

**ANTHROPOGENIC IMPACTS ON THE BLUEFIN TUNA  
(*THUNNUS THYNNUS* L.) TRAP FISHERY OF SARDINIA  
(WESTERN MEDITERRANEAN)**

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SUMMARY

*Mediterranean traps harvest the ancestral migratory flow of bluefin tuna at a fixed site. Therefore it is reasonable to consider that environmental alterations generated by social and economic events at a local scale are disruptive to the pathways of tuna schools and thus account for catches variability. The southwestern area of Sardinia has been the location of important trap fisheries and historically was prized for lead and zinc mining resources from the 16<sup>th</sup> century. The cumulative impacts of environmental alteration resulting from mining are well documented on land and in the coastal zones but there is little information on fisheries. We applied an asymmetrical ANOVA to test for perturbations due to mining processes on catch variability in three nearby traps. We used Auto Correlation Functions and Spectral Analysis to verify cyclical fluctuation in landings and environment variables relating to the mining industry. We found that the Run-off variable had significant effects. It was a "pulsing reflective boundary" for tuna schools in the in-shore trap which resulted in a 7-year oscillation of captures. Excluding the negative trend that characterizes trap landings, our results emphasize the importance of small scale spatial analysis to detect secondary effects in the pattern of captures.*

RÉSUMÉ

*Les madragues de la Méditerranée capturent le flux migratoire ancestral de thon rouge à un site fixe. Il est donc raisonnable de considérer que les changements environnementaux générés par les évènements socio-économiques à une échelle locale pourraient avoir perturbé la route des bancs de thonidés et expliquer la variabilité des captures. La zone sud-ouest de la Sardaigne est la zone d'opération d'importantes pêcheries à la madrague et était historiquement très prisée, dès le 16<sup>ème</sup> siècle, pour ses ressources minières en plomb et zinc. Les impacts cumulés des changements environnementaux résultant de l'exploitation minière sont bien documentés en ce qui concerne les zones terrestres et côtières mais il n'existe que peu d'informations sur les pêcheries. Nous avons appliqué une ANOVA asymétrique afin de tester comment les processus miniers ont perturbé la variabilité des captures de trois madragues avoisinantes. Nous avons utilisé les fonctions d'auto-corrélation et d'analyse spectrale pour vérifier la fluctuation cyclique des débarquements et des variables environnementales concernant l'industrie minière. Nous avons observé que la variable d'écoulement avait des effets significatifs, créant un effet « reflet » de frontière pour les bancs de thonidés dans la madrague côtière, ce qui a donné lieu à une oscillation des captures pendant 7 ans. Hormis la tendance négative qui caractérise les débarquements des madragues, nos résultats mettent en évidence l'importance de l'analyse spatiale à petite échelle pour détecter les effets secondaires du schéma des captures.*

RESUMEN

*Las almadrabas mediterráneas capturan el ancestral flujo migratorio de atún rojo en un sitio fijo. Por tanto, es razonable considerar que las alteraciones medioambientales generadas por sucesos sociales y económicos a escala local son perjudiciales para las rutas de los bancos de túnidos y por tanto se reflejan en la variabilidad de las capturas. La zona sudoccidental de Cerdeña ha sido la ubicación de importantes pesquerías de almadrabas e históricamente ha contado con recursos mineros de plomo y zinc desde el siglo XVI. Los impactos acumulativos de las alteraciones medioambientales resultantes de la actividad minera están bien documentados en tierra y en las zonas costeras, pero existe poca información al respecto sobre las pesquerías. Se ha aplicado un ANOVA asimétrico para probar las perturbaciones debidas a los procesos mineros en la variabilidad de la captura de tres almadrabas cercanas. Se han*

