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# Meteorological and climatic variability influences anthropogenic microparticle content in the stomach of the European anchovy Engraulis encrasicolus

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| **Abstract:** | Meteorological and climatic phenomena affect oceanographic characteristics and, consequently, anthropogenic microparticle aggregation. The same phenomena influence the ecology of pelagic fish, but whether there is a connection between meteorological and climatic characteristics and microparticle ingestion remains unknown. In the NW Mediterranean during the springs of 2011-2014, the incidence of contaminated European anchovies (35±17%) and microparticle abundance in the stomach content (0.46±0.25 microparticles ind$^{-1}$) may have owed to higher concentrations of microparticles due to hydrodynamism. Year 2011 showed a higher fragment contribution (60±17%). The statistical analysis indicated a link between fragment abundance and climatic characteristics, with low North Atlantic Oscillation index values for the previous cold season indicating the transport of water from the polluted Tyrrhenian Sea. Low-density microplastic (polyethylene and polypropylene) was found, a selection due to the pelagic behaviour of anchovy. Fibre abundance remained quite constant throughout the 4-year period, pointing to diffused input not dependent on meteorological forcing. In 2012, anchovies were subjected to bottom-up limitation, due to adverse meteorological forcing (high early spring temperatures, low rainfall). The anchovies mainly ingested fibres through less energy-expensive filter-feeding. Therefore, meteorological and climatic forcing regulates microparticle intake by fish and should be considered for pollution mitigation. |
| **Response to Reviewers:** | Editor:<br>Hydrobiologia attempts to strictly follow the rules of nomenclature, with the correct use of parentheses around species authorships. As such, the parentheses around the author and year of Engraulis japonicum on line 277 should not be present, according to FishBase, https://www.fishbase.se/summary/Engraulis-japonica.html and art 51.3 of ICZN, http://iczn.ansp.org/wiki/Article51<br>Please, check and amend all species names used in the text. |

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| | Only two species were cited, we corrected the authorship following FishBase |

# Meteorological and climatic variability influences anthropogenic microparticle content in the stomach of the European anchovy *Engraulis encrasicolus*.

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## Abstract

Meteorological and climatic phenomena affect oceanographic characteristics and, consequently, anthropogenic microparticle aggregation. The same phenomena influence the ecology of pelagic fish, but whether there is a connection between meteorological and climatic characteristics and microparticle ingestion remains unknown. In the NW Mediterranean during the springs of 2011-2014, the incidence of contaminated European anchovies (35±17%) and microparticle abundance in the stomach content (0.46±0.25 microparticles ind$^{-1}$) may have owed to higher concentrations of microparticles due to hydrodynamism. Year 2011 showed a higher fragment contribution (60±17%). The statistical analysis indicated a link between fragment abundance and climatic characteristics, with low North Atlantic Oscillation index values for the previous cold season indicating the transport of water from the polluted Tyrrhenian Sea. Low-density microplastic (polyethylene and polypropylene) was found, a selection due to the pelagic behaviour of anchovy. Fibre abundance remained quite constant throughout the 4-year period, pointing to diffused input not dependent on meteorological forcing. In 2012, anchovies were subjected to bottom-up limitation, due to adverse meteorological forcing (high early spring temperatures, low rainfall). The anchovies mainly ingested fibres through less energy-expensive filter-feeding. Therefore, meteorological and climatic forcing regulates microparticle intake by fish and should be considered for pollution mitigation.

**Key words:** European anchovy, anthropogenic microparticles, meteorological and climatic influence, Ligurian Sea, NW Mediterranean

## Introduction

In the Mediterranean Sea, the European anchovy *Engraulis encrasicolus* (Linnaeus, 1758) represents, together with sardine, an important percentage of the pelagic fish captured for human nutrition (Lleonart & Maynou, 2003). Therefore, any alteration in the anchovy stock (i.e. due to overfishing, climatic changes and pollution) can directly influence the health as well as the economic dimension of human society.

