# Can the effects of anthropogenic pressures and environmental variability on nekton fauna be detected in fishery data? Insights from the monitoring of the artisanal fishery within the Venice lagoon

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# 1. Introduction

Transitional waters are highly productive ecosystems that are affected by both a naturally high variability in environmental conditions and multiple anthropogenic pressures (Costanza et al., 1997; Elliott and Quintino, 2007; Vasconcelos et al., 2007). In order to effectively manage driving forces on European transitional water ecosystems, and thus preserve the services provided, the Water Framework Directive (WFD; Directive 2000/60/EC) requires the evaluation of ecological status, based on indices sensitive to anthropogenic pressures rather than to natural variability (Uriarte and Borja, 2009).

Fish are an ecologically and economically important component of transitional waters potentially influenced by the alteration of environmental conditions (Elliott and Dewailly, 1995; Elliott et al., 2007). As a result, several fish-based multi-metric indices have been developed to assess the ecological status of these ecosystems in Europe, and more recently anthropogenic pressures have been additionally incorporated in order to validate such indices (Aubry and Elliott, 2006; Cabral et al., 2012; Fonseca et al., 2013; Pasquaud et al., 2013). This process allows the evaluation of the sensitivity of fish-based multi-metric indices to human pressures and can promote the development of ecological status assessment methods that are fully compliant with WFD requirements (Hering et al., 2010). In this light, the choice of metrics to be included in an index is particularly relevant, as their sensitivity to human alteration should be verified (i.e. the metric should show a decrease with increasing pressure values), taking into account natural variability of the system while keeping such a relationship ecologically interpretable (Cabral et al., 2012; Pérez-Domínguez et al., 2012; Schoolmaster et al., 2012, 2013a, 2013b). In transitional waters, several human activities can generate pressures which may in turn lead to a number of direct or indirect disturbances to fish populations. The main anthropogenic pressures are related with chemical pollution, physical changes, energy and thermal pollution, radioactivity and biological pollution (species invasions and pathogens) (Marchand et al., 2002). As Vasconcelos et al. (2007) exemplified, multiple anthropogenic activities can lead to degradation of water and sediment quality (e.g. wastewater discharges and use of chemicals in agriculture), habitat loss (e.g. bank reclamation) or reduction of prey availability (e.g. sediment management). All these can potentially affect nekton fauna at various levels of biological organisation, e.g. by directly increasing mortality of individuals or indirectly causing shifts in community composition through alterations of ecosystem processes.

Fishing is one of the human activities which, while taking advantage of the high productivity of transitional water ecosystems, can also have a role in generating system pressures for example by removing nektonic biomass or by leading to modifications to the habitat (McHugh, 1967; Nixon, 1982; Blaber et al., 2000; Elliott, 2002). On the other hand, the species composition and biomass of fishery landings strongly depend on the ecological status of the system (Pérez-Ruzafa and Marcos, 2012). Although Mediterranean coastal lagoons support important fishery activities and maintain aquaculture exploitation (Kapetsky and Lasserre, 1984; Ardizzone et al., 1988), the role of fishery as a cause of pressure for fish communities is poorly investigated in such ecosystems. In Mediterranean transitional waters, fixed gears such as fyke nets and fishing barriers at the sea inlets are probably the most important fishery techniques (Cataudella and Ferlin, 1984; Ardizzone et al., 1988; Chauvet, 1988; Pérez-Ruzafa and Marcos, 2012). Such fisheries take advantage of fish movement within or between the transitional system and the adjacent marine and freshwater areas, and are highly seasonal due to the presence and migration of different species (Granzotto et al., 2001; Provincia di Venezia, 2009).

Monitoring of artisanal fisheries can provide useful information on fish assemblages or on the status and evolution of some populations, provided sampling effects are accounted for (e.g gear characteristics and selectivity) (Malavasi et al., 2004a; Provincia di Venezia, 2009; Pranovi et al., 2013). Nekton data from fishery monitoring could be in some cases routinely collected, enhancing the possibility of gathering a large and robust dataset. Moreover, if fishery data could be also used to contribute to the assessment of ecological status, it would help in containing sampling costs related to scientific monitoring.

In this study, data were analysed from a plurennial monitoring plan of the artisanal fishery (fyke nets) in the Venice lagoon in order to test the effects of human pressures on nekton assemblage, namely fish and invertebrates. We followed a model-based approach (Warton et al., 2014) in order to test *a priori*-formulated hypotheses about the different role of natural variability, anthropogenic pressures and the artisanal fishery in affecting the lagoon nekton assemblage, and to understand whether monitoring of the artisanal fishery can be used to assess the relationship between nekton assemblage and anthropogenic pressures in transitional waters. The issues addressed in this study represent a crucial step for setting up an ecological status evaluation system based on monitoring of the local fishery. This could be important to optimise the effort of collecting field data and to harmonise different monitoring programmes.

## 2. Materials and methods

### 2.1. Venice lagoon and study areas

The Venice lagoon is a large coastal lagoon (about 550 $km^2$) in the North-Adriatic Sea (Italy) (Figure 1) It is a microtidal system with mean tide amplitude of 1m (Umgiesser et al., 2004). It is a shallow system comprised of three sub-basins delimited by two main watersheds (Solidoro et al., 2004). There is a high spatial and temporal variability in morphological and physico-chemical parameters, as well as a mosaic of habitats, including saltmarshes, seagrass meadows, bare or sparsely vegetated mudflats and sandflats (Franzoi et al., 2010; Solidoro et al., 2010).

For the purpose of this study, five broad homogeneous areas were identified in the lagoon, based on the degree of confinement (Solidoro et al., 2004), main habitat types, salinity and sediment characteristics: Chioggia (CH), Ca' Zane (CZ), Lido (LD), Lago dei Teneri (LT) and Ponte della Libertà (PL) (Figure 1). CZ and PL both experience high water residence times (>20 days) with euhaline conditions and predominance of muddy substrata often covered by macroalgae, with some marsh areas only within CZ. LT is also very confined (>20 days water residence time), but it shows polyhaline conditions and dominance of saltmarsh habitats, with presence of some bare or macroalgae-covered mudflats. LD and CH are characterised by euhaline conditions, low residence times (<7 days) and seagrass-dominated sandy habitats.

**Figure 1 about here.**

### 2.2. Monitoring programme and nekton assemblage

Fyke nets represent the most important gear type of the fishery of the Venice lagoon (Granzotto et al., 2004; Provincia di Venezia, 2009; Pranovi et al., 2013). Fyke nets employed here consist of a barrier of about 50 m in length and 1.3 m in height, with a mesh size of 0.6 cm, which guides the fish towards four cone shaped, unbaited traps (Malavasi et al., 2004a). Artisanal fishery activity in the five lagoon areas was monitored on a monthly basis in two seasons (spring and autumn), corresponding to the two major fishing periods (Provincia di Venezia, 2009). Data were collected during the years 2001 to 2003 and 2009 to 2013 in order to obtain a representative view of species composition and biomass of nekton assemblage inside the lagoon. For each study area an average number of 79.38 (Standard Deviation: 42.25) traps were inspected during each season.