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*utilizados Funciones de autocorrelación y Análisis espectral para verificar la fluctuación cíclica en los desembarques y las variables medioambientales relacionadas con la industria minera. Hemos descubierto que la variable de escorrentía tenía efectos importantes. Era un efecto reflejo de frontera de los bancos de túnidos en la almadraba costera que produjo 7 años de oscilación en las capturas. Excluyendo la tendencia negativa que caracteriza a los desembarques de las almadrabas, nuestros resultados resaltan la importancia de análisis espaciales a pequeña escala para detectar efectos secundarios en el patrón de capturas.*

## KEYWORDS

*Bluefin tuna, trap fishing, time series analysis, environmental effects, Mediterranean Sea*

### 1. Introduction

The Atlantic bluefin tuna, *Thunnus thynnus* L., has been documented as an important element of Mediterranean culture for more than 12,000 years. With the exception of the last 30 years, this great fish has always provided sustainable fisheries in the Mediterranean Sea. During the course of numerous historical periods, from the beginning of the fisheries to the present day, the magnificent bluefin tuna have been a source of food, have provided an economic base, and functioned as a central core of the culture for the people of the region. They have been a source of income that goes far beyond just the fishermen because it includes net makers, boat builders, the processing, shipping and selling of fish products for coastal communities of the Iberian Peninsula, the Atlantic coast of North Africa, the Mediterranean, Adriatic and Aegean Seas, the Dardanelles, the Sea of Marmora, Bosphorus and the Black Sea.

Archaeological records clearly show that bluefin tuna has been a fundamental component of the diet of the peoples of the Mediterranean from 9000 years BC up to the present (Powell, 1996). There is abundant documentation of the important role of tuna in the Mediterranean since the 8th century BC by the trading cultures of Phoenicia, Carthage, Greece, the Roman, Byzantine and Ottoman Empires (Will, 1986; Curtis, 1991), as well as in the literature of ancient Greece and Rome, the ancient coinage of the Mediterranean (Tekin, 1996) and in modern history (Rubino, 1994).

For extended periods, this highly migratory fish ranges over the Mediterranean Sea and in the Atlantic Ocean, from 60°N Lat. to 40°S Lat, feeding on squids and fish. Their extensive oceanic migration is followed by an aggregation of schools that enter the Strait of Gibraltar, and along with resident Mediterranean bluefin head towards their ancestral migration pathways in the Mediterranean Sea.

Adult bluefin have been captured for thousands of years in a trap system (**Figure 1**) that is often presumed to have been introduced to the western Mediterranean basin during the Arabic colonisation in the 7th Century AD (Smith, 1968) but there is little documentation to support this. In reality, when the Arabs first occupied Sicily they found tuna fisheries already in place. During the period of Arab-Norman domination of Sicily (800-1200 AD) and in medieval Sicily, fishing rights for tuna were often granted as royal prerogatives (Smith, 1968). There is significant evidence that the trap technology could very possibly have originated from Greece in the first millennium BC in the Black Sea, the Bosphorus and Aegean Sea (Devedjian, 1927; Tekin, 1996).

Traditional traps were usually located in close proximity to solar evaporation salt production sites and salt works (Curtis, 1991). Amphorae were produced in the region specifically to transport bluefin preserved with salt or olive oil. Commercial traffic in such fish products was extremely common throughout the Mediterranean, from Gibraltar to the Black Sea (Will, 1986; Curtis, 1991) throughout the 3rd century AD.

Traditional traps maintained their location for hundreds of years, harvesting bluefin along the pathways of migration with few technical changes to the equipment.

According to ICCAT data (Anon., 1997), only in the last 30 years have traditional traps shown a sharp decrease both in numbers of total gears deployed and total catches (**Figure 2**). Nowadays no more than nine active traps are still working in the Mediterranean and eight in the eastern Atlantic and Strait of Gibraltar (Morocco: Principé\*, Punta Negra°, Los Cenizosos°, Kénitra°, Cap Spartel°; Spain: Conil°, Barbate°, Zahara°, Tarifa° and Ceuta\*; Tunisia: Sidi Daoud\*; Libya, Zreg\*; Italy: Portoscuso\*, Isola Piana\*, Porto Paglia\*, Cala Vinagra\*, Favignana\*) (\*=Mediterranean traps; °Atlantic or Strait of Gibraltar traps).

