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Vulnerability of artisanal fisheries to climate change in the Venice Lagoon[a]

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Within the context of global warming, the western coast of the northern Adriatic Sea can be regarded as an extremely vulnerable area. Owing to the local geographic features, this area has been described as the Venetian lacuna, where Mediterranean Sea climatic conditions are replaced by Atlantic Ocean ones, supporting the presence of glacial relicts, such as sprat *Sprattus sprattus*, flounder *Platichthys flesus* and brown shrimp *Crangon crangon*. Nektonic assemblage therefore represents a good candidate in terms of an early proxy for thermal regime alterations. It represents a dynamic component of the lagoon ecosystem, changing in space and time, actively moving through the entire system, and dynamically exchanging with the open sea. Here, the first signals of the change have been already detected, such as the presence of alien thermophilic species. Within this context, since the beginning of the century, sampling of the nektonic assemblage has been carried out, integrating them with landings data from the fish market. Vulnerabilities to thermal regime changes have been tested by (1) categorizing species according to the mean distribution area in terms of latitudinal range (over 45°, 30°–45° and below 30°), and (2) analysing both spatial and temporal variations within fishing grounds. Results indicated a high potential vulnerability of the artisanal fishery to climate change, as the commercial catch is entirely composed of species from cold (>45° N) and temperate (between 45° and 30° N) latitudes. At present no alien thermophilic species have been recorded within the lagoon, which is possibly a sign of good resilience of the assemblage. Finally, abundance of species from cold latitudes has decreased during the past decade. All of this has been discussed in the context of the mean annual temperature trend.

Key words: global changes; landings; northern Adriatic Sea; small-scale fishery; temperature; time series.

INTRODUCTION

Climate change is one of the major drivers affecting structure and function of both terrestrial and marine ecosystems, and effects are expected to grow in the near future (Cramer *et al.*, 2001; Hughes *et al.*, 2003; Parmesan & Yohe, 2003; Rosenzweig *et al.*, 2008; Drinkwater *et al.*, 2010). Mediated mainly by modifications

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in thermal regimes, ocean currents and coastal upwelling, several changes in marine ecosystems have been described already, such as shifting in geographic distributions towards higher latitudes (Parmesan, 2006; Hiddink & Hofstede, 2008; Ben Rais Lasram *et al*., 2010), increasing extinction rates (Thomas *et al*., 2001; Cheung *et al*., 2009) and reorganization of local communities in relation to substitutions of native species by exotic thermophilic ones (Mills *et al*., 2004; Ben Rais Lasram & Mouillot, 2009). Even if the real effects of these changes on a global scale are currently under discussion, on a local scale they are producing significant change in terms of structure and function of marine ecosystems (Drinkwater *et al*., 2010.

Among other human activities, global changes are expected to directly affect fisheries worldwide (Cheung *et al*., 2009; Brander, 2010). Changes both in productivity and distribution areas, decreasing of target species abundance, species replacement, direct effects of warming on growth, survival, migratory behaviour and reproductive rates of many species are expected to greatly affect marine resources and their exploitation, with social and economic costs for human populations (Brander, 2007).

In relation to the exposure to global changes, some areas and habitats, such as semi-enclosed basins and polar areas, where the range shifts are physically constrained, could be more vulnerable than others. For the Mediterranean Sea basin, the potential vulnerability exists where this inland sea acts as a cul de sac for endemic species as highlighted by Ben Rais Lasram *et al.* (2010). Within this context, the western part of the northern Adriatic Sea shares similar geography. This area, together with the Gulf of Lion, represents one of the coldest zones of the Mediterranean Sea basin, and has been described as the Venetian lacuna. This is defined as an interruption of the Mediterranean Sea due to the presence of Atlantic climate conditions. Its terrestrial composition was first described by Marcello (1960), noting the absence of typical Mediterranean plants. Successively, an effect on marine environment was recognized, namely to intertidal assemblages (Sacchi, 1978), and the geographical limit of the lacuna was found to coincide with the winter season isotherm of 7° C.

The Venice Lagoon, located in the middle of the lacuna, could be especially vulnerable in this context, being a semi-enclosed area, inside two other basins with the same peculiar features (Adriatic and Mediterranean Seas). Owing to the millenary coexistence, local populations are strongly linked with the lagoon environment, with fishing activities deeply rooted in local traditions. At present, the exploitation of marine renewable resources occurs as two different activities: an artisanal fishery (Granzotto *et al*., 2001; Libralato *et al*., 2004) and recent mechanical clam harvesting, developed about three decades ago after the introduction of Manila clam *Ruditapes philippinarum* in the lagoon in 1983 (Pranovi *et al*., 2006).

Being multigear and multitarget, the artisanal fishery in the lagoon can be defined as a small-scale fishery according to the current European Commission classification (*i.e*. fishery performed by boats <12 m overall length equipped with passive gear). Conversely, the clam harvest, being a single-target activity carried out with mechanized gear that disturbs the ecosystem (Pranovi *et al*., 2004), can be defined as a semi-industrial fishing activity. During recent decades, the interaction between the two activities presented a source of conflicts, with negative direct impacts of the mechanical harvesting on the artisanal fishery (Pranovi *et al*., 2003; Granzotto *et al*., 2004). For the above reasons, the vulnerability of the artisanal fishery in the Venice Lagoon represents an interesting issue to be analysed in terms of relevance for its social, economic and ecological implications (AdriaMed, 2005; Battaglia *et al*., 2010).