The content of the traps was inspected on board and samples were collected to confirm identification in the laboratory. Catches (including target species and by catch) were identified at species level and weighted (± 1 g), in order to obtain the cumulative biomass per species. This was expressed in terms of catch per unit effort (CPUE), i.e. catch (in g) was standardised per trap and temporal unit, the latter accounting for the number of days since the previous visit by the fishermen (Pranovi et al., 2013). Species richness (S) and biomass (B) were calculated for each sample.

Both fish and cephalopods were considered due to their relevance to the local fisheries (Granzotto et al., 2004; Provincia di Venezia, 2009; Pranovi et al., 2013). The green crab, *Carcinus aestuarii*, although representing a very important target of the fishery (Pranovi et al., 2013), was not considered in the analyses, due to its benthic habits and to peculiar fishing practices, based on the selection of the moulting specimens (Matozzo et al., 2013; Pranovi et al., 2013). While decapods (including *Crangon crangon*, *Melicertus kerathurus*, *Processa macrophthalma* and a number of species belonging to the genus *Palaemon*) can be relevant to the local fishery, these were only recorded from 2009 onwards, and therefore they were excluded from the analysis (a preliminary exploration of the 2009-2013 data indicated their minor contribution to the results).

The recorded species were categorised according to the role played with respect to the artisanal fishery: target species, directly pursued by the fishery; incidental species, i.e. non-target species incidentally caught and with commercial value; discarded species, with no commercial value (Pranovi et al., 2013). In addition, Estuarine Use Functional Groups (EUFG) defining the main ecological utilisation of the lagoon by the species were adopted and modified after Potter et al. (2013). The attribution of EUFG to the species was undertaken taking into account the specific use of the Venice lagoon (Malavasi et al., 2004a; Franco et al., 2008; Franzoi et al., 2010), as well as the type of habitat used by the species (e.g. some species were classified as marine stragglers, and not estuarine residents or estuarine opportunists, due to their exclusive use of marine-like habitats included within the lagoon boundaries, even if they were found frequently and with relatively high abundances). Feeding Mode Functional Groups (FMFG) were adapted from Franco et al. (2008, 2009b), in order to characterise the species in terms of feeding behaviour. The attribution of FMFG to the species was carried out taking into account the life stage predominantly found in fyke nets. As one species can be allocated to multiple FMFG, the species contribution to a single guild was assigned in proportion to the relevance of each feeding mode for the species, by identifying the importance (%) of different guild allocations within the diet, on the basis of the literature (“www.fishbase.org”; Froese and Pauly, 2015) and of available data for the Venice lagoon (Franzoi, unpublished data). Guilds for nektonic invertebrates were also defined on the basis of available information in the scientific literature (Blanc and Daguzan, 1998; Pinczon Du Sel et al., 2000; Alves et al., 2006; Palomares and Pauly, 2014). A complete list of the nekton species considered in the analysis and the respective categorisation in terms of EUFG, FMFG and fishery category is shown in Appendix (Table A.1).

### 2.3. Environmental conditions

In each study area a series of environmental variables was estimated using spatial data collected in previous studies or measured *in situ* during this study. Variables not collected *in situ* were considered fixed in time (i.e. temporal variability is assumed to be negligible over the study period), and are: % area covered by saltmarsh (Mag. Acque, 2002; marsh); % area covered by seagrass bed habitat (*Cymodocea nodosa*, *Nanozostera noltii* and *Zostera marina* monospecific and mixed assemblages; Rismondo et al., 2003; Curiel et al., 2014; seagcover); bottom depth averaged by study area (in metres; Mag. Acque, 2002; bat); average distance of grid cells composing each study area from the nearest sea inlet (metres; dist; evaluated on a regular grid with a cell size of 100m); sand content in bottom sediments averaged by study area (as % sand; Mag. Acque - SELC, 2005; Mag. Acque - Thetis, 2005; sab); water residence time averaged by study area (days; Cucco et al., 2009; restime); water speed averaged by study area (expressed as cm/s; Molinaroli et al., 2007; wsp). Variables including temporal variability are: water salinity averaged by area in each sampling occasion (±1 PSU – Practical Salinity Units; this study; sal); water turbidity averaged by area and in each sampling occasion (± 1 FTU – Formazin Turbidity Units; this study; torb); water temperature recorded in each sampling occasion (±0,1° C; this study; temp); anomalies in water temperature (°C; Mag. Acque - SAMA, 2013; anoT).

### 2.4. Anthropogenic pressures

A set of indicators of anthropogenic pressure was developed, adapting the scheme proposed by Aubry and Elliott (2006) according to the available knowledge for the Venice lagoon and to the relevance for nekton fauna of each indicator (Table 1). Three main categories of pressures were identified, which were related to: I) Morphology, II) Resource and Habitat Use and III) Environmental Quality.

Five indicators of Morphological pressure were selected (Table 1): intertidal area loss; seagrass habitat loss; gross change in bathymetry; interference with hydraulic circulation due to the presence of human infrastructures; relative sea level rise. The temporal variability of these indicators within the study period

(2001-2013) was assumed to be negligible and therefore only spatial variability (differences among areas) was considered in the analysis. The Resource and Habitat Use category included five indicators (Table 1): artisanal fishery; shellfish aquaculture; intensity of marina development; boat traffic; intensity of shipyards. The marina, navigation and shipyard indicators were maintained fixed in time due to the lack of time series of data. Seven indicators of Environmental Quality were selected (Table 1), representing: water chemical quality; sediment chemical quality; sediment quality biological effects; ecological status of macrobenthos; chlorophyll-*a* concentration; nutrients concentration; dissolved oxygen. Biological effects of sediment quality and benthic state were kept fixed in time, due to lack of data available over time. When seasonal values were not available for the other indicators, these were replaced with nearest-in-time values.

Values of each pressure indicator were standardised according to a five-level classification scoring (Table A.2). Pressure levels were evaluated for each element of a 1km x 1km cell grid covering the lagoon extent and the mean pressure level for each indicator in each study area was obtained by overlaying the grid maps

## 2.5. Data Analysis

### *2.5.1. Model calibration*

Generalized Linear Models (GLMs; McCullagh and Nelder, 1989) were fitted to link response variables to temporal, environmental and pressure predictors, as described in the next paragraphs. Models for number of species (S) and biomass (B) of functional groups (univariate analyses) and for presence-absence and biomass of species (multivariate analyses) were fitted considering different combinations of predictor variables and the most suitable error term (depending on the type of response variable), in order to build the set of models representing the different hypotheses considered in this study.