Beyond the progressive reduction in bluefin stock, the spatial competition with other gears, the high values of the cost/benefit rate of the traps, the causes of deep crisis of Mediterranean trap fisheries can also be attributed to anthropogenic perturbation in the developed coastal zones. Over the last few centuries the Mediterranean sea has, in fact, witnessed a large increase in human presence. Moreover, due to factors such as a favourable climate, communications and economic resources, most of the human settlements are concentrated along the coasts. This has led to a chain-effect disturbance of coastal ecosystems which have consequently affected biological resources such as the bluefin tuna. Tuna habitually live in open waters but, of course, during spawning migration move closer to the coastline.

Considering the great importance that *Thunnus thynnus* have for Mediterranean populations both from a cultural and economic point of view, tuna fishing and tuna migration routes should be preserved from excessive human impact. In this paper our aim is to consider the influence of some local scale environmental variables on tuna catches over about two centuries.

The objectives of this paper are to analyse time series of trap captures and some local explorative variables resulting from the mining industry, in order to identify patterns of variability.

## 2. Material and methods

### 2.1 Trap fishery and gear description

The trap fisheries of Sardinia have an ancient origin; the first trap was introduced during Spanish domination in the late XIV century. Cetti (1777), in his classic 18<sup>th</sup> century book on the natural history of Sardinia, followed by Angotzi (1901), showed the location of at least 25 traps on the west coast of Sardinia and they discussed the fact that there are no migrant bluefin on the east coast and hence no traps on that coastline.

Four historical traps in the south western area are still working today: Portoscuso, Isola Piana, Porto Paglia and Cala Vinagra.

The traps considered are situated in southwest Sardinia (**Figure 3**). Due to gear positions and orientation we can hypothesise that the migration path of tuna schools in the area follows a semicircular clockwise direction. The gear used is defined as “tonnara di corsa” (arrival trap) because they capture tunas during the reproductive migration when specimens have ripening gonads. The gear is composed of 5 rooms (grande-bordonaro-bastardo-camera e camera della morte, from east to west) that together form the “castle”, which is connected to the coastline by the tail. The traps arrays are deployed at a depth of between 5 m (tail) to a maximum of 42 m (the castle) where the sea bottom consists of a wide, gently sloping continental shelf at the traps of Porto Paglia and Portoscuso and narrow, less gently sloping bed at Isola Piana. The substratum is characterized by coarse sand, thin shingle and rubble.

### 2.2 Mining industry

The south-western region of Sardinia is an ancient mining district. It is one of the few areas in Italy where historical mining activity took place over two thousand years (Manconi, 1986), with much exploratory activity until the last thirty years when all mining ceased (late 1960s) (Boni *et al.*, 1999). Lead, silver and copper were extracted in Roman times, followed later by zinc and barium. The presence of many mining scrubber and surge stations which were active after 1870 prevented the flooding of the mines but they dramatically changed the natural outflow and output of the rivers in the area. A number of scientific documents report evidence of the environmental consequences of mining activity, abandoned mines and recent industrial development, both on land and in the marine environment (Leita *et al.*, 1989; Caboi *et al.*, 1993; Boni *et al.*, 1999), but there is little information on the effect on pelagic fisheries.

### 2.3 Detection of mine perturbation: BACI design

There are many practical problems in the detection of human perturbation on trap landings. Firstly, the large temporal variance meaning that catch data is often very “noisy”. Secondly, bluefin can show a marked lack of concordance in their trajectories from trap to trap which results in considerable statistical interaction between changes in mean abundances from site to site and from time to time.