The aims of this paper are: to offer a description of the present situation of the artisanal fishery in the Venice Lagoon; to analyse landings time series for detecting modifications (*e.g*. regime shifts), potentially related to climate changes; to assess the potential vulnerability of the renewable resources exploitation to climate changes in the Venice Lagoon.

MATERIALS AND METHODS

SAMPLING ACTIVITIES

Sampling was conducted over two periods from 2001 to 2003 and 2009 to 2010. Fyke nets were deployed and the catches were examined monthly (mean ± S.E. = 22.2 ± 2.4 traps per month) when fishermen emptied them. Four sampling areas, located in the three main basins, ensured data represented the primary lagoon fishing grounds (Fig. 1). Collected specimens were classified and counted, and for each taxon the total wet mass was recorded directly onboard (only cases of dubious attribution were transferred to the laboratory as samples).

Fishermen visited the traps relative to the expected catch amount (which varied seasonally), thus optimizing their effort. Because of this, the amount of catch observed during sampling may have represented the outcome of one or more days' fishing depending on the time of year. Therefore, in order to obtain homogenous data, a standardization in terms of catch (g) per trap per day was performed, taking into the account the number of days since the previous visit by the fishermen. Once the composition of the catches was characterized, the complete time series of landings for targeted species, from 1945 to 2011, was reconstructed with data from the fish market of Chioggia, which represents the most important market in the area. As interests were to analyse the global trend of each exploited species, no correction was applied given that species were simultaneously targeted by different fishing gears in the lagoon and at sea.

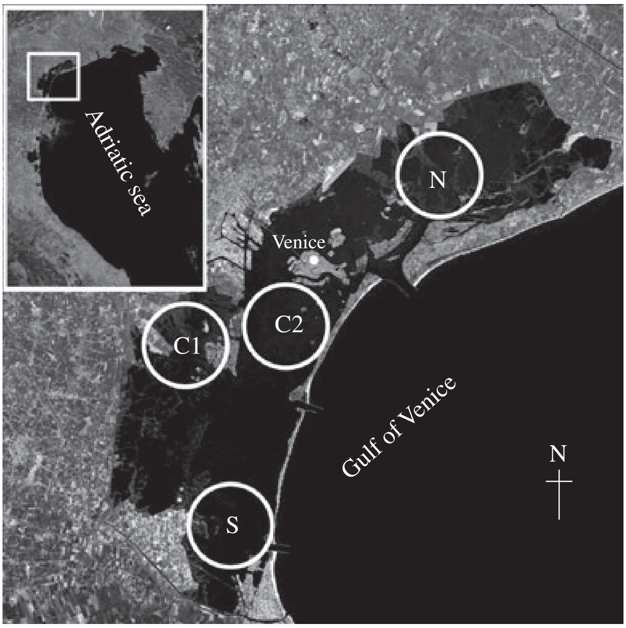

FIG. 1. Sampling areas in Venice Lagoon (N, northern basin; C1 and C2, central basin; S, southern basin).

DATA ANALYSIS

Species were grouped as target (species targeted by the fishing activity), incidental (species of commercial interest but not representing the main target) and discard (species with no commercial value). A further classification was carried out according to ecological guilds (Malavasi *et al.*, 2004; Franco *et al.*, 2006), *i.e.* estuarine (all the life cycle in the lagoon), marine migrant (regularly migrating between lagoon and sea environment), marine stragglers (occasionally present in the lagoon, preferring marine salinity areas), anadromous and catadromous species (regularly migrating between freshwater and marine areas and *vice versa*, passing through the lagoon) and finally freshwater species (typical of freshwater environment and occasionally recorded in the brackish waters).

In order to assess the thermal affinity of each sampled species, distributional data for the Northern hemisphere were obtained from the online database of the Ocean Biogeographic Information System (OBIS; www.iobis.org) within the Global Biodiversity Information Facility (GBIF; http://data.gbif.org/). Arbitrary latitudinal thresholds were set at 30° N (southern limit of the Mediterranean Sea basin) and 45° N (northern limit of the basin, excluding the northernmost parts of the Adriatic and Black Seas), defining a northern cold zone (>45° N), a central temperate zone (between 45° and 30° N; typical of the Mediterranean Sea) and a southern warm zone (<30° N). The main latitudinal ranges for the species were estimated by means of the median and interquartile range of the latitudinal component of the distributional data. Finally, the thermal affinity for each taxon was attributed based on whether its median fell in the cold, temperate or warm zone. In cases where the interquartile range was not fully included in the same zone as the median, an intermediate thermal affinity was attributed. Globally, six groups were defined: cold, cold–temperate (CT), temperate, temperate–warm (TW), warm and ubiquitous species. This classification was applied both for analysing the field samples catch composition, and for studying temporal trends in the reconstructed time series of landings. Differences among categories were analysed by using the Mann–Whitney U-test.