Response variables (univariate and multivariate analysis)

Nekton data were analysed both in a univariate and a multivariate fashion. Firstly, nekton data were summarised in a set of variables -or metrics- quantifying different characteristics of the assemblage. These metrics were computed as biomass and species richness of Estuarine Usage Functional Groups (16 metrics), Feeding Mode Functional Groups (16 metrics) and fishery categories (6 metrics). All metrics were independently used as response variables in GLMs fitted using Table 2 formulas (univariate analysis), and choosing the most appropriate distribution family, after the visual inspection of the mean-variance relationship

(Warton, 2008; Warton et al., 2012). Secondly, following the approach of the `manyglm` software package (Wang et al., 2012), binomial GLMs were fitted using presence/absence information of each species and following the same formulation proposed for univariate data (Table 2), and inferences were carried out at the assemblage level (Wang et al., 2012; Warton et al., 2012) (multivariate analysis). A similar approach was replicated on biomass data, developing negative binomial GLMs for each species contributing to 95% of total biomass and combining results in a global analysis.

Predictor variables

In order to represent the effects of the temporal variability on the response variables, the interaction between the factors *Season* and *Year* was considered as a predictor in the model. Environmental conditions were summarised by performing a principal component analysis, and the first three axes were considered as predictors of environmental variability in fitted models. The predictors used as indices of pressures for the three considered categories were the average values of the indicators within each category (Morphology pressures, Resource and Habitat Use pressures - excluding the fishery -, Environmental Quality pressures). As in this study a particular attention was paid to the role of the artisanal fishery, its indicator (see 2.4) was considered as a separate predictor variable in model building.

Model structure

Models were fitted using different structures in order to hypothesise different contributions of the predictor variables (Table 2). Eight model formulations, belonging to four model categories, were built addressing the following hypotheses: none of the considered predictors affects the response variable (category *m0*); response variable is influenced by temporal factor alone (category *m1*); response variable is affected by temporal and environmental factors (category *m2*); response variable is affected by anthropogenic pressures (with or without environmental conditions, and excluding fishery pressure) (category *m3.X*); and response variable is affected by the fishery (with or without environmental conditions and other anthropogenic pressures) (category *m4.X*) (Table 2). Not all models were nested (e.g. one included within another more complex one), but the category of models were conceptually hierarchically designed (e.g. environmental variables or anthropogenic pressures cannot be included in a model if temporal factor has not been considered yet).

#### 2.5.2. *Comparison of models*

Fitted models were analysed to understand if nekton data showed a relationship with the anthropogenic pressure categories, by:

- comparing models (both for univariate and multivariate approaches) by means of Likelihood Ratio tests between chosen sets of nested models (Table 2). These comparisons were carried out to disentangle the contribution of the different type of predictor variables considered (temporal factors, environmental conditions, anthropogenic pressures and artisanal fishery pressure). For example, for a given metric, the comparison (Test 2.1, Table 2) of a model fitted using temporal factor and environmental conditions (m2.0, Table 2) with another one including also anthropogenic pressures (excluding artisanal fishery) (m3.1, Table 2), suggests if the inclusion of anthropogenic pressures significantly improves the model in the case that temporal factor and environmental conditions were already included;

- computing the deviance explained by each model, in order to estimate the magnitude of the effect in addition to its significance (see previous point);

- averaging all the candidate models (Table 1) for each univariate metric following an Information Theory Criterion, to carry out global inference on the estimated averaged parameters for pressure variables (univariate analysis). In particular, models were averaged using the $AIC_c$ weights, and considering the 'top-models', i.e. the models representing the 95% confidence model set (Grueber et al., 2011);

- averaging (unweighted mean values) the parameters of the models of all species for each category of pressure, to summarise the effects of pressure indicators on nekton assemblage (multivariate analysis);

# 3. Results

## 3.1. Nekton assemblage

During the study period, 59 fish and two cephalopod species were recorded from fyke nets and included in the analysis (Table A.1). Gobiidae, Sparidae, Syngnathidae and Mugilidae were the most numerous families in terms of species numbers (with 8, 8, 7 and 5 species respectively), while *Sepia officinalis* and *Sepiola rondeletii* were the only two species of cephalopod recorded. Two fish species, *Atherina boyeri* and *Zosterisessor ophiocephalus*, accounted for 58% of the total biomass (39% and 19% respectively).

Nine species out of the 61 forming the whole nekton assemblage were targets of the fishery and accounted for 78% of the total biomass, with 11 incidental species accounting for an additional 16%. Thus, 94% of the total biomass caught with fyke nets was composed by species with some commercial value (target + incidental species), with the 41 discarded species representing only 6% of biomass of the analysed catches. Among nekton species, eight EUFG were identified: anadromous (A), catadromous (C), estuarine (ES), solely estuarine (ESs), freshwater stragglers (FS), marine estuarine-dependent (ME-D), marine estuarine-opportunist (ME-O) and marine stragglers (MS). MS was the richest EUFG, with 26 species, followed by ME-O (12), ES (11), ME-D (5) and ESs (4 species). A, C and FS EUFG were all represented by one species each. ES was the dominant guild in terms of biomass (60% of the total), with *A. boyeri* and *Z. ophiocephalus* accounting for 95% of the guild biomass (64% and 31% respectively). ESs accounted only for 0.4% of the total biomass.

Eight FMFGs were identified: macrobenthivores (Bma), microbenthivores (Bmi), detritivores (DV), hyperbenthivores/piscivores (HP), herbivores (HV), hyperbenthivores/zooplanktivores (HZ), omnivores (OV) and planktivores (PL). Bmi and Bma were the FMFG with more species among nekton assemblage. *Z. ophiocephalus*, *Solea solea* and *Platichthys flesus* accounted together for 73% of Bmi biomass, while *Z. ophiocephalus*, *S. officinalis* and *P. flesus* accounted for 79% of Bma biomass. Twenty species were allocated to the HP guild, with seven of them showing exclusively this feeding mode. *Z. ophiocephalus* and *S. officinalis* were the dominant species within the HP guild, accounting for 75% in terms of biomass. Fourteen species were HZ with only three of them being exclusive to this guild. *A. boyeri* alone accounted for 99% of the HZ guild biomass. Six omnivorous species were found, all being allocated in multiple FMFG except for *Diplodus puntazzo*. Mugilids accounted for the totality of the DV guild. Engraulids and clupeids entirely accounted for the PL guild.

## 3.2. Environmental conditions and anthropogenic pressures

The five study areas were clearly ordered along the first principal component (Figure 2a), which can thus be interpreted as a gradient from more dynamic and marine-like conditions, typically observed in proximity to the sea inlets (areas CH and LD), towards more confined areas (LT and CZ). In addition, the observations within each study area were scattered along the second principal component, due to the interannual and seasonal variability (Figure 2a). The dispersion along the third component was similar to that of the second axis with the points belonging to the different areas largely overlapping, but CH and LT - the least and the most confined areas - indicated a lower turbidity level (Figure 2b). The first component of the PCA performed on environmental variables identified a main spatial confinement gradient as ascribed to changes in water residence time, seagrass cover, sediment grain size and water speed, while the second component was strongly influenced by variables with a sharp seasonal variability (water temperature and dissolved oxygen) and the third component was related to variables changing over time (water temperature anomaly) or in time and space (turbidity) (Fig. 2b).