One of the emerging pollution threats to pelagic fish and to ecosystems in general is the increasing concentration of anthropogenic microparticles (dimension lower than 5 mm; Arthur et al., 2009) in the water column (Eriksen et al., 2014; Deudero & Alomar, 2015; van Sebille et al., 2015; Belzagui et al., 2020). These materials can have different morphologies, but microplastic fragments and fibres in particular have been the focus of previous research, the latter being synthetic or natural and coming from clothes and textiles (Laedwig et al., 2015; Remy et al., 2015). All these anthropogenic microparticles are potential pollutant carriers, given that they are composed of materials that are chemically modified and stained (Turner, 2019). In addition, they can absorb hydrophobic and metal compounds and play an important role in the environmental distribution of these substances (Sillanpää & Sainio, 2017; Rios-Fuster et al., 2019; Yu et al., 2019; Enfrin et al., 2020). Microparticles may be ingested by large and small metazoans, by active predation or via passive filtration (Boerger et al., 2010; Davison & Asch ,2011). Beyond potential mechanical damage (Cedervall et al., 2012; Pedá et al., 2016), microparticles can exert a chemical, toxic action through releasing of all the toxic substances in the organisms that ingest them (Lima et al., 2020). The threat is real, given that anthropogenic microparticle ingestion has already been observed in commercial pelagic fish such as anchovies (Neves et al., 2015; Nadal et al., 2016; Tanaka & Takada, 2016; Jovanović, 2017; Compa et al., 2018; Rios-Fuster et al., 2019). Nevertheless, the real effects are not yet totally understood (Remy et al., 2015; Ferreira et al., 2019).

The origin, distribution, accumulation and availability of microparticles have been related to the origin of surface water masses, to surface currents and to the influence of near-surface winds (Lebreton et al., 2017). Lima et al. (2021) have proposed a global model of microfibre accumulation based on the main oceanographic properties (current velocity and direction, surface sea temperature and salinity, wind speed). The relevant role of sea temperature and salinity has been observed, confirming the results of other local approaches (Lusher et al., 2015; Kanhai et al., 2018). Furthermore, convergence areas have been identified where accumulation is enhanced (van Sebille et al., 2015; Jiang et al., 2020).

The Mediterranean Sea has been indicated as an area of microparticle accumulation (Eriksen et al., 2014; Suaria et al., 2016; Lima et al., 2021) due to its morphology and high human density. In the NW Mediterranean (specifically the Ligurian Sea), hydrodynamic structures such as frontal areas and gyres may play a role in microparticle accumulation (Collignon et al., 2012; Fossi et al., 2012; Baini et al., 2018). In the Ligurian Sea, sea surface temperature and salinity, as well as the speed and direction of currents are regulated by large-scale phenomena. The North Atlantic Oscillation (NAO) is the dominant mode, responsible for atmospheric behaviour throughout the year (Marshall et al., 2002). The NAO, especially during the winter/cold season, determines the volume of waters that enter from the southernmost Tyrrhenian Sea (Astraldi et al., 1999; Vignudelli et al., 1999). Given the link between climatic and meteorological characteristics (as summarised in the NAO index) and the circulation and oceanographic properties of the Ligurian Sea, an influence of NAO on microparticle density and accumulation is likely. Therefore, it is probable that anchovies in the Ligurian Sea ingest microparticles depending on the climatic-meteorological conditions, although this relationship is yet to be defined.

This work aimed to gather information on the relationship between the climatic and meteorological characteristics and the microparticle content of anchovy, in terms of abundance, morphology (fibre or fragment) of microparticles found in anchovy stomachs and incidence of contaminated individuals. The study focused on the spring period because this is crucial for anchovy. In fact, from March to May the fish suddenly increase in dimension and gonad maturity and begin their reproductive period, requiring additional food (Politikos et al., 2011; Bonanno et al., 2016; Compa et al., 2018). Consequently, they are at greater threat of ingesting non-natural microparticles.