According to the conceptual model for understanding disturbance effects on population variability (Underwood, 1994), if there is a local perturbation that affects bluefin tuna pathways towards traps, it would appear as a statistical interaction between the differences in mean captures in presumable Impact and Control trap locations Before the disturbance and the resulting difference After the disturbance has taken place. An illustrated example of the concept of the Before/After/Control/Impact (BACI) approach is reported in **Figure 4ab**. Another important condition in applying the BACI approach is that both locations (Impact and Control) must be sampled at the same time.

These conditions are fully suitable in our case study. We assume the Porto Paglia trap as the Impact site, because of its proximity to the Mining Hot Spot. Here there were many inland and coastal scrubber stations which discharged residual waste from the mines through the natural outflow and output of the few local rivers.

Portoscuso and Isola Piana were chosen as Control sites. Moreover, to apply the experimental design, it was necessary to split data into the time range Before/After. Due to the fact that the activation of mechanized mining (during the industrial revolution) in late 1800s corresponded to a notable increase in mining production, we chose 1880 as the Before/After time split (Manconi, 1986) (**Figure 5**).

The data used refers to BFT captures (number of fish log transformed) from 1825 to 1973 ( $n = 149$ ) (Addis *et al.*, 1997).

Asymmetrical ANOVA was performed considering the following source of variation: Before vs. After; Impact vs. Controls. Where results were statistically significant, a post-hoc test (Schaffé test) was applied to verify all pair-wise combinations of data.

#### 2.4 Data analysis

A time series of mining-related factors were identified following detailed investigation of the archives. Three different variables were considered for our purpose: mining production (M) i.e. the tons of Zn and Pb in the period 1832-1979; Run-off index (RO), meaning an index of the hydrological processes that drain the tailing reservoirs into local streams that in turn flow into the shore face of the trap area (period 1918-1973); Shipping (Ship), i.e. the maritime traffic in terms of the number of boats for the area from first decades of 1900s.

In order to obtain an insight into the strength of the relationship over time for each time series (Zuur *et al.*, 2007), data auto-correlation functions (ACF) were calculated for the mining-related variables previously described and bluefin tuna catches for the three traps considered.

ACF gives an indication of the amount of association between variable  $Y_t$  and  $Y_{t-k}$ , where the time lag  $k$  takes the values 1, 2, 3, etc. The correlation coefficient is used to quantify the association, and always consists of values between -1 and 1 (Diggle, 1990). The ACF plots show a slow moving auto-correlation function indicating the presence of a trend, whereas an oscillating auto-correlation is evidence of a cyclical pattern in the time series (Zuur *et al.*, 2007). The interpretation of ACF plots is an important step that precedes the analysis of the cycle.

The cyclical patterns of data were studied using single spectral analysis (Platt and Denman, 1975) which is a method that cannot account for missing values and it requires that the series be stationarized through a sequence of transformation steps (Legendre and Legendre, 1998). Periodograms were smoothed with a Parzen window to identify spectral densities with the highest significance of contribution to the cyclical events (Parzen, 1961). Finally, a cross-spectrum analysis (bivariate Fourier analysis) was used to identify for synchronicity in singular fluctuations.

### 3. Results

The final data modelled with the Before/After and Control/Impact design are reported in the box plots in **Figure 7**. The series at Porto Paglia showed a sharp decrease in captures in the After phase.

The asymmetrical analysis of variance showed significant differences in the Before vs. After ( $p < 0.01$ ) and Control vs. Impact comparison ( $p < 0.01$ ). A post-Hoc test which considers all pairwise combinations provided the following results: Before Impact vs After Impact ( $p < 0.001$ ); Before Controls vs. After Controls ( $p = n.s.$ ); Before Impact vs. After Controls ( $p = n.s.$ ); Before Controls vs. After Impact ( $p < 0.001$ ); After Controls vs. After Impact ( $p < 0.001$ ).

### 3.1 ACF and Spectral analysis

In **Figure 7** reports the ACF plots for traps data and the environment variables. The trap series showed a marked trend pattern for Portoscuso (PS) and Isola Piana (IP). Porto Paglia (PP) has a trend pattern together with a secondary cyclical behaviour.