In the case of the PCA performed on anthropogenic pressures, it was not easy to recognise a geographical pattern in the pressure gradient, as all three axes were influenced by variables representing pressures with a strong spatial component (interference with hydrographic regime, relative sea level rise, gross change in bathymetry) or variables changing over time both with a seasonal (e.g. average concentration of Dissolved Inorganic Nitrogen) or inter-annual dynamic (area affected by aquaculture activities) (Fig. 2c and 2d). However, the distribution of the areas along the first component partially corresponded to the one described by the principal component analysis on environmental variables; with an ordination from the innermost area (LT), where the loss of intertidal area, the sediment chemical quality and the macrobenthos state were the greatest pressures, to the area closest to the sea inlet (CH), where pressures related to sea level rise, aquaculture, interference with hydrographic regime pressures and the loss of seagrass were more important (Figure 2c). However, on this ordination CZ differed in location compared to the previous PCA, as if pressures in CZ could be associated with the ones of a less confined area (Figure 3a). The second axis combined LD and PL against the others stations, due to a higher importance of pressures related to the intensity of navigation and density of shipyards in these areas (Figure 2c), while the third component distinguished CZ and PL from the other areas for being less affected by bathymetric change (Figure 2d).

**Figure 2 about here.**

### 3.3. Effects of temporal factors, environmental conditions, and anthropogenic pressures upon nekton assemblage

***Univariate comparison***

All the univariate GLMs for biomass-related metrics were fitted using a negative binomial distribution, while the models for the number of species metrics were fitted using a Poisson distribution. All the models explained a low to moderate proportion of deviance (Figure 3), with few exceptions related to metrics with very sparse (i.e. zero inflated) data matrix, probably due to overfitted models. All the metrics indicate a significant seasonal pattern, as the effect of temporal factor alone (test 0) was significant ($p<0.001$) for all metrics, except for the biomass of catadromous EUFG, and for the species richness of anadromous and freshwater straggler EUFG and herbivore FMFG (Figure 3). It is worth noting that data for these groups of species were strongly zero inflated. In general, the metrics show a significant seasonal pattern.

The inclusion of environmental conditions (test 1) had a significant effect ($p<0.01$) on all biomass metrics except for catadromous EUFG and omnivorous FMFG, and on the same species richness metrics for which temporal factor alone was significant. This means that for most of the metrics, the differences between observations can in part be explained by environmental conditions, in addition to the contribution of temporal factors.

When only temporal factor was already considered, the effect of including all anthropogenic pressures with the exception of the fishery (test 2.0) proved significant ($p<0.05$) for most of the metrics (but see biomass of catadromous EUFG and species richness of anadromous EUFG and herbivores FMFG; Figure 3).

Including pressures with both temporal and environmental conditions already considered (test 2.1) significantly ($p<0.05$) contributed to explain the variance of many metrics, with the exception of the biomass of incidental catches, catadromous, freshwater stragglers, marine estuary-dependent and detritivorous species and the number of species of target, total catches, anadromous EUFG and of herbivorous FMFG. Hence, in a large number of cases, adding the information on anthropogenic pressures to the temporal and environmental factors assists in explaining the variance in the nekton assemblage data.

In general, the inclusion of artisanal fishery pressure resulted in significance for a smaller number of cases (Figure 3). The inclusion of fishery pressures when temporal factors, environmental variables and the other pressures were already included in models (test 3.2), resulted in significance of fewer metrics than in the case of the inclusion of the fishery when temporal factor alone (test 3.1) or temporal factor and environmental variables (test 3.0) were already included in the analysis. However, this is not true for all metrics: for those metrics representing the biomass of the EUFG, significance was more likely for the fishery if all the other factors were previously included in the model.

When considering the model averaged parameters associated to the different indicators of pressure (Figure 4), the fishery showed a slightly negative effect only on biomass of discarded catches, anadromous and marine-estuarine opportunist EUFGs and both detritivorous and planktivorous FMFGs. Similarly, the fishery negatively affected the species number of incidental catches, estuarine and marine estuarine-opportunist EUFGs and macrobenthivorous, detritivorous and hyperbenthivorous/piscivorous FMFGs. Overall though, the fisheries effect on the considered metrics seemed to be negligible, since the coefficients associated with this pressure were often very close to zero (Figure 4). Moreover, in many cases, these effects were characterised by a small influence (low Akaike weights) on the averaged models. In addition, a positive effect of the fishery was observed for biomass of target and total catches, of estuarine, solely estuarine and marine straggler EUFGs and of benthivorous FMFGs (Figure 4).

Compared with the fishery, a stronger effect (larger $\beta$ coefficients) of the other pressure categories was evident (Figure 4). No common pattern could be identified among metrics, except for the biomass of the fisheries-related metrics (discarded, incidental, target and total catches), which seemed to be negatively affected by both morphology-, resource use- and environmental quality-related pressures. Overall, pressures related to morphological alterations had marked negative effects on biomass of discarded, incidental, target and total catches, as well as biomass of estuarine EUFG and of both microbenthivorous and omnivorous FMFGs. Resource use pressures showed the most negative effects on biomass of discarded catches and hyperbenthivorous/zooplanktivorous FMFG. Finally, environmental quality degradation had a particularly negative effect on biomass of target and total catches, marine estuarine-opportunist EUFG and four FMFGs (both macro- and microbenthivorous, hyperbenthivorous/psicivorous and planktivorous species).

**Figure 3 about here.**

**Figure 4 about here.**

### ***Multivariate comparison***

Only the effect of temporal factor (test 0) was significant ($p<0.001$) when analysing GLMs performed on species presence/absence in the whole nekton assemblage (Table 3). None of the pressure categories proved significant in determining species composition of the assemblage as a whole.

In contrast, a higher number of significant effects ($p<0.01$) were detected when comparing GLMs performed on the biomass distribution across the species in the assemblage. The effect of temporal factors (test 0) was significant, as well as the effect of adding environmental conditions when temporal factors were already considered (test 1), adding anthropogenic pressures excluding the fishery when temporal factors were already considered (test 2.0), adding anthropogenic pressures excluding the fishery when both temporal factor and environmental conditions were already considered (test 2.1) and adding fishery pressure when both temporal factor and environmental conditions were already considered (test 3.0) (Table 3).

Five target species commonly found in fyke nets showed significant effects of anthropogenic pressures most frequently across tests (see supplementary materials, Table A.3). *S. officinalis* showed a significant effect in six tests (five of which performed on species presence/absence and one on biomass), while *A. boyeri* and *Liza aurata* showed a significant effect in five tests (three of which performed on species presence/absence and two on biomass). In addition, the effect of pressures also proved significant for the presence of *Pomatoschistus minutus* and *Z. ophiocephalus* (three and two tests respectively). With both temporal and environmental factors already considered (Test 2.1), pressures related to morphological alterations and resource use negatively affected the probability of target species presence as *Anguilla anguilla*, *L. aurata*, *Sparus aurata* and *Z. ophiocephalus*, with *A. boyeri* showing a negative effect only for resource use pressures. In contrast, the presence of *P. flesus* and *P minutus* (target species) was affected positively or not affected by both these pressure categories. Similarly, environmental degradation had a negative effect on the presence of *P. flesus, P. minutus*, *S. aurata* and *S. officinalis* with both temporal and environmental factors already considered, while it showed a positive effect on *A. anguilla*, *A. boyeri*, *L. aurata* and *Z. ophiocephalus*. The fishery affected the likelihood of four target species presence when it was considered as the only pressure (Test 3), having a positive effect on *A. boyeri*, *L. aurata* and *Mugil cephalus* and a negative impact on *S. officinalis*.