The time series (1970–2011) of the water temperature (annual mean) for the Venice Lagoon and the winter North Atlantic Oscillation (NAO) have been reconstructed with respective values collected from local databases (see also www.istitutoveneto.it) and on the U.S. National Oceanographic and Atmospheric Administration (NOAA) climate prediction centre website (www.cpc.ncep.noaa.gov). The presence of regime shifts in the time series has been detected by applying the sequential t-test analysis of regime shift (STARS) developed by Rodionov (2004, 2005), based on a sequential t-test analysis. Temporal trends have been analysed by plotting annual landings for each target species against both water temperature and NAO. The same procedure was applied to landing data aggregated on the basis of the species thermal affinity.

Statistical significance of correlations was tested through the application of generalized additive models (GAM; Hastie & Tibshirani, 1990). GAM represents a semi-parametric regression technique for exploring relationships between response and predictor variables, having greater flexibility for drawing out the long-term non-linear trends than chain or linear modelling methods. Some predictors can be modelled non-parametrically, using a smoothing function, in addition to linear and polynomial terms, allowing the response shape to be fully determined by the data.

The following additive formulation was used: $Y = a + s_1(V_1) + \ldots - s_n(V_n) + \varepsilon$, where a is the intercept, s the thin plate smoothing spline function (Wood, 2003), $V \ldots V_{\mathrm{n}}$ the predictors and ε the random error. Model fitting and testing were carried out using the MGCV package (Wood, 2006), in R 2.13 (R Core Development team; www.r-project.org).

RESULTS

FIELD SAMPLING ACTIVITY

The complete list of sampled species is given in Table I. In terms of biomass contribution, target species (11 taxa) accounted for c. 80% of total catches, incidental catches (11 taxa) for 19% and discarded species (33 taxa) for c. 2%

TABLE I. List of taxa recorded from the Venice Lagoon

Scientific name	Common name	Ecological guild	Fishery category	Climatic affinity
Alosa fallax	Twaite shad	Anadromous	Discard	Cold
Anguilla anguilla	European eel	Catadromous	Target	Cold
Aphanius fasciatus	Mediterranean killifish	Estuarine	Discard	Temperate
Atherina boyeri	Sand smelt	Estuarine	Target	Temperate
Belone belone	Garfish	Marine migrant	Discard	Cold–temperate
Boops boops	Bogue	Marine straggler	Discard	Temperate–warm
Carcinus aestuarii	Green crab	Estuarine	Target	Temperate
Chelidonichthys lucerna	Tub gurnard	Marine migrant	Discard	Ubiquitous
Chelon labrosus	Thicklip gray mullet	Marine migrant	Incidental	Cold–temperate
Conger conger	Conger eel	Marine straggler	Discard	Cold
Crangon crangon	Brown shrimp	Marine migrant	Target	Cold
Dicentrarchus labrax	European sea bass	Marine migrant	Incidental	Cold
Diplodus annularis	Annular seabream	Marine migrant	Discard	Temperate
Diplodus puntazzo	Sharpsnout seabream	Marine straggler	Discard	Temperate
Diplodus sargus	White seabream	Marine straggler	Discard	Temperate
Diplodus vulgaris	Two-banded seabream	Marine straggler	Discard	Temperate
Engraulis encrasicolous	European anchovy	Marine migrant	Discard	Temperate–warm
Gambusia holbrooki	Eastern mosquitofish	Estuarine	Discard	Temperate
Gobius cobitis	Giant goby	Marine straggler	Incidental	Temperate
Gobius niger	Black goby	Estuarine	Incidental	Cold
Gobius paganellus	Rock goby	Estuarine	Incidental	Cold
Hippocampus guttulatus	Long-snouted seahorse	Estuarine	Discard	Ubiquitous
Hippocampus hippocampus	Short-snouted seahorse	Estuarine	Discard	Cold–temperate
Knipowitschia panizzae	Adriatic dwarf goby	Estuarine	Discard	Temperate
Lithognathus mormyrus	Sand steenbras	Marine migrant	Incidental	Temperate
Liza aurata	Golden grey mullet	Marine migrant	Target	Temperate
Liza ramada	Thinlip grey mullet	Catadromous	Incidental	Cold–temperate
Liza saliens	Leaping mullet	Marine migrant	Incidental	Temperate
Mullus surmuletus	Surmullet	Marine migrant	Incidental	Cold–temperate
Palaemon spp.	Rockpool prawn	Estuarine	Target	Cold
Parablennius sanguinolentus	Rusty blenny	Marine straggler	Discard	Temperate
Penaeus spp.	Shrimp	Marine migrant	Incidental	Temperate
Platichthys flesus	European flounder	Marine migrant	Target	Cold