## Materials and Methods

### *Study area and sampling*

In the Ligurian Sea, the hydrodynamic characteristics are mainly controlled by two main currents (Fig. 1): the East Corsica Current (ECC, flowing northwards between Italy and the island of Corsica, carrying relatively warm waters), and the West Corsica Current (WCC, flowing northwards but off the western coast of Corsica, characterised by colder waters) (Astraldi et al., 1999). The velocity of these currents changes seasonally, being linked to the broader climatic characteristics (NAO) and, locally, to the different coasts' morphological characteristics and meteorological forcing.

Sampling was performed along the eastern Ligurian coast (Fig. 1). In the sampling area, the bottom depth ranged between 55 m and 120 m. A commercial fishing boat (27 m in length, gross tonnage 94 tonnes, power 397 kW) was equipped with purse seine fishing gear (net dimensions: 800 m in length and 120 m in height, capture was performed along the entire water column depending on bottom depth, 14 mm mesh size). The purse seine was placed in the sea during the night (from midnight to 4:30 a.m.), to collect all the fish attracted by an artificial light on the boat.

Samples were collected during the springs (March, April, and May) of 2011 to 2014, although in 2014, sampling was carried out only in March and April. Depending on the wind-wave conditions, during each month, samples were collected on a minimum of 1 to a maximum of 5 sampling dates. On each sampling date, 16 ± 4 individuals (median value 15 individuals; see Appendix-Table 1 for details) were randomly isolated, their characteristics were determined and their stomach content was analysed to find any microparticle they had ingested, as described below.

### *Laboratory analyses*

All fish were acquired directly from fishers within 5 h after their capture, stored in a clean cooler box and brought to the laboratory within the next 2 h.

All the analyses undertaken are described in a previous study (Capone et al., 2020). Briefly, the fish were measured to the nearest 0.5 cm (total length), and weighed (wet weight, ± 0.1 g with a Kern PCB electronic balance). Fulton's condition factor was calculated using the following formula: $K=100 * \text{weight} / \text{total length}^3$ (Froese, 2006). Gonads were removed to determine the gonadosomatic index (GSI), calculated as the wet weight contribution of gonads to the wet weight of the specimen minus its gonad weight.

Each fish's stomach content was transferred to a Petri dish, where its stomach walls were carefully washed with 70% ethanol, after cutting longitudinally with a micro-dissecting lancet. This material was used for the identification of microparticles, following previous protocols (Lusher et al., 2013; Nadal et al., 2016; Alomar

& Deudero, 2017). A dissecting microscope (Zeiss Stemi DV4) at 8× to 32 × magnification was used to differentiate microparticles from other natural materials. Before use, all tools used for sample processing and sorting were carefully cleaned with ethanol and checked under the dissecting microscope. The sample treatment and analysis were performed in a room specifically used for these analyses, to avoid contamination. A white 100% cotton lab coat was always worn during all analysis procedures and clean filter paper was placed next to the sample during stomach dissection and microscopic analysis, to evaluate any air-borne contamination. After analysing each stomach, the filter paper was observed with the same microscope and the fibres found were subtracted to the results of the stomach analysis. Generally, these fibres were blue, and were found only occasionally.

All microparticles not resembling natural materials (namely those that were mouldable, with consistent thickness, and that did not break when pressed with forceps; Bellas et al., 2016) were counted. Their morphological type (fragment or fibre) was recorded. Fragments were measured with a Leica Z16 APO stereomicroscope equipped with Leica Application Suite software.

All fragments were analysed with transmission Fourier Transform Infrared (FT-IR) spectroscopy (4000–700 $cm^{-1}$ PerkinElmer Spectrum 65) using commercial and custom-made spectral databases for microplastic identification. By contrast, fibres were too small to be analysed with this method.