When considered together with other pressure category (Test 3.2), in contrast, the fishery negatively affected the presence of *A. anguilla* and *S. Officinalis* only, while being negligible for other target species. Additionally, test 2.1 indicated that morphological pressures had a negative effect upon biomass of *A. boyeri* and *L. aurata*, while both resource use and environmental quality pressures were positively related to biomass of these species.

On average, pressures related to morphological changes, resource and habitat use, as well as pressures on environmental quality showed negative effects on the biomass of the assemblage, while only pressures on environmental quality negatively affected the average probability of presence of the single species within the assemblage (Figure 5). Both for presence/absence and for biomass, the effect of fishery pressure seemed to be negligible (Figure 5).

**Figure 5 about here.**

## 4. Discussion

We investigated the potential use of data gathered during the monitoring of the artisanal fishery in the Venice lagoon to describe the relationship between nekton assemblage (including fish and cephalopods) and anthropogenic pressures in transitional waters.

The Venice lagoon represents a good case study, since a traditional form of fishing is carried out within its boundaries by local fishermen throughout the year in most part of the basin (Provincia di Venezia, 2009; Pranovi et al., 2013). Moreover, this lagoon, given its wide area and complex hydro-morphology, is characterised by a mosaic of habitats and multiple environmental gradients that lead to a high level of environmental variability (Solidoro et al., 2010). The Venice lagoon is also subjected to a variety of pressures, and their variability in space and time is rather well documented (Franco et al., 2009a; Solidoro et al., 2009). The combination of natural heterogeneity in time and space with the unevenness of anthropogenic pressures and impacts can change ecosystem organisation and functioning (Brigolin et al., 2014). Therefore it was crucial to take into account these sources of heterogeneity, evaluating anthropogenic pressures, environmental conditions and nekton assemblage in different areas, different times of the year, and between years. For the areas considered in this study, spatial variability in environmental conditions and anthropogenic pressures seems to be stronger than the temporal, as highlighted by the Principal Component Analysis (Figure 2). This is due to the marked spatial variability, but also due to the assumptions at the basis of this work (pressures definition), and the data availability constrains.

The main anthropogenic pressure gradients within the lagoon are associated with morphological changes such as habitat loss and alteration of the hydrodynamic conditions, as previously noted (Franco et al., 2009a; Molinaroli et al., 2009; Sarretta et al., 2010), with also alterations of environmental quality being an important pressure category. Indeed, despite the stricter regulations and the decline of industrial activities in the last decades, persistent contaminants such as heavy metals and organic compounds are still stored in lagoon sediments, directly affecting the associated benthic compartment (Secco et al., 2005; Bernardello et al., 2006).

The whole nekton assemblage as assessed by using fyke net catches did not show a significant relationship with the environmental variability of the lagoon when considering its species composition, whereas the biomass structure of assemblages indicated the effect of temporal, environmental and pressure factors. Indeed, species occurrence in the catches changed significantly according only to season and year (test 0), as a result of the temporal dynamics in nekton populations such as recruitment and migrations (Elliott and Hemingway, 2002). Environmental variability and anthropogenic pressure did not have significant effects on catch composition, in terms of species richness and presence-absence of species.

On the contrary, anthropogenic pressures significantly explained part of the variability on the biomass of catches, in addition to both temporal variability alone (test 2.0) and with environmental conditions (test 2.1). Species biomass in the assemblage proved to be sensitive not only to pressures related with morphological change, resource use (excluding artisanal fishery) and environmental quality, but also in a smaller degree to the effects of the artisanal fishery. The latter may be due to changes in population structure related to the removal of individuals of target species, hence leading to the observed alteration in the biomass of the assemblage. Regarding the effects of morphological degradation, it is not easy to identify the effects of physical disturbance of the environment for mobile or migratory species, as they may change their distribution and behaviour, but this could be simpler for resident species (Marchand et al., 2002). Some authors have suggested that the degradation or loss of habitats affects fish species richness in estuaries (Harrison and Whitfield, 2004; Cabral et al., 2012; Harrison and Kelly, 2013). Our results confirm that the effects of pressures acting on the lagoon morphology are stronger for resident species (e.g. ES biomass and biomass of *Z. ophiocephalus* and *S. officinalis* see fig. 4 and Tab A.3), but they can be significant also for migrant species (e.g. ME-D biomass and biomass of *A. anguilla* and *L. saliens*; see fig. 4 and Tab A.3). However, it is interesting to note that these effects can be manifested in our study as impacts on biomasses (univariate and multivariate tests) rather than on metrics accounting for species richness and assemblage composition (presence/absence tests). Many studies (e.g. Brandão et al., 2013; Fonseca et al., 2014; Gonçalves et al., 2014) describe the effects of chemical pollutants on fishes, but these effects usually cannot be easily observed and quantified at the population level, especially if pollution is present at sub-lethal levels (Hamilton et al., 2015). Marchand et al. (2002) suggest that for some types of pollutants, the effects are unlikely to be detrimental, because fishes avoid highly polluted areas. The significant effects of pressures on quality of matrices observed in this study are probably more related to enrichment in nutrients and organic matter, leading to anoxic crises, than to chemical pollution (in agreement with the patterns observed, for example, by Uriarte and Borja, 2009).

Several of the metrics responded in a coherent way to the impacts of human pressures. As an example, biomass of estuarine resident species, benthivores, hyperbenthivores/piscivores, target species and of total catches indicated a clearly negative response to morphological alterations. This result could be related to the role within these categories of some species, for example the grass goby *Z. ophiocephalus*, for which the impacts on the essential habitat for its reproduction (i.e. seagrass meadows; Malavasi et al., 2004b) might determine a decrease on the population biomass. However, biomass of both target and total catches demonstrated a strong negative response to all three main pressure categories.

In this study, the biomass of marine estuarine-opportunists was negatively influenced by pressures acting on quality of matrices. Similar results were found by Amara et al., (2009), who recorded lower growth and body condition in juveniles of *P. flesus* (marine migrant) exposed to higher levels of chemical pollution in French estuaries. On the other hand, the biomass of solely estuarine species revealed a positive relationship with pressures related to environmental quality in the Venice lagoon. The species of this guild (e.g. the lagoon goby *Knipowitshia panizzae*) are more likely to be adapted to high levels of natural variability typical of transitional waters (Franco et al., 2008), and therefore might be also able to cope with poor environmental conditions. Indeed, some studies suggest that estuarine resident species may be able to develop resistance to chemical pollution as an adaptation to long-term exposure (Nacci et al., 1999; Matthiessen and Law, 2002; Fonseca et al., 2013) and this might give them an additional competitive advantage in colonising and benefiting from lower quality areas, where less tolerant species are excluded or of reduced abundance.