TABLE I. continued

Scientific name	Common name	Ecological guild	Fishery category	Climatic affinity
Pomatomus saltatrix	Bluefish	Marine straggler	Discard	Temperate–warm
Pomatoschistus canestrinii	Canestrini's goby	Estuarine	Discard	Temperate
Pomatoschistus marmoratus	Marbled goby	Estuarine	Discard	Temperate
Pomatoschistus minutus	Sand goby	Marine migrant	Target	Cold
Salaria pavo	Peacock blenny	Estuarine	Discard	Temperate
Salmo trutta	Brown trout	Fresh water	Discard	Cold
Sardina pilchardus	European pilchard	Marine migrant	Discard	Temperate
Sepia officinalis	Common cuttlefish	Marine migrant	Target	Cold
Sepiola rondeletii	Dwarf bobtail squid	Marine straggler	Discard	Temperate
Solea solea	Common sole	Marine migrant	Incidental	Cold
Sparus aurata	Gilthead seabream	Marine migrant	Target	Temperate
Sprattus sprattus	Sprat	Marine migrant	Discard	Cold
Symphodus cinereus	Gray wrasse	Marine straggler	Discard	Temperate
Symphodus doderleini	Doderlein's wrasse	Marine straggler	Discard	Temperate
Symphodus roissali	Five-spotted wrasse	Estuarine	Discard	Temperate
Syngnathus abaster	Black-striped pipefish	Estuarine	Discard	Temperate
Syngnathus acus	Greater pipefish	Marine migrant	Discard	Cold
Syngnathus tenuirostris	Narrow-snouted pipefish	Estuarine	Discard	Temperate
Syngnathus typhle	Broadnosed pipefish	Estuarine	Discard	Cold
Trachurus trachurus	Atlantic horse mackerel	Marine straggler	Discard	Temperate
Umbrina cirrosa	Shi drum	Marine migrant	Discard	Warm
Zosterisessor ophiocephalus	Grass goby	Estuarine	Target	Temperate

[Fig. 2(a)]. For the ecological guilds [Fig. 2(b)], the observed pattern is related to the exploitation of a typical nektonic assemblage in a transitional water area. Estuarine and marine migrant species were well represented in the catches (18 and 21 species), accounting for 43 and 18% in biomass, and 12 species belonging to the marine stragglers category (<1% of total biomass). Finally, a moderate contribution to total catches came from the catadromous species group (37%), comprising only two species, [European eel *Anguilla anguilla* (L. 1758) and thinlip grey mullet *Liza ramada* (Risso 1827)] (see also Table I).

Data collected show some differences between the three basins, with significantly higher catches (Mann–Whitney U-test, $P < 0.05$) collected in the central part of

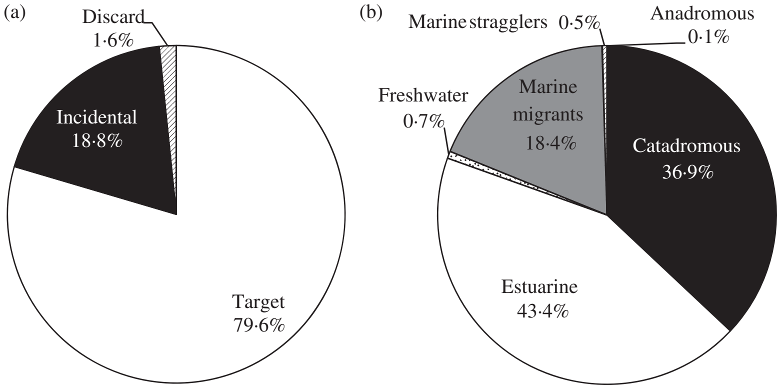

FIG. 2. Catch composition (in biomass, standardized data) in relation to (a) fishing activity and (b) ecological guilds from the Venice Lagoon.

the lagoon [Fig. 3(a)]. There is also a clear seasonality of catches, with significantly (Mann–Whitney U-test, $P < 0.05$) higher values recorded in autumn [Fig. 3(b)].

In relation to thermal affinity groups, data collected show that in terms of target species, catches are entirely composed of cold and temperate species (28 and 72%); whereas incidental catches and discard species are more heterogeneous. Temporal analysis of thermal affinity groups showed an oscillating pattern with a negative peak recorded in 2003 (statistically significant in comparison with both 2009 and 2010, Mann–Whitney U-test, $P < 0.05$). This represented the warmest year of the time series, being characterized by a heat wave during the summer (Fig. 4).

TIME SERIES ANALYSIS

In order to analyse long-term variations and possible relationships with climate parameters, starting from the target species list, the time series of landings from 1945 to 2011 has been reconstructed with fish market data (Fig. 5). Different phases are recognizable: a sharp increasing trend between the 1950s and 1960s, culminating at the beginning of 1970s, then a declining trend with the minimum value recorded in 1999, followed by a slight recovery. The presence of different phases was also confirmed by the application of the STARs (Fig. 5). Given the temperature time series (1970–2011), a significant change of regime recorded in the second half of 1980s was clearly visible in terms of anomalies (Fig. 6); thus, the attention has been focused on the transition recorded in the second half of the 1980s. For almost all series, total catches and the 12 target species highlight a significant decrease in values during this period (Table II).

In terms of thermal affinity, a decreasing trend of both temperate and cold species abundance has been detected, more pronounced for the latter [Fig. 7(a)].

Possible correlations between landings and climate variables were investigated by contrasting different groups and species *v*. water temperature and the NAO index. Both cold and temperate groups showed a significant (tested with GAM) negative correlation with the water temperature [Fig. 7(a)]; this was confirmed by all the target species with the exception of gilthead seabream *Sparus aurata* L. 1758 and golden grey mullet *Liza aurata* (Risso 1810) for which a positive and