Explorative variables revealed a marked trend pattern for the Mining (M) and maritime traffic (Ship) and a cyclical pattern for the Run-off (RO).

Because of their cyclical behaviour, Run-off and Porto Paglia variables were selected for spectral analysis.

The patterns highlighted by the spectral analysis conducted on Porto Paglia and Run-off series (**Figure 8**) reveals a match between two oscillation periods, estimable approximately at about 7 years. We finally tested for the synchronicity of observed oscillation with cross spectral analysis. The periodogram representing the cross amplitude of Run-off and Porto Paglia series indicates the highest peak corresponds to periods of 7-year intervals, i.e. the pattern of synchronicity of data (**Figure 9**).

## 4. Conclusion

The analysis of trap captures has frequently been useful to better understand the fluctuation of abundance of bluefin (Ravier and Fromentin, 2001) and their relationships with long term climatological indices (Ravier and Fromentin, 2004). On a small spatial scale, information on the effects of environmental factors on trap captures is scant with exception of Sarà *et al.* (2007) and Lemos and Gomes (2004).

Our aim was to analyse data on an alternative approach considering small scale spatial changes in the time series. Results highlighted how traditional traps can be affected by local environmental disturbances. The first step of our investigation was to understand if there was a connection between the tuna fishing and mining operations that occurred over a long period of time in the south-western coast of Sardinia. An asymmetrical design and ANOVA test conducted between the BACI components (Before/After - Control/Impact) confirmed our suspicion that mining perturbation affected bluefin catches in the case of the nearest trap to the mining hot spot: the in-shore trap at Porto Paglia. After this confirmation, it was necessary to undertake further investigation in order to detect how mining perturbation affected the marine environment and consequently bluefin migration patterns.

For this reason we consider three different variables correlating to mining activities that we presumed influence tuna catches; a complete time series analysis was applied. The only variable that proved to have a direct effect on tuna catches was the Run-off index, which shows a synchronized periodicity of about 7 years with the Porto Paglia series. Such synchronization evidently resulted in a “boundary effect” that approximately every 7 years made marine environmental conditions not suitable for the in-shore migration pathways.

It is well known that tunas are particularly influenced by ocean boundaries (Murphy, 1959; Blackburn, 1965; Sund *et al.*, 1981; Laurs *et al.*, 1984; Fielder and Bernard, 1987), and these boundaries can also have negative effects on tuna migrations.

Disturbance is a key factor of ecosystems. It affects every level of biological organization and spans a broad range of spatial and temporal scales. With sources that can be either natural or anthropogenic, and either endogenous or exogenous, disturbances are inherently diverse (White 1979; White & Jentsch 2001). In our case study we considered a wide temporal scale and a narrow spatial scale. The variation in catches observed for the Porto Paglia trap and its connection with the mining run off, highlighted that a local scale disturbance could indeed affect a phenomenon such as bluefin tuna spawning migration. Considering the multiple human-related interests located along the coastal zone, there may be more uninvestigated factors of environmental perturbation that may be sources of data variability (**Figure 9**).

The process of pulsing boundary identified clearly refers to a past time series, but there is scientific evidence that discharge from mines is still active in abandoned mines (Caboi *et al.*, 1993). Due to the fact that Porto Paglia trap started operations in 2007 after a long period of closure, our future aims could be the verification of a pattern of captures as an indicator of the restoration of ancient migration pathways of bluefin schools.

The scientific evidence shows that modern development, specifically current fishing and marketing and management practices threaten the bluefin population of the western Atlantic Ocean (Safina and Klinger, 2008), north-eastern Atlantic (Cort and Nøttestad, 2007; McKenzie and Myers, 2007) and the Mediterranean Sea.

In 2007 the Standing Committee on Research and Statistics of ICCAT raised many concerns about the current situation of the Mediterranean trap fisheries, stating that “*if this unique source of information also disappears from the east Atlantic, it will be highly detrimental for scientific monitoring and the assessment of east Atlantic and Mediterranean bluefin tuna*”.