The partial differences in the response of different guild categories suggest a certain degree of complementarity between them. Hence, this supports the value of the followed approach in interpreting nekton assemblage structure, due to the use of functional rather than taxonomical categories (Elliott et al., 2007; Franco et al., 2008; Mouillot et al., 2013; Henriques et al., 2014), suggesting the implementation of an indicator set (i.e. metrics) of different aspects of the community potentially influenced by anthropogenic impacts.

## 4.1. Artisanal fishery

The role of the artisanal fishery in affecting the nekton assemblage was considered in conjunction with other anthropogenic pressures, as suggested by Blaber et al. (2000). Overall, the fyke net fishery was less important compared with other pressure categories. For biomass and species composition of most EUFG, FMFG and of the whole assemblage, the effect of the artisanal fishery was negligible (univariate analysis, Figures 3 and 4). A marginal positive response to the pressure was observed on biomass of estuarine and solely estuarine residents, as well as on biomass of microbenthivores (a FMFG including a large variety of species belonging to different EUFG and fishery categories). Remarkably, fishery pressure indicated a similar positive effect upon biomass of both target and total catches, although with a high associated variability.

Fishing in the Venice lagoon is performed using a variety of traditional gears, with fyke nets being the most important (Granzotto et al., 2001; Provincia di Venezia, 2009). The extraction of data from this activity is similar in many ways to a scientific survey: it is carried out throughout the year and the basin using a single type of gear, which has similar length, height and mesh size and is normally deployed for a comparable amount of time (Provincia di Venezia, 2009; Pranovi et al., 2013). All these characteristics allow the spatial and temporal comparison of collected samples by means of a standardised CPUE. Nevertheless, selection of fishing sites is mainly made in order to maximise yields. This may explain both the positive effect on target species and the negligible effect of the fishery in other cases, since a higher fishing effort is often justified in areas where higher abundance and biomass of targeted species are known to be supported. However, this positive link can persist in time only if the exploitation is carried out at biological sustainable levels. Indeed, the overall effort of the artisanal fishery (average of the whole basin) was relatively stable over the study period, even if it demonstrates a strong seasonality and high spatial variability (Provincia di Venezia, 2015). The present levels of fishing activities are lower than the ones recorded in the past, and indications suggest that changes in yields recorded in the last decades are not caused by overfishing, but rather by other human-induced changes in environment quality (Libralato et al., 2004).

The results highlighted above suggest that the fyke net-based artisanal fishery in the Venice lagoon is possibly undertaken at a sustainable level for the nekton fauna, considering that no significant effect was observed on the species (or group of species) composition or biomass of the lagoon nekton assemblages. Furthermore discarded levels are low, with up to 6% of the total biomass being discarded (Pranovi et al., 2013). However it should be noted that benthic invertebrate species, not considered in this study, can also be caught by fyke nets, and can even represent a significant share of the total biomass in the catch, both in terms of target species (i.e. crabs; Pranovi et al., 2013) and discarded species (e.g. gastropods). Only *ad hoc* fishery-independent surveys could fully investigate the overall sustainability of this type of artisanal fishery further. Such surveys would need totake into account the relationship between fishing effort and the response of the ecosystem, which is not necessarily linear. The effects of fishing effort could therefore be only evident after a certain critical threshold has been reached (Henriques et al., 2014). It was important however, for the goals of the present work, to understand if the activity used to gather information on nekton assemblage negatively affected the assemblage itself. Fisheries in transitional waters are poorly studied, despite the fact that theyrepresents a relevant economic activity in these ecosystems (Pérez-Ruzafa and Marcos, 2012). In particular, while many of the existing studies focus on the assessment of fisheries within transitional waters in terms of its impact on fish communities and overall ecological quality (Blaber et al., 2000; Rodríguez-Climent et al., 2012; Guillemot et al., 2014), there has not been any research regarding the potential use of fishery data to assess ecological status, even if it is clear that yields are strongly influenced by environmental conditions and anthropogenic pressures (Pérez-Ruzafa and Marcos, 2012).

In Europe, appropriately modified fishing gears are widely employed in scientific monitoring of fish fauna in transitional waters. Fine mesh, small beach seine nets are used in shallow water habitats within Italian coastal lagoons (Franco et al., 2006, 2009b), with modified beach seine nets being used also for the WFD assessment of transitional waters in the UK, where a multi-gear approach (i.e. including also the use of fyke nets, beam trawls and otter trawls) is applied (WFD-UKTAG, 2009). In French Mediterranean lagoons, fyke nets similar to those used by local fishermen are preferred (Mouillot et al., 2005; Brehmer et al., 2013). Beam and otter trawls are widely used in deeper habitats across estuaries in northern Europe, such as in UK and Germany (Elliott and Hemingway, 2002), and are also employed in French and Portuguese Atlantic estuaries (Pasquaud et al., 2010; Fonseca et al., 2013).

All sampling methods are affected by a degree of selectivity and their catch efficiency depends on both target species and habitat characteristics. Hence, due to the spatial diversity of transitional water ecosystems and the different fish assemblages they support, the choice of sampling gear is critical (Rozas and Minello, 1997; Elliott and Hemingway, 2002). Franco et al. ( 2012) showed that active gears (i.e. seines) gather punctual information at small spatial and temporal scales, while passive gears (i.e. fyke nets) tend to integrate on larger time (e.g. day-night cycle) and space scales, without detecting eventual different roles of habitats. In this light fyke nets could be more suitable for the comparison of relatively large areas, such as the ones considered here (14 - 39 $km^2$), or for the assessment of whole water bodies, where multi-gear approach is unfeasible.

## 4.2. Implications for the evaluation of ecological status

Our study supports the hypothesis that artisanal fishery data could represent an effective source for ecological status assessment of the Venice lagoon, since it provides a non-invasive sampling method and allows the use of pressure-sensitive metrics. Several fish-based multi-metric indices have been developed in recent years to assess the environmental status of European transitional waters under the Water Framework Directive (e.g. Coates et al., 2007; Franco et al., 2009b; Breine et al., 2010; Delpech et al., 2010; Cabral et al., 2011). As shown by Pérez-Dominguez et al. (2012), most of the metrics included in such indices are measures of community composition and structure, such as species richness and diversity. In addition, many of these indices follow the guild approach (Elliott and Dewailly, 1995; Elliott et al., 2007; Pérez-Domínguez et al., 2012). In contrast, biomass does not seem to be incorporated into published fish-based indices complying with WFD (Cabral et al., 2012; Pérez-Domínguez et al., 2012), even if a few proposed methods include fyke net sampling to obtain fish data (Coates et al., 2007; Breine et al., 2010). In fact, biomass could serve as a proxy indicator for the secondary production of a system, which can be affected by loss or degradation of transitional habitats (Deegan et al., 1997; Hughes et al., 2002).