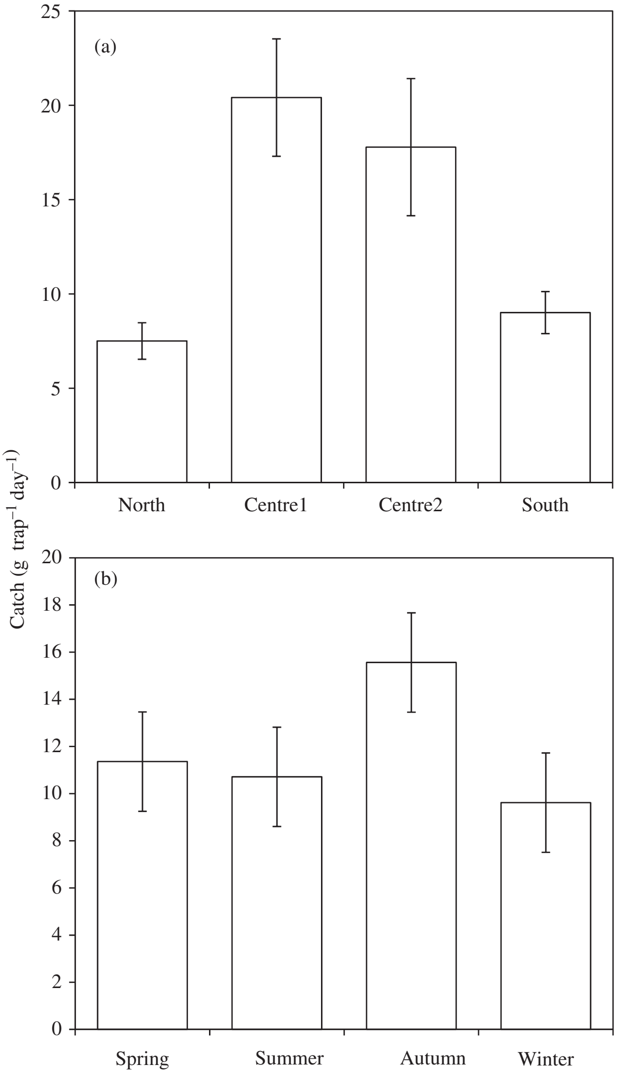

FIG. 3. Mean ± S.E. catch values for (a) different areas within the Venice Lagoon and (b) season.

no relationship were detected [Fig. 7(b)]. The analysis contrasting landings *v*. the NAO index highlighted no significant correlation.

DISCUSSION

Small-scale fisheries worldwide are recognized for their substantial contributions towards fish production and to be very relevant for their social, economic and ecological implications. Moreover, as underpinned also by the code of conduct for responsible fisheries (FAO, 1995), small-scale fisheries could represent, at least in some areas, a valid alternative to industrial fishery in terms of sustainable exploitation.

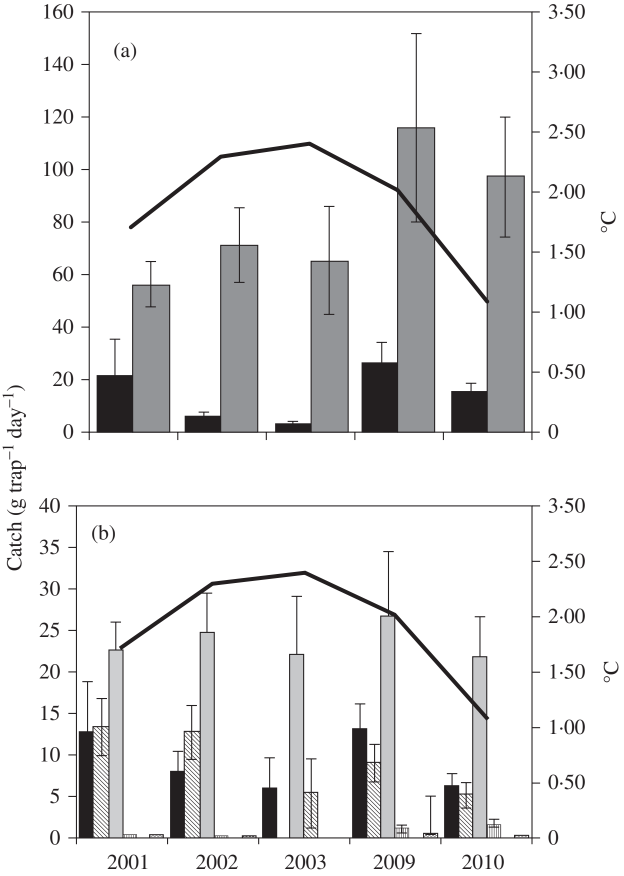

FIG. 4. Temporal variations of the thermal affinity groups represented in (a) the target species [■, cold; ▒, temperate; ——, sea surface temperature (SST) anomaly] and (b) in the total catch (■, cold; ▧, cold and temperate; ▒, temperate; ▥, temperate and warm; □, warm; ▩, ubiquitous; ——, SST anomaly) during the sampling periods within the Venice Lagoon. Catch values are means ± S.E.

According to the results obtained, the artisanal fishery in the Venice Lagoon is configured as a small-scale fishery, characterized by a large variety of target species and a marked seasonality.

The total catch composition, characterized by a high number of taxa, completely reflects the nektonic assemblage described in the lagoon environment (Malavasi *et al.*, 2004; Franco *et al.*, 2006), being composed of all the main ecological guilds typical of transitional waters. Targeted species represent the most abundant and regularly present groups in the lagoon, including resident species (estuarine), marine migrants and catadromous species. The marine stragglers by comparison, due to their random presence in the catches, are considered to be incidental or discard by local fishermen.