*Climatic and meteorological variables*

In the NW Mediterranean Sea, the NAO is the dominant mode, responsible for atmospheric behaviour throughout the year (Marshall et al., 2002) and regulating long-term sea surface temperature and circulation (Vignudelli et al., 1999; Bolle, 2002). Astraldi et al. (1999) have shown an inverse correlation between the ECC’s water transport and winter NAO index values. In the winter/cold season, the NAO exerts a strong influence on the NW Mediterranean’s ecological dynamics (Fernández de Puelles et al., 2007): enhanced vertical mixing of the water column enables a proper nutrient supply to reach the euphotic zone (Fernández de Puelles & Molinero, 2007) and favours the production of the organisms that are trophic targets for pelagic fish. Following these observations, the monthly NAO index values were obtained from https://www.cpc.ncep.noaa.gov. The winter/cold season averages were obtained from https://crudata.uea.ac.uk/cru/data/nao/values.htm, e.g the October-March NAO index average and the

December-February NAO index average. The monthly NAO index values (www.cpc.ncep.noaa.gov) from October to December were averaged to obtain a further NAO index mean value, given that in the study area the spring season, during which phytoplanktonic production occurs, can start from early February (Misic et al., 2011).

Air temperature was recorded at the meteorological station of Genova Sestri Ponente, while rainfall data were obtained from the meteorological station of the Department of Chemical, Civil and Environmental Engineering (University of Genova). In this study, the latter data are presented as the sum of the rainfall of the 4 days before each sampling, to consider the time between a rain event and the arrival of the continental water at sea.

### *Statistical analyses*

The results for each sampling date (n=32) were used to perform the statistical analyses.

Pearson's correlation coefficient was used to test the significance of the relationships among variable trends (STATISTICA software).

A multivariate analysis was performed to highlight similarities between groups of samplings. The data for each variable were previously normalised (subtracting the mean value and dividing by the standard deviation calculated for the entire data set for each variable). A principal component analysis was performed using the PRIMER 6β programme package (Clarke & Warwick, 2001) on the normalised values of the NAO index (winter and monthly), air temperatures (minimum and maximum air temperature for each sampling date, Tmin and Tmax, respectively) and rainfall (cumulative value for the 4 days before each sampling), to characterise the environmental scenario for each sampling date. Analysis of similarities (ANOSIM) was carried out on the same variables using the PRIMER 6β programme package. ANOSIM is an approximate analogue of the standard univariate analysis of variance (ANOVA) test, which allows testing of the null hypothesis that there are no differences between groups of samples specified by the levels of a single factor. ANOSIM was applied on similarity matrices, created using the Euclidean distances on the normalised data of the climatic (winter NAO index and monthly NAO index) and meteorological (Tmin, Tmax and rainfall) variables.

Brodgar software (Brodgar 2.5.6 package, 2011, Highland Statistics Ltd.) was used to perform a redundancy analysis (RDA) (Zuur et al., 2007). The analysis was applied on the normalised data of all the samplings, to evaluate whether the microparticles (represented by the abundance of fibres and fragments per individual and by the incidence of contaminated individuals) and the fish characteristics (length, weight, Fulton's condition factor, and GSI) were influenced by the climatic features indicated by the winter NAO index averages, the monthly NAO index, the meteorological features represented by the cumulative rainfall in the 4 days before sampling and the atmospheric temperature on the day of sampling (min and max). To test the order of importance of the explanatory variables, an automated forward selection model was applied. In particular, the 'conditional effects' that show the increase in the total sum of the eigenvalues after including a new variable during the forward selection were calculated. Finally, a permutation test was applied (number of permutations: 499) to test the null hypothesis that the explained variation is larger than a random contribution.

## Results

### *Climatic and meteorological characteristics*

The climatic and meteorological data (winter/cold season and monthly NAO index, temperature and rainfall) were analysed using a multivariate PCA. The results (PC1 explaining 45.8%, PC2 24.9%) (Fig. 2) highlighted the different climatic and meteorological characteristics of the years.