Our study indicates that metrics calculated on biomass are more effective in detecting anthropogenic stressors compared with measures of species composition, when using fyke nets as sampling gear. In the absence of size related metrics, biomass also proved to be a good indicator of the effects of fishing activities, as recorded in other aquatic environments (Vallès and Oxenford, 2014). Compared to biomass, the use of species presence/absence led to the coexistence of a variety of different responses (highly positive, negative and negligible) in our study, ultimately resulting in an ambiguous representation. The importance of the interpretability of response variables, their sensitivity to anthropogenic pressures and robustness against natural 'noise' is crucial when evaluating ecological status (Rice, 2003; Noges et al., 2009).

The use of biomass-based metrics to detect changes in nekton communities was previously proposed by other authors (Guillemot et al., 2014; Henriques et al., 2014; Vallès and Oxenford, 2014). Here, we suggest that an evaluation of ecological status based on fishery monitoring data should focus on biomass data grouped considering a functional guild approach. This work shows some metrics responding to anthropogenic pressures, but further considerations are needed to choose which metrics, or combination or metrics, would result in the most effective index. Here a wide range of characteristics of nekton assemblage were analysed in relation to anthropogenic pressures and it was not possible to analyse in detail the interpretation of each comparison, nor to examine the causal link with human activities or to search for a combination of metrics maximising the correlation with anthropogenic pressures. In fact, even if the objective is to develop an index with a strong responsiveness to human disturbance, if only information on bivariate correlations with pressures are available, it is not possible to say which combination will result in a sensitive multi-metric index (Schoolmaster et al., 2012).The selected method for data analysis was based on the building of a series of nested models for the observed data, and the subsequent comparison of chosen sets of such models. This allowed us to explicitly answer ecological questions (Warton et al., 2014) based on alternative *a priori* hypotheses about the different contribution of seasonal and annual variability, environmental heterogeneity and anthropogenic pressures in affecting the nekton assemblage. It was possible to test the effect of pressures on the nekton assemblage as a whole and on a series of macro-descriptors summarising important characteristics of the assemblage. This model-based approach is acknowledged to be a more interpretable, flexible and efficient way to handle ecological data, compared to other classical multivariate analysis techniques (Warton et al., 2014). This approach allowed us to disentangle the contribution the different types of predictor variables, ultimately enabling the discrimination between the effects of anthropogenic pressures and environmental variability on nekton assemblage. We argue that such an approach represents an effective way to cope with the "estuarine quality paradox", i.e. the difficulty to detect anthropogenically-induced stress in estuaries due to the adaptation of the biota to the naturally high variability within such ecosystems (Elliott and Quintino, 2007; Elliott and Whitfield, 2011). Since biological indicators must be able to measure the ‘signal’ of anthropogenic effects over the ‘noise’ of this natural variability (Whitfield and Elliott, 2002), the estuarine quality paradox is regarded as a strong handicap to assess the ecological status of transitional waters (Dauvin and Ruellet, 2009).

## 5. Conclusions

The results of this study have major implications on several aspects of research and management of transitional water ecosystems: (i) indicating the critical importance of evaluating the relationship between nekton assemblage and anthropogenic pressures, and suggesting the most suitable metrics for this purpose considering the estuarine quality paradox (Elliott and Quintino, 2007); (ii) confirming the effectiveness of the guild approach in such a context, particularly by considering biomass-related metrics; (iii) exemplifying the effectiveness of model based community analysis, which allows to explicit answers to ecological questions and to test *a priori* formulated hypotheses; (iv) investigating a poorly researched subject in estuarine ecology such as the role of the artisanal fishery in affecting nekton communities, and disentangling the contribution of this activity from other anthropogenic pressures; (v) suggesting that an artisanal fishery performed with fyke nets can represent a viable source of ecological data in coastal lagoons; (vi) suggesting that fyke net-based artisanal fishery in the Venice lagoon, carried out at the present level of effort, is possibly sustainable with regard to the nekton assemblage, since its role as a pressure is negligible compared with the other anthropogenic stressors.

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909

# 8. Tables

**Tab. 1 Anthropogenic pressures indices and references**

| Category | Description | Label | References |
|---|---|---|---|
| Morphological | intertidal area lost (% area between -0.5 and +0.5 m lost between 1972 and 2002) | Intert | Sarretta et al., 2010 |
| Morphological | gross change in bathymetry (relative change in bottom depth between 1972 and 2002, taking a variation of ± 0.75m as minimum significant change) | Bathy | Sarretta et al., 2010 |
| Morphological | seagrass habitat loss (relative loss between 1990 and 2002) | Seag | Caniglia et al., 1992; Rismondo et al., 2003 |
| Morphological | relative sea level | Rise | Carbognin et al., 2010; Teatini et al., 2012 |
| Morphological | interference with hydrographic regime (changes in sediment resuspension related to alteration of hydraulic circulation due to the presence of human infrastructures) | Hydro | D'Alpaos, 2010 |
| resource/habitat use | aquaculture | Aqua | G.R.A.L., 2006, 2009; Provincia di Venezia, 2009 |
| resource/habitat use | fisheries (density of fyke nets as no. traps/km2) | Fish_class | Mag. Acque - Agriteco, 2004, 2007; Provincia di Venezia, 2009; "www.gralvenezia.it," 2015 |
| resource/habitat use | intensity of marina developments (no. berths/ km2) | Marina | "www.pagineazzurre.com," 2014, "www.portolando.eu," 2014 |
| resource/habitat use | navigation (no. boat passages/day) | Traffic | Mag. Acque - COSES, 2002; Mag. Acque - Technital, 2002 |
| resource/habitat use | intensity of shipyards | Shipyard | "www.portodichioggia.it," 2014; www.port-venice.com, 2014 |
| environmental quality | water chemical quality (the number of substances whose concentrations did not comply with imperative concentration values set for the Venice lagoon - D.M. 23/04 1998) | WatChemQual | Mag. Acque - Thetis, 2004, 2005b; ARPAV-ISPRA, 2013; Mag. Acque - SAMA, 2013 |
| environmental quality | sediment chemical quality | SedChemQual | (Apitz et al., 2007) |
| environmental quality | sediment quality biological effects (Weighted Average Toxicity Index (WATI), which integrates the results of different ecotoxicological tests on different matrices) | Wati | Losso and Volpi Ghirardini, 2010 |
| environmental quality | Benthos (Multivariate-Azti Marine Biotic Index; M-AMBI) | Mambi | Mag. Acque - Thetis, 2006; Muxika et al., 2007; ARPAV-ISPRA, 2013 |
| environmental quality | nutrients (DIN;RP mean) | DIN; RP | Mag. Acque - Thetis, 2004, 2005b; ARPAV-ISPRA, 2013 |
| environmental quality | Chlorophyll | Chla | Mag. Acque - Thetis, 2004, 2005b; ARPAV-ISPRA, 2013; Mag. Acque - SAMA, 2013 |
| environmental quality | Dissolved Oxygen | Od | Mag. Acque - Thetis, 2004, 2005b; ARPAV-ISPRA, 2013; Mag. Acque - SAMA, 2013 |