In relation to the economic classification of catches, the artisanal fishery is a low discard incidence activity (<2% in biomass), as described for other small-scale Mediterranean fisheries (Kelleher, 2005; Matić-Skoko *et al.*, 2011). The fishery also shows a strong seasonality, both in terms of total catch and catch composition,

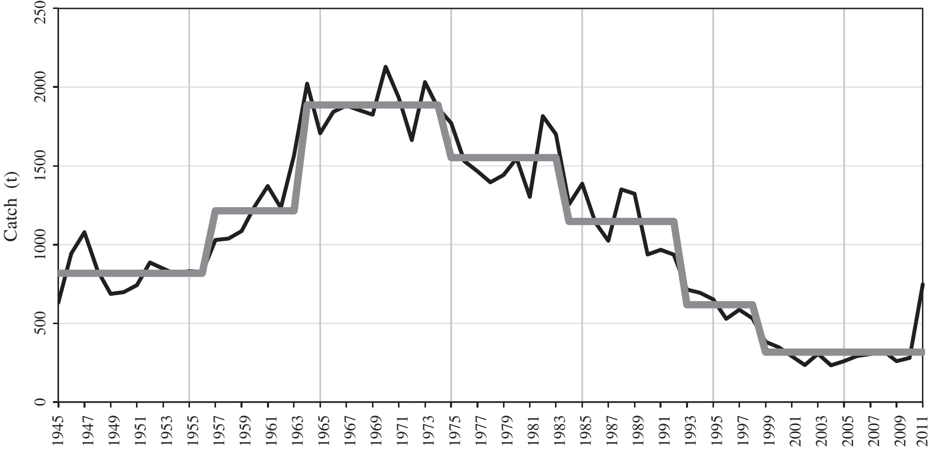

FIG. 5. Temporal trend in landings of artisanal fishery target species from the Chioggia fish market (——); different phases detected by the sequential *t*-test analysis of regime shift (STARS) are also reported (——).

confirming the ability of fishermen to change their habits according to the different environmental and ecological conditions in order to optimize catch and maximize profitability (Colloca *et al.*, 2004; Tzanatos *et al.*, 2005; García-Rodríguez *et al.*, 2006; Battaglia *et al.*, 2010). The fishing activity in the lagoon is strongly related to habitat distribution (which, for example, can explain the spatial differences of catches in terms of different habitat configurations of fishing grounds), tidal currents and seasonal cycles. All of this directly requires the ecological knowledge of fishermen (in relation to life cycles of species, migrations, seasonality, feeding habits, influence of environmental factors such as tidal currents, morphology, salinity and temperature). Together with high cultural and heritage value (Matić-Skoko *et al.*, 2011), this knowledge represents an important source of diversity that has to be conserved (Silvano & Valbo-Jørgensen, 2008; Eddy *et al.*, 2010).

The combination of field and fish-market data, allowed the time series of landings of species targeted by artisanal fishery in the lagoon, from 1945 to today to be reconstructed. The time series analysis highlighted the presence of different phases that can be roughly summed up in an initial increasing phase, a stable period in the central part, and finally a long decreasing trend in landings.

All of the recognizable different phases are in accordance with those described by Libralato *et al.* (2004), and are explainable in terms of: (1) increasing fishing effort, both in relation to the number of vessels and diffusion of engine-powered boats, and increasing ecosystem carrying capacity owing to the first effects of the eutrophication during the first expansion, (2) the reaching of the carrying capacity in the stable phase and (3) finally, synergic effects of different causes (*e.g*. anoxia events, dystrophic crises and explosion of the mechanical clam harvesting) in the decline recorded since the 1980s (Libralato *et al.*, 2004).

Within the context of describing possible effects of climate changes, attention was focused on the regime shift in total catches in the mid-1980s. Defined by deYoung *et al.* (2008) this shift is as an extensive and relatively abrupt change, happening

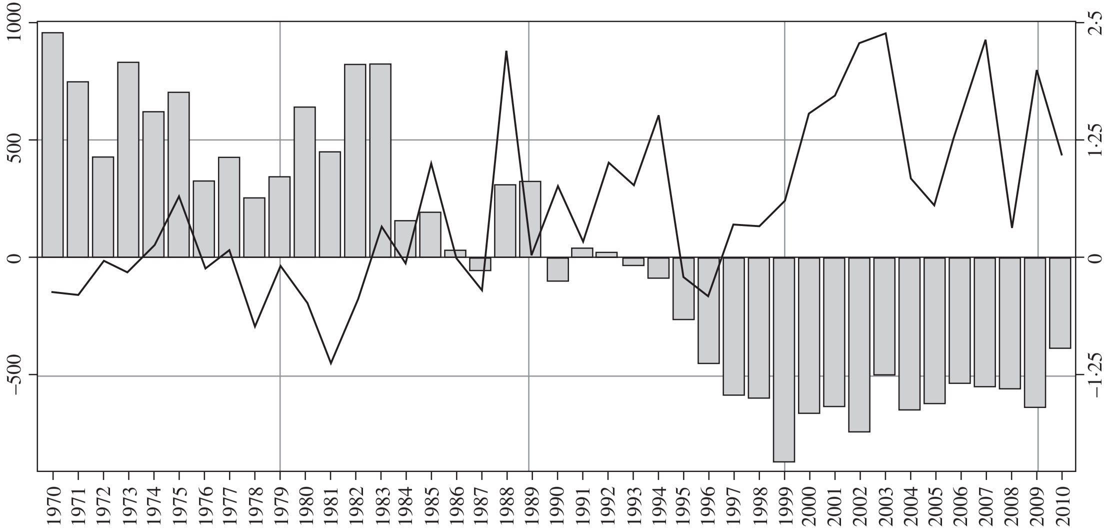

FIG. 6. Time series of landings (▨) and temperature anomalies (——) in the Venice Lagoon 1970−2010.