Year 2011 was characterised by lower winter/cold season NAO index values and higher monthly NAO index values (Fig. 3). Year 2013 and, especially, years 2012 and 2014, showed an opposite distribution on the plot. Years 2012 and 2014 showed a lower scattering along PC2 (dominated by air temperature values). In 2014, the distribution along PC2 owed to the absence of May sampling. In 2012, the distribution along PC2 highlighted the peculiar characteristics of the year (Fig. 4). The Tmin of March 2012 (11.0±0.5°C) was higher than in the other years (2011: 8.7±1.0°C, 2013: 7.5±0.6 °C, 2014: 8.2°C). On the contrary, 2012 showed the lowest Tmin among the years in April (7.6 °C), the other years reaching values higher than 12°C. The same dynamic was seen in May 2012 (12.4±0.7°C), with the other years showing values higher than 14°C.

ANOSIM performed on years (sample statistic global R 0.587; significance level of sample statistic 0.1%) (Table 1) confirmed both that year 2011 differed from the other years and that there was a difference between 2012 and 2013.

Years 2011 and 2013 showed the highest peaks of rainfall (over 60 mm for the 4 days before the sampling) in March and April, while the other years showed lower maxima, with 2012 reaching a maximum of 20 mm in April and May and 2014 only 5 mm in April (Fig. 4).

### *Anchovy characteristics and microparticles*

The data pertaining to anchovy characteristics and microparticles as well as the relationships between them are presented and discussed in a previous study (Capone et al., 2020). Nevertheless, a summary may be useful in this study; moreover, all the data for the 32 samplings are reported in Appendix -Table 1.

Fig. 5 reports the general trends over time of the anchovies' main characteristics. The markers report the average for each month in the 4 years (bars denote standard deviation), while lines represent a descriptive (not statistical) trend for each year. In nearly every case, 2011 showed the highest values, namely longer (on average 12.5±0.9 cm) and heavier anchovies (on average 12.9±3.4 g) and higher Fulton's factor (0.65±0.03) and sexual development (GSI on average 1.2±1.3%). In general, the increase in the length and the weight of the fish was higher from March to April, and lower from April to May. However, year 2012 showed an initial hindrance to growth, which was partially recovered in May, although the values were lower than the other years. The GSI trends increased sharply for 2011 and 2014, while they were similar in March and April 2012 and 2013 and increased only in May. Fulton's factor showed a peculiar 2014 trend, with a decrease in April.

Microparticles were found in 24±10% (March 2011) to 53±28% (May 2012) of the analysed individuals, with an average value for all the observations of 35±17%. Fig. 6 reports the fibre and fragment abundance per individual. All the data±SD for the 32 samplings are reported in Appendix - Table 1. The contribution of the two microparticle types was largely dominated by fibres in 2012 and 2014 (on average 92±17% and 98±4%, respectively) and in 2013 (64±39%). By contrast, the year 2011 showed a dominance of fragments (60±17%).

Fibres were the most abundant (Fig. 6), with values of up to 1.17±0.41 fibres ind$^{-1}$ (18 May 2012). Year 2011 showed the lowest values, with maxima of 0.27±0.46 fibres ind$^{-1}$ (2 April). Fairly low values were also seen in year 2013 (maximum of 0.59±0.80 fibres ind$^{-1}$ on 1 March).

Fragments showed opposite trends (Fig. 6), with higher values in 2011 (up to 0.43±0.76 fragment ind$^{-1}$ on 9 May) compared to the other years (maxima on 25 April 2013 of 0.17±0.39 fragment ind$^{-1}$). Fragments were observed on all the 2011 sampling dates, in 67% of the 2013 sampling dates, in 33% of the 2012 sampling dates and only once (25%) in 2014. The FT-IR analyses for 2011 identified the composition of 41 fragments, while 3 were not recognised as plastic, but as organic materials such as cellulose. Polyethylene was the most represented plastic polymer (71% in March, 87% in April, and 73% in May), while the other recognised fragments were composed of polypropylene. The FT-IR analyses on the few fragments in the other years confirmed the dominance of polyethylene.