The trap fishery is in trouble and with its decline many important cultural elements of the local communities are also at risk and could be lost unless precautionary measures are implemented.

### Acknowledgments

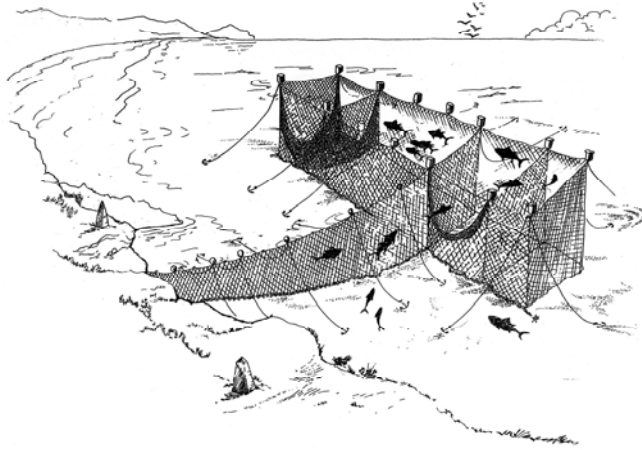
We would like to express our thanks to Mr Giuliano and Salvatore Greco of the Ligure Sarda Spa. (Carloforte, Italy), to all tonnarotti fisherman and professional divers of the Isola Piana trap. Many thanks go to Prof. John Mark Dean, University of South Carolina, for his continuous support and precious suggestion.

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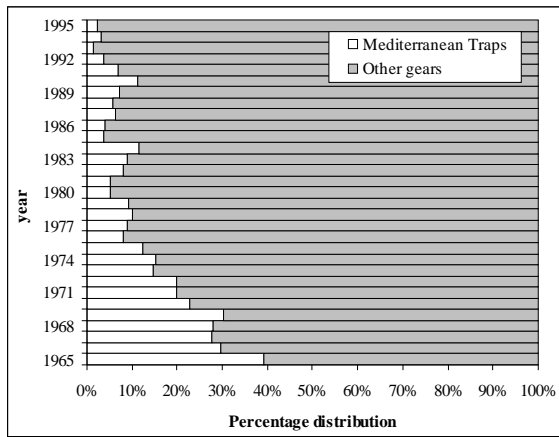
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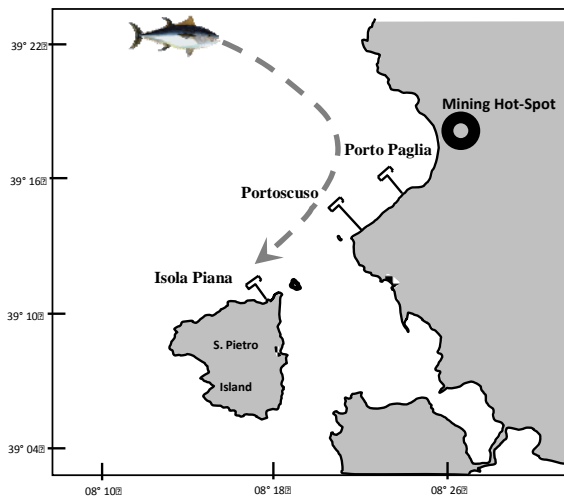
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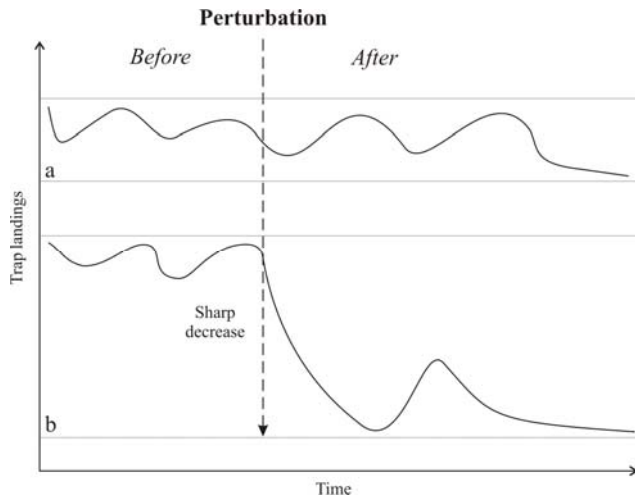
**Figure 1.** Illustration of a traditional Mediterranean trap with five chambers.