**Tab. 2 Structure of models used to assess the relation between nekton community temporal factor, environmental conditions and anthropogenic pressures and scheme of comparison ($Y_i$: response variables; PC1, PC2, PC3: Principal Components of the PCA on environmental data; P_morpho: Pressures acting on morphology; P_Use: Pressures related to the use of the resources and habitat; P_Quality: Pressures affecting environmental quality of matrices; P_Fish: Pressures related to the activity of artisanal fishery).**

| Label | Model structure /comparison | Description - Response variable affected by: |
|---|---|---|
| m0 | Yi ~ constant + εi | None of the considered factors |
| m1 | Yi ~ Season X Year + constant + εi | Temporal factor only |
| m2 | Yi ~ Season X Year + PC1 + PC2 + PC3 + constant+εi | Temporal factor and environmental conditions |
| m3.0 | Yi ~ Season X Year + P_Morpho + P_Use + P_Quality + constant + εi | Temporal factor and anthropogenic pressures (artisanal fishery excluded) |
| m3.1 | Yi ~ Season X Year+ PC1 + PC2 + PC3 + P_Morpho + P_Use + P_Quality + constant + εi | Temporal factor, environmental conditions and anthropogenic pressures (artisanal fishery excluded) |
| m4.0 | Yi ~ Season X Year + PC1 + PC2 + PC3 + P_Fish + constant + εi | Temporal factor, environmental conditions and artisanal fishery pressure |
| m4.1 | Yi ~ Season X Year + P_ Fish + constant + εi | Temporal factor and artisanal fishery pressure |
| m4.2 | Yi ~ Season X Year + PC1 + PC2 + PC3 + P_Morpho + P_Use + P_Quality + P_ Fish + constant+εi | Temporal factor, environmental conditions, anthropogenic pressures including the one related to artisanal fishery |
| | | **Testing the effect of:** |
| Test0 | m0 vs m1 | Temporal factor |
| Test1 | m1 vs m2 | Inclusion of environmental conditions if only temporal factor was considered before |
| Test2.0 | m1 vs m3.0 | Inclusion of anthropogenic pressures (artisanal fishery excluded) if only temporal factor was considered before |
| Test2.1 | m2 vs m3.1 | Inclusion of anthropogenic pressures (artisanal fishery excluded) if temporal factor and environmental conditions were considered before |
| Test3.0 | m2 vs m4.0 | Inclusion of artisanal fishery pressure if temporal factor and environmental conditions were considered before |
| Test3.1 | m1 vs m4.1 | Inclusion of artisanal fishery pressure if temporal factor was considered before |
| Test3.2 | m3.1 vs m4.2 | Inclusion of artisanal fishery pressure if temporal factor, environmental conditions and other anthropogenic pressures were considered before |

**Tab. 3 Summary of the significance results for the multivariate comparisons of nested models. Significant global p-values are in bold and underlined. A complete framework of the results for the multivariate comparisons is presented in supplementary materials (Table A.3), including species showing significant effect of anthropogenic pressures (if applicable).**

| Response variable | Test | Tested effect | p-value |
|---|---|---|---|
| Presence/Absence of all species | Test 0 | Temporal factors | **0.001** |
| | Test 1 | Environmental conditions (temporal factors already included) | p>0.05 |
| | Test 2.0 | Anthropogenic pressures (fishery excluded; temporal factors already included) | p>0.05 |
| | Test 2.1 | Anthropogenic pressures (fishery excluded; temporal factors and environmental conditions already included) | p>0.05 |
| | Test 3.0 | Fishery related pressures (temporal factors and environmental conditions already included) | p>0.05 |
| | Test 3.1 | Fishery (temporal factors already included) | p>0.05 |
| | Test 3.2 | Fishery related pressures (temporal factors, environmental conditions and other pressures already included) | p>0.05 |
| Biomass (Biomass of species whose cumulative biomass represent the 95% of the total) | Test 0 | Temporal factors | **0.001** |
| | Test 1 | Environmental conditions (temporal factors already included) | **0.001** |
| | Test 2.0 | Anthropogenic pressures (fishery excluded; temporal factors already included) | **0.001** |
| | Test 2.1 | Anthropogenic pressures (fishery excluded; temporal factors and environmental conditions already included) | **0.001** |
| | Test 3.0 | Fishery related pressures (temporal factors and environmental conditions already included) | **0.008** |
| | Test 3.1 | Fishery (temporal factors already included) | p>0.05 |
| | Test 3.2 | Fishery related pressures (temporal factors, environmental conditions and other pressures already included) | p>0.05 |

# Figure captions

**Fig. 1** The Venice lagoon and the five study areas (CH: "Chioggia"; CZ: "Ca' Zane"; LD: "Lido"; LT: "Lago dei Teneri"; PL: "Ponte della Libertà").

**Fig. 2** Biplots of the Principal Component Analysis on environmental variables: first two axes (A) and first and third axis (B). Biplot of the PCA on indicators of pressure: first two axes (C) and first and third axis (D).

**Fig. 3** Panel plot summarising the results of the nested comparison of models for the community metrics (univariate comparison): the size of the square is inversely proportional to the p-value and the shade of grey is proportional to the explained deviance. Biomass (B; left panel) and number of species (S; right panel) for fishery-related metrics (discarded, incidental, target and total catches), Estuarine Usage Functional Groups (A: anadromous; C: catadromous; ES: estuarine; ESs: solely estuarine; FS: freshwater stragglers; ME-D: marine estuarine-dependent; ME-O: marine estuarine-opportunists; MS: marine stragglers) and Feeding Mode Functional Groups (Bma: macrobenthivores; Bmi: microbenthivores; DV: detritivores; HP: hyperbenthivores/piscivores; HV: herbivores; HZ: hyperbenthivores/zooplanktivores; OV: omnivores; PL: planktivores). For each comparison test, the effects tested are indicated as follows: t = temporal factor; e = environmental conditions; p = anthropogenic pressures (other than fishery); f = artisanal fishery pressure.

**Fig. 4** Averaged coefficients (±C. I.) for the 4 considered pressure categories (x-axis) for the models of biomass (B; left column of plots) and number of species (S; right panel of plots) for (a) fishery-related metrics (discarded, incidental, target and total catches), (b) Estuarine Usage Functional Groups (A: anadromous; C: catadromous; ES: estuarine; ESs: solely estuarine; FS: freshwater stragglers; ME-D: marine estuarine-dependent; ME-O: marine estuarine-opportunists; MS: marine stragglers) and (c) Feeding Mode Functional Groups (Bma: macrobenthivores; Bmi: microbenthivores; DV: detritivores; HP: hyperbenthivores/piscivores; HV: herbivores; HZ: hyperbenthivores/zooplanktivores; OV: omnivores; PL: planktivores). The size of the dots are proportional to the Akaike weights used for model averaging.

**Fig. 5** Averaged coefficients (±S. E.) for the four considered pressure categories (x-axis) for the models of presence/absence (left panel) and biomass (right panel) for all considered species.