*Relationships of anchovy characteristics and microparticles with climatic and meteorological characteristics*

The results of the RDA performed using fish characteristics and ingested microparticle features as response variables and climatic and meteorological characteristics as explanatory variables are reported in Table 2 and Fig. 7. The RDA explained 52% of the variance (axis 1: 30%, axis 2: 15%). The response variables were mainly influenced by the variability of the December-February NAO index average and the minimum air temperature.

Table 3 reports the results of the analysis performed to ascertain whether the climatic and meteorological variables correlated with the fish characteristics and ingested microparticles. The correlations between the climatic and meteorological variables and the fish characteristics were positive for temperature, in accordance with the increases in dimensions and sexual maturation during the year. No correlations were found for rainfall. All significant correlations of the NAO index averages with the fish characteristics were, instead, negative, while the monthly NAO index showed no significant correlations.

The incidence of contaminated fish was not linked to meteorological or climatic variables.

Higher values of the NAO index averages were related to a larger number of fibres per individual and to a lower number of fragments per individual.

## Discussion

The mean frequency of individuals containing one or more items was variable, from a minimum of 13% to a maximum of 100% (averaging all the observation 35±17 %), with an average of 0.46±0.25 items ind$^{-1}$ (0.13-1.18 items ind$^{-1}$). These values are higher than the results obtained for *E. encrasicolus* along the Spanish Mediterranean coast by Compa et al. (2018), who found a frequency of 15% (7-27%) and from 0.07 to 0.33 microparticles per individual; and also higher than the data reported by Rios-Fuster et al. (2019) for the same area (frequency of 3% and 0.03±0.16 items ind$^{-1}$). However, our results are lower than the 77% found in the highly polluted Tokyo Bay for *Engraulis japonicum* Temminck & Schlegel 1846 (on average 2.3 items ind$^{-1}$) (Tanaka & Takada, 2016).

It has been reported that the presence and concentration of microparticles in seawater influences these items' abundance in the stomach content (Bellas et al., 2016; Nadal et al., 2016; Setälä et al., 2018). We have no data related to microparticle availability in seawater during the sampled years, but previous observations related to the surface layer have highlighted the presence of an accumulation site for microplastics in the eastern coastal Ligurian Sea, where our sampling was performed (Fossi et al., 2012). This area has also been confirmed as a ''hot spot'' for microplastics by Collignon et al. (2012), due to its peculiar hydrodynamic characteristics and wind regime. Therefore, the greater microparticle abundance in anchovies from the present study than in those of the Spanish coast (Compa et al., 2018) may have owed to accumulation and the higher availability of microparticles in the eastern part of the coastal NW Mediterranean.

We found major differences in terms of microparticle type among years (fragments dominating for 60±17% in 2011 vs fibres reaching the highest contribution of 84±27% in the other years). This indicates that anchovies may be subjected to different types of microparticle contamination, despite being captured in the same area.

Several authors have observed that fibres are more abundant in the marine environment than fragments (Claessens et al., 2011; Barrows et al., 2018; Zhu et al., 2018) and that fish can feed on these anthropogenic microparticles (Lusher et al., 2013; Ferreira et al., 2019). Neves et al. (2015) found that 65.8% of the ingested microplastics in commercial fish off Portuguese coasts were fibres and 34.2% were fragments. Fibre's contribution to the total items found in stomachs during the 2012-2014 period identified in the present study is similar to the 83% observed by Compa et al. (2018) for *E. encrasicolus*. The abundance of ingested fibres ind$^{-1}$ was in general similar among the years, despite the lower values of 2011. The quite constant fibre abundance per individual observed in the present study is in agreement with previous observations. In fact, it has been observed that fibres are largely distributed in the water column, especially offshore (Enders et al., 2015; Lima et al., 2021) and that the abundance of microparticles in the stomach content depends on their concentration in seawater (Bellas et al., 2016; Nadal et al., 2016; Setälä et al., 2018).