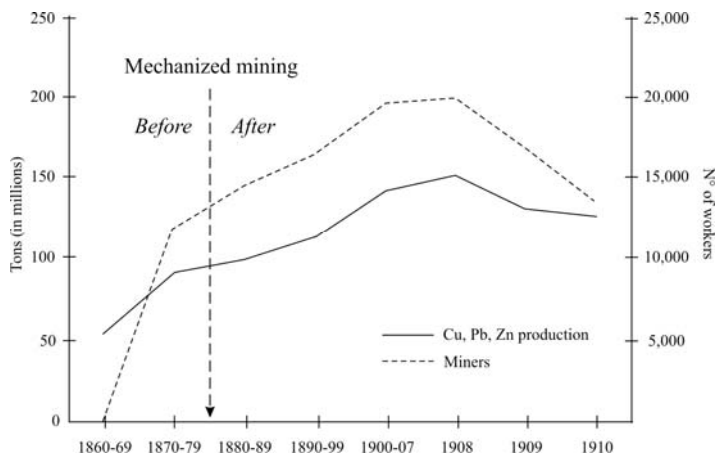
**Figure 2.** Percentage distribution of bluefin tuna captures by gears in the Mediterranean Sea.



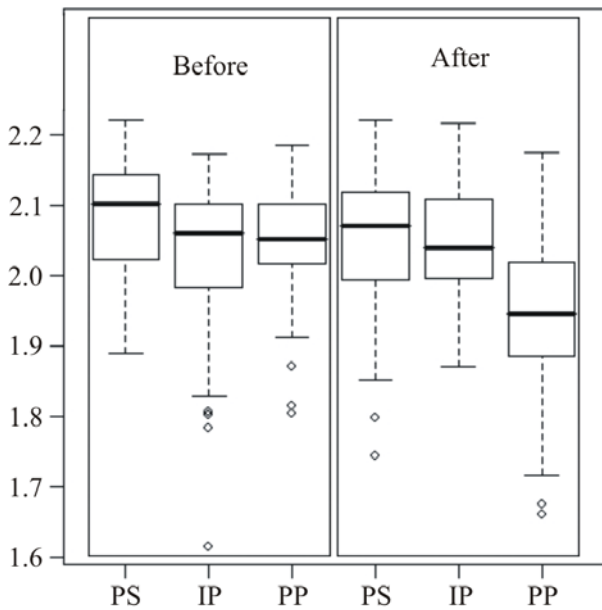
**Figure 3.** Location of the trap fisheries studied.



**Figure 4.** General scheme of the Control (c) and Impact (d) locations approach considering a time split of Before and After the perturbation.



**Figure 5.** Mining production and number of employees in the mining industry in southwestern Sardinia. The period 1870-1880 saw the introduction of mechanized mining, determining a rise in production.



**Figure 6.** Data modelled for the asymmetrical design.

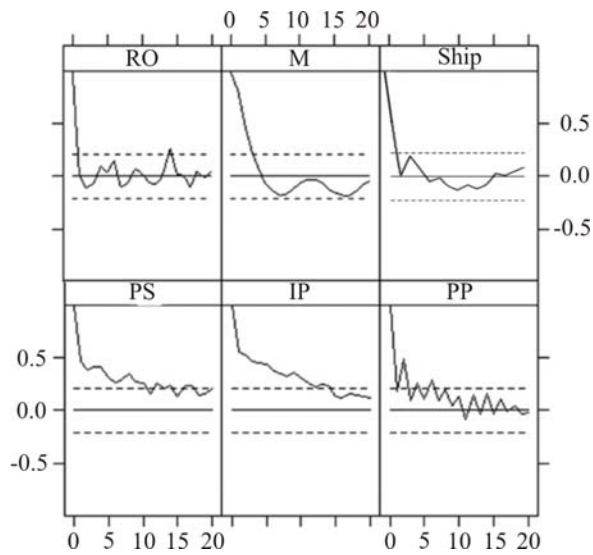


Figure 7. Results of Auto Correlation Function of data.