Table II. Significant regime shift detected in the second half of 1980s; downward arrow indicates decreasing trend from that year forward

Year	1984	1985	1986	1987	1988
Anguilla anguilla		↓			
Crangon crangon				↓	
Platichtys flesus	↓				
Pomatoschistus minutus			↓		
Palaemon spp.		↓			
Sepia officinalis	↓				
Atherina boyeri			↓		
Carcinus aestuarii (f.e.)				↓	
Carcinus aestuarii (mo.)					↓
Liza aurata					
Sparus aurata					
Zosterisessor ophiocephalus	↓				
Total catches	↓				

Carcinus aestuarii (f.e.), female with eggs; *Carcinus aestuarii* (mo.), specimens during the moulting phase.

within a few years, between contrasting persistent states of a system. It seemed to be related with changes in the thermal regime of the lagoon and with a regime shift (increasing variation) of the sea water temperature (SST) recorded both in 1984 and 1988. The presence of a negative shift in this period is confirmed by almost every target species. This was in agreement with other work from different areas in the Mediterranean Sea, showing a regime shift detected both in environmental (*i.e.* SST) and biological variables (Oguz & Gilbert, 2007; Conversi *et al.*, 2010; Matić *et al.*, 2011). In the same period (late 1980s) abrupt changes have also been recorded in different Atlantic areas, such as the North Sea, Baltic Sea and Wadden Sea with a positive correlation both with water temperature and the NAO index, confirming a climate driver (Alheit *et al.*, 2005; Weijerman *et al.*, 2005). This further confirms the presence of strong relationships (*via* teleconnection) between the Atlantic and Mediterranean Sea climate (Lionello & Galati, 2008; Querenda *et al.*, 2011).

In relation to thermal affinity of species, target catches, both in field and landings data, were almost entirely composed of cold and temperate species, with the temperate group largely dominating. It is interesting to note that among the target species, brown shrimp *Crangon crangon* and European flounder *Platichthys flesus* (L. 1758) can be considered Atlantic relicts of the Mediterranean Sea basin (Borsa *et al.*, 1997; Campos *et al.*, 2012), being distributed only in the coldest part (with boreal features), such as the northern Adriatic Sea. The time series analysis reveals a decreasing trend for both these groups and a significant inverse correlation with water temperature during recent decades. The same pattern has been detected for most target species, with the exception of *S. aurata*. These patterns can be explained by the effects of climate change on fish phenology, specific to recurrent temperature-dependent events, such as reproduction and migration, which can ultimately affect recruitment. Evidence of these effects is growing in the available literature, especially in terms of earlier