The microparticle content of the fish stomach did not correlate with local meteorological conditions such as rainfall. Especially for fibres, the continental inputs via river outfalls and urban wastewaters have been indicated as the main sources to the sea (Browne et al., 2011; Lima et al., 2014; Hartline et al., 2016; Lebreton et al., 2017). Rainfall exerts a positive influence on these sources, favouring fibre inputs by increasing soil drainage and river flow into the sea. Nevertheless, the coastal circulation often transports the fibres offshore (Lima et al., 2021), thus limiting the significance of a direct correlation between fibre concentrations and continental water inputs, as well as fibre ingestion by fish. In addition, the Ligurian region does not have large rivers and the cities are rather small compared to other areas, for instance, on the Tuscany coast or along the rivers that flow into the Tyrrhenian Sea (Arno in Tuscany and Tevere in Lazio). A limited local continental input of contaminated waters may explain the absence of correlation between the ingested fibre abundance and rainfall events, indicating continuous and diffused accumulation processes.

The fragment number per individual was higher in 2011 than in the other years, suggesting that the dominance of fragments in this year was probably an anomaly. ANOSIM indicated a separation between the environmental conditions of 2011 and of the other years. Furthermore, the fragment number negatively correlated to the NAO index averages, and the December-February NAO index average was the most significant among all the explanatory variables of the RDA.

The NAO index can be considered a good proxy for long-term series on environmental variables, because it records the overall physical variability, integrating local climatic changes (Drinkwater et al., 2003). Astraldi et al. (1999) have shown an inverse correlation between the ECC's water transport and the winter NAO index. With a negative NAO index, cold and dry air masses from the polar regions prevail, generating an increase in the flow of warmer water across the Corsica Channel from the Tyrrhenian Sea. The mean values of the winter/cold season NAO index of 2010-2011 were the lowest among the studied years, below -1. This threshold is considered a critical value as, whenever the NAO index drops below this limit, the water transport through the Corsica channel is significantly increased, while for higher values, it diminishes considerably (Vignudelli et al., 1999). Baini et al. (2018) found in the Northern Tyrrhenian Sea (Tuscany waters) a significant concentration of microplastics, especially fragments, at offshore sampling sites (> 10 km from the coast) in winter and spring season, with an accumulation in the gyre generated at the boundary between the northern Tyrrhenian Sea and the Ligurian Sea. A more intense flux of the ECC, correlated with the constantly negative NAO index values of winter 2010 and January 2011 (-0.88), may have favoured the increased transport of such microplastic fragments, composed mainly of polyethylene (>66%) and polypropylene (28%), the most used polymers (Gago et al., 2018). A similar composition was found in the stomach content of the anchovies of the present study (76% and 24% for polyethylene and polypropylene, respectively). The pelagic behaviour of anchovy (Rumolo et al., 2016) may play a role in the chemical composition of the microparticles found in their stomachs. In fact, pelagic fish ingest particles that float in the water column given their low density, such as polyethylene and polypropylene (characterised by densities of 0.89-0.98 g $cm^{-3}$ and 0.85-0.92 g $cm^{-3}$, respectively; Enders et al., 2015).

In the NW Mediterranean, environmental characteristics determine the establishment of phyto- and zoo-planktonic blooms (Lacroix et al., 2001; Fernández de Puelles et al., 2007), and the abundance of plankton in turn determines the success of anchovy development (Bonanno et al., 2014). Thus, cold and wet early spring conditions, which increase the nutrient availability to phytoplankton due to water column mixing (Fernández de Puelles & Molinero, 2007) and continental inputs (Pesce et al., 2018), favour anchovy growth and reproductive development in the early spring.

Therefore, the higher fragment abundance per individual of 2011 owed not only to the potentially higher availability of fragments carried by the northward current from the Tyrrhenian Sea, but also to the better conditions of the individuals (higher Fulton’s factor values representing the status of the fish: the higher the value, the better the fish’s condition). These body conditions sustained the active particle-feeding mode, given that this can ensure a high energy gain after capture, despite the considerable energetic effort of predation (James et al., 1989). However, the active predator behaviour of healthy organisms may expose them to a higher intake of fragments that resemble the morphological characteristics of some crustaceans, molluscs, or other zooplankton (Boerger et al., 2010; de Sá et al., 2015).