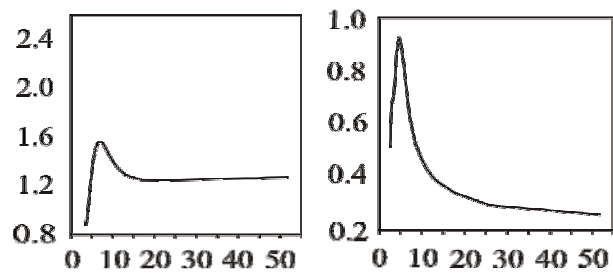


Figure 8. Spectral densities of the Porto Paglia data (left) and the run-off variable (right).

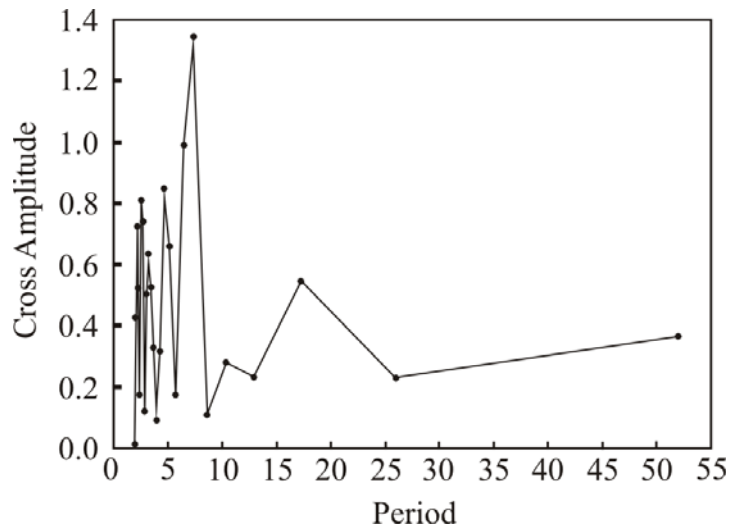
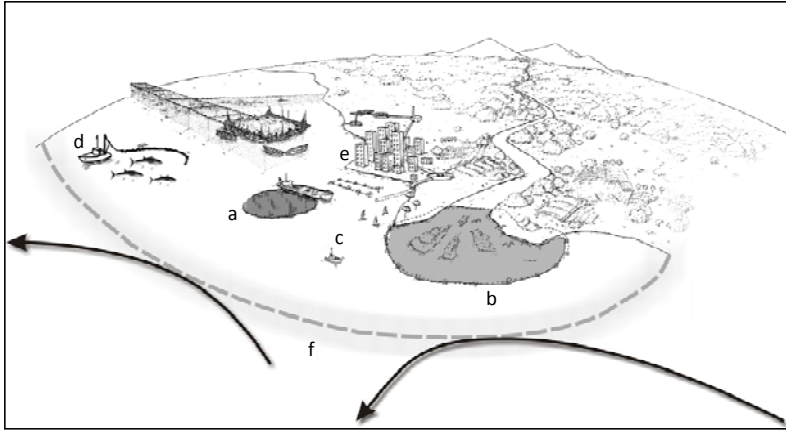


Figure 9. Plot of the cross spectral densities.



**Figure 10.** Illustration of different sources of local perturbation in a trap fishery (a. spilling; b. run-off; c. shipping traffic; d. gear competition; e. coastal urbanization) which can cause a boundary effect in the migration pathways of bluefin tuna (f).