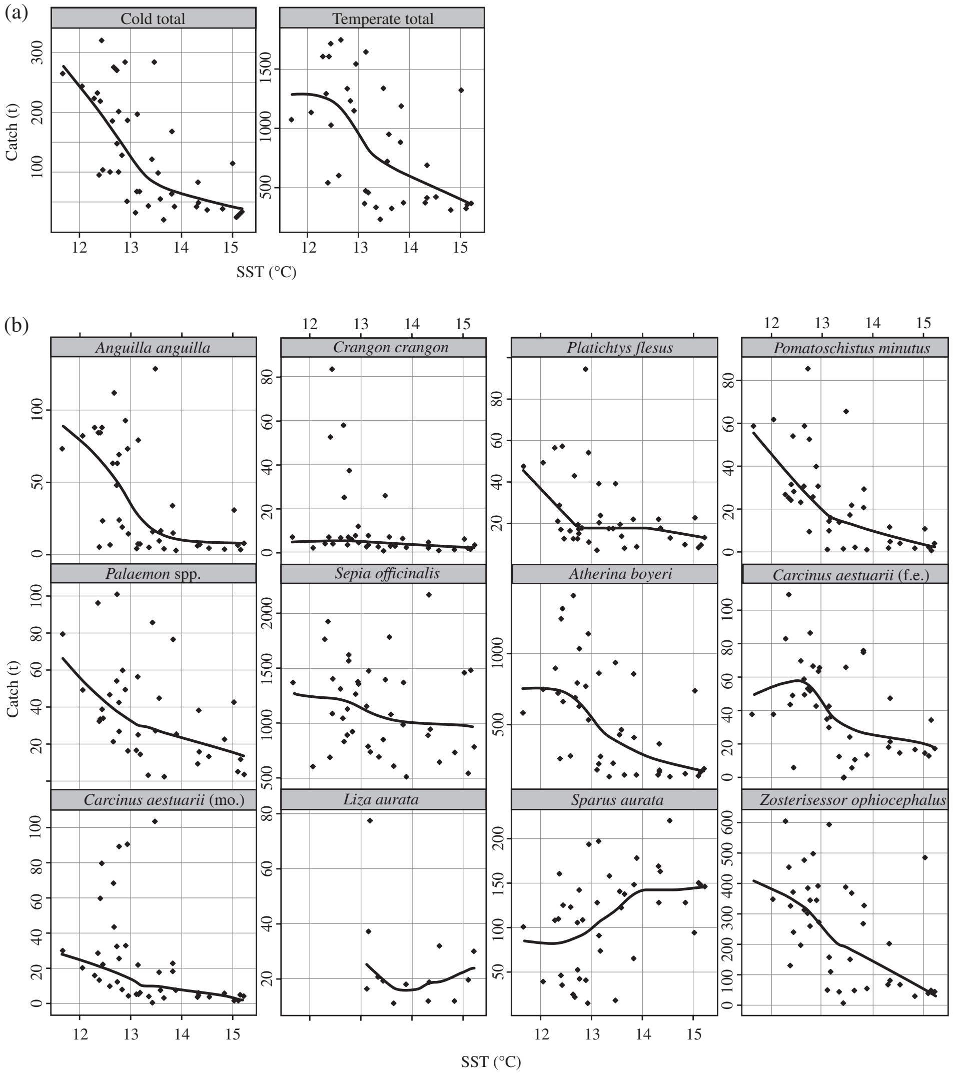

FIG. 7. Relationship between landings in terms of (a) thermal affinity groups in target species and (b) each target species and sea surface water temperature (SST) [*Carcinus aestuarii* (f.e.), female with eggs; *Carcinus aestuarii* (mo.), specimens during the moulting phase]. Curves fitted by locally weighted scatter-plot smoothing (LOESS).

breeding seasons, shift in migration dates, earlier larval appearance as a response to warming in commercially important freshwater and marine fishes (Gillet & Quetin, 2006; Pilling *et al.*, 2007; Taylor, 2008; Genner *et al.*, 2010). Similar results have been recently shown for a resident estuarine fish in the Venice Lagoon, the grass goby *Zosterisessor ophiocephalus* (Pallas 1814) (Zucchetta *et al.*, 2012). This work indicated that reproductive investment was positively correlated to temperature anomalies with breeding peaks occurring earlier in warmer years. This evidence suggests that temperature anomalies may determine a certain degree of mismatching between reproduction and food availability for larval and juvenile phases with possible negative impacts on recruitment. Accordingly, this may result in the negative trends observed by the present work.

The situation of *P. flesus* is heterogeneous. For areas located in the upper part of its range, a positive relationship with water temperature has been described (Genner *et al.*, 2004). Conversely, in proximity to the lower limits of distribution, negative effects of increasing temperature have been detected (Cabral *et al.*, 2001; Genner *et al.*, 2004; Vinagre *et al.*, 2009).

Sparus aurata is probably the warmest among the temperate species considered here and this could partially explain the recorded pattern. This species has experienced a large northward expansion in different places, in relation to water temperature increase (Cabral *et al.*, 2001; Coscia *et al.*, 2012).

No significant correlations have been detected between species or groups and the NAO index. This is in contrast with findings by Conversi *et al.* (2010). They reported a significant influence of this index on the biological regime shifts recorded in some Mediterranean Sea areas such as the Gulf of Lion and Adriatic Sea. This discrepancy could be explained by the fact that, at present, evidence of NAO effects on Mediterranean meteorological and ecological conditions are weak and lack convergence (Lionello & Galati, 2008; Vicente-Serrano & Trigo, 2011). Additionally, as the NAO effects are mainly mediated by river discharges (Struglia *et al.*, 2004), no real effects could be detected in the lagoon due to the river's diversion over past centuries in order to counteract the filling in of the basin.

Globally, results obtained seem to confirm the hypothesis that the northern Adriatic Sea area represents a kind of refugium for cold species, but also highlight the vulnerability of this nektonic assemblage to climate change. Since the Mediterranean surface waters are expected to warm by an average of 3.1° C by the end of the 21st century (Somot *et al.*, 2006), a general northward shift of fish ranges is expected, leading to the gradual replacement of cold and temperate species by thermophilic ones. In this process, semi-enclosed areas such as the Adriatic Sea and, inside it, the Venice Lagoon, might act as reservoirs, but may also become a cul-de-sac for species that simply cannot further migrate (Ben Rais Lasram *et al.*, 2010). From a fishery perspective, however, this change in the nektonic assemblage composition, with species substitution, may not be so deleterious, as fishermen usually can react very quickly to changes in resource exploitation. This was recently demonstrated in the Venice Lagoon with the Manila clam introduction and the following development of a fishing activity, producing >40 000 t per year in less than a decade (Pranovi *et al.*, 2004). This substitution, however, could be partially blocked by habitat fragmentation (Ben Rais Lasram *et al.*, 2010); lagoons, for example, are patchily distributed within the Mediterranean Sea basin and so migrations of estuarine species among them could be slow or almost impossible due to the presence of inhospitable areas.

In conclusion, in spite of the fact that northward shifts of thermophilic species are largely demonstrated in the Adriatic Sea (Dulčić & Grbec, 2000; Dulčić *et al.*, 2010, 2011), their presence in the lagoon has not been detected, which is possibly a sign of good resilience of the assemblage. A clear decreasing trend of both cold and temperate species, however, has been recorded, and a possible synergic effect of the increasing water temperature detected. All this highlights the vulnerability of artisanal fishery in the Venice Lagoon to climate change.

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