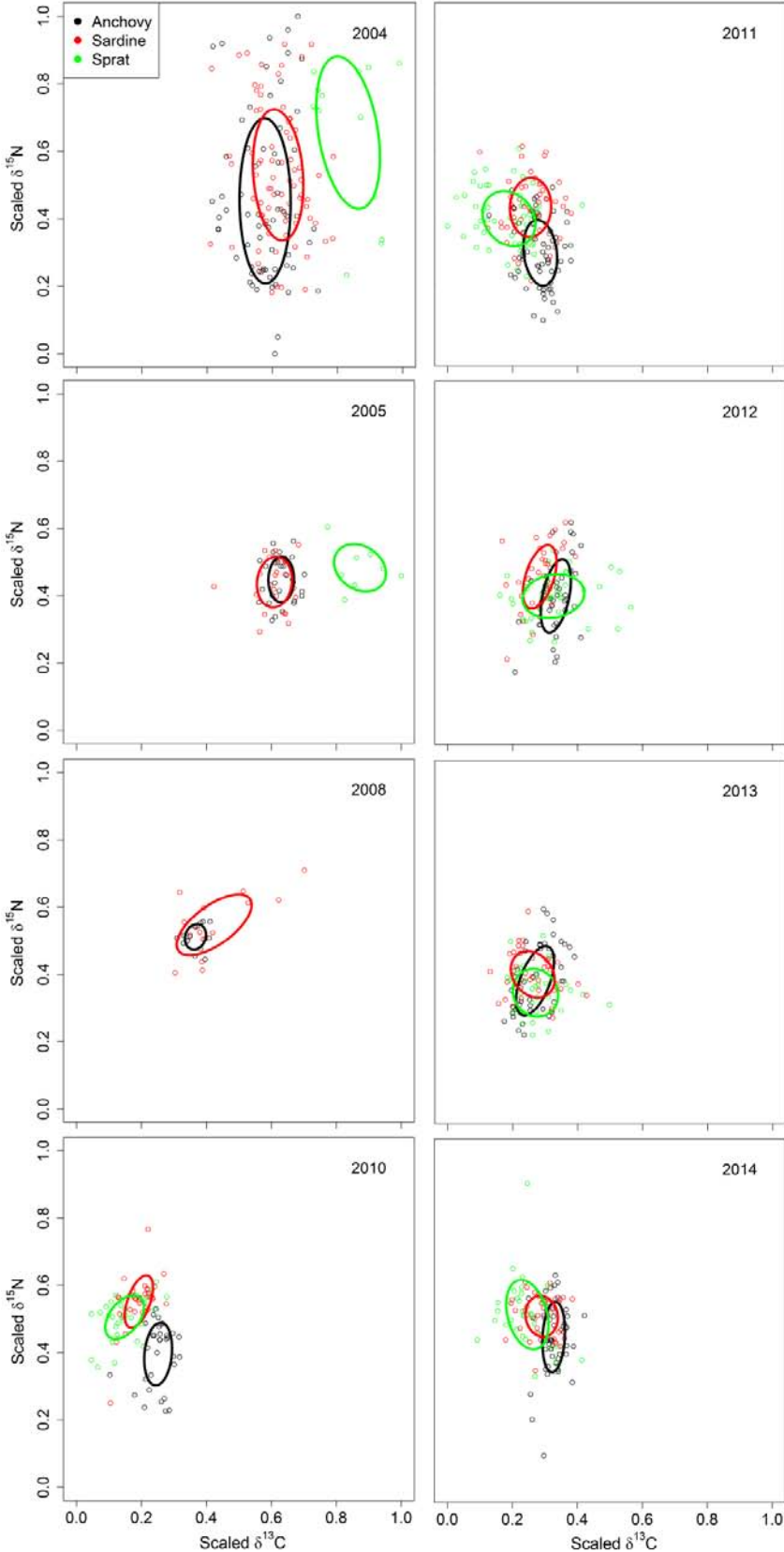


Figure 5.