By contrast, March 2012 was quite warm and dry and the NAO index values were always positive from October to January. The anchovies were smaller and sexual maturation increased only in May, because of a bottom-up limitation induced by the climatic and meteorological conditions. Smaller and lighter anchovies may prefer the less energy-expensive filter-feeding mode, passively collecting fibres together with phytoplankton and small zooplankton.

## Conclusions

In the Ligurian Sea, the European anchovy is subjected to microparticle intake, given that one third of the analysed specimens were found to contain fibres and/or fragments. Fragments showed different values from the fairy stable fibre content in the individuals' stomachs, indicating that the same species in the same area may be affected differently by microparticles. In our study, climatic variables were found to exert an effect on the contamination of fish by microparticles, on the one hand by potentially increasing the northward transport of contaminated waters from the Tyrrhenian Sea, while on the other hand by favouring the good status of individuals, allowing them to perform the energy-expensive bite-predation feeding of fragments. Thus, the dominance of fibres or fragments in the individuals depended on oceanographic and meteorological characteristics, highlighting the close link between different global processes and ecosystem alterations (anthropogenic microparticle ingestion).

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## Conflicts of interest /Competing interests

The authors declare that they have no conflict of interest nor competing interests.

## Data availability

The data supporting the findings of this study are available within the article and its supplementary information file.

## Code availability

Not applicable

## Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Alessandro Capone and Mario Petrillo. The first draft of the manuscript was written by Cristina Misic and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

## References

Alomar, C. & S. Deudero, 2017. Evidence of microplastic ingestion in the shark *Galeus melastomus* Rafinesque, 1810 in the continental shelf off the western Mediterranean Sea. Environmental Pollution 223: 223-229.

Arthur, C., J. Baker & H. Bamford, 2009. Effects and fate of microplastic marine debris, in: Proceedings of the International Research Workshop on the Occurrence. Tacoma, WA: NOAA Technical Memorandum, NOS-OR&R-30 pp.

Astraldi, M., S. Balopoulos, J. Candela, J. Font, M. Gacic, G.P. Gasparini, B. Manca, A. Theocharis & J. Tintoré, 1999. The role of straits and channels in understanding the characteristics of Mediterranean circulation. Progress in Oceanography 44: 65–108.

Baini, M., M.C. Fossi, M. Galli, I. Caliani, T. Campani, M.G. Finoia & C. Panti, 2018. Abundance and characterization of microplastics in the coastal waters of Tuscany (Italy): The application of the MSFD monitoring protocol in the Mediterranean Sea. Marine Pollution Bulletin 133: 543-552.

Barrows, A.P.W., S.E. Cathey & C.W Petersen, 2018. Marine environment microfiber contamination: Global patterns and the diversity of microparticle origins. Environmental Pollution 237: 275–284. https://doi.org/10.1016/j.envpol.2018.02.062.

Bellas, J., J. Martínez-Armental, A. Martínez-Cámara, V. Besada & C. Martínez-Gómez, 2016. Ingestion of microplastics by demersal fish from the Spanish Atlantic and Mediterranean coasts. Marine Pollution Bulletin 109: 55–60.

Belzagui, F., C. Gutierrez-Bouzán, A. Alvarez-Sánchez & M. Vilaseca, 2020. Textile microfibers reaching aquatic environments: a new estimation approach. Environmental Pollution 265: 114889.

Boerger, C.M., G.L. Lattin, S.L. Moore & C.J. Moore, 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60: 2275–2278.

Bolle, H.-J. (Ed.), 2002. Mediterranean Climate: variability and trend. Springer-Verlag, Berlin, 450pp.

Bonanno, A., M. Giannoulaki, M. Barra, G. Basilone, A. Machias, S. Genovese, S. Goncharov, S. Popov, P. Rumolo, M. Di Bitetto, S. Aronica, B. Patti, I. Fontana, G. Giacalone, R. Ferreri, G. Buscaino, S. Somarakis, M.-M. Pyrounaki