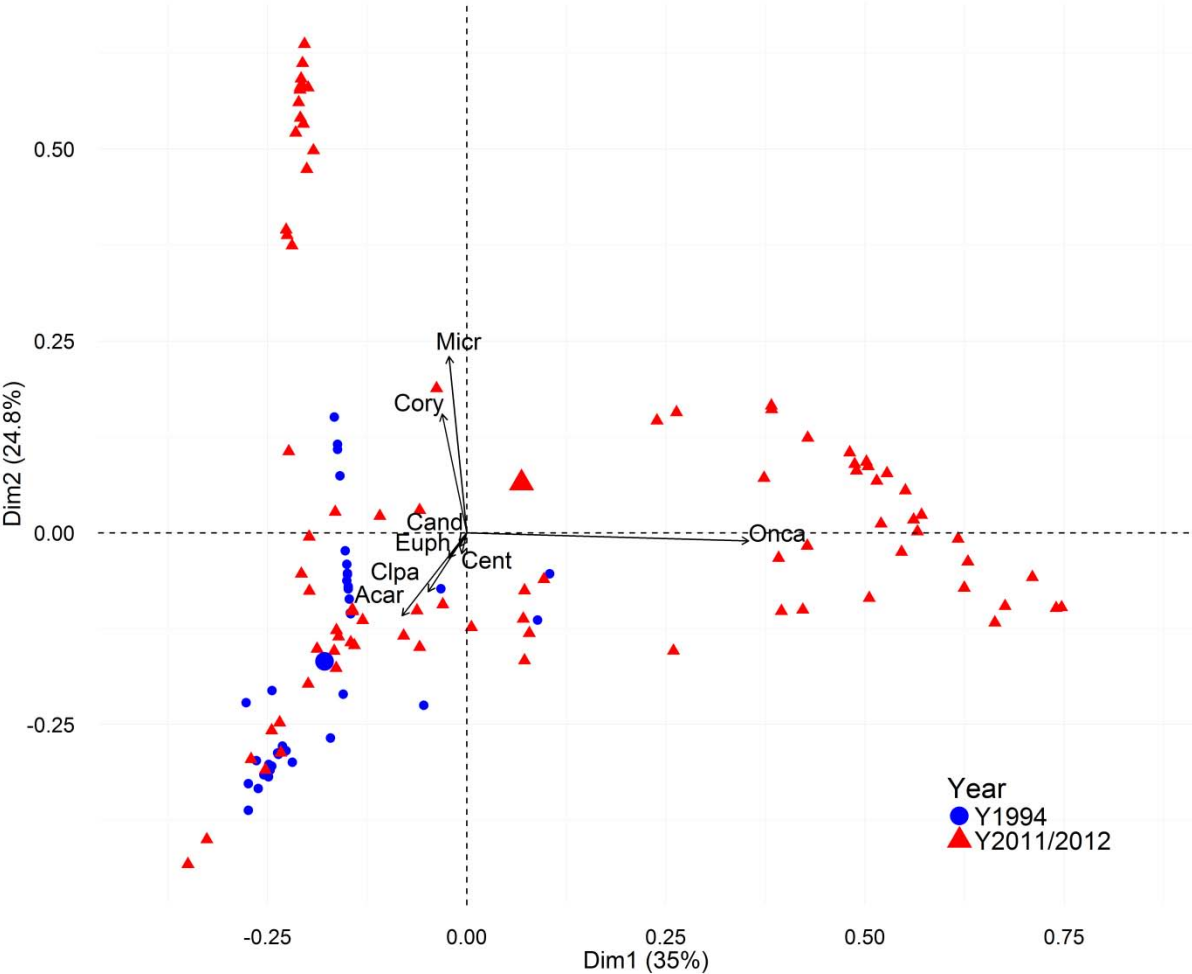


Figure 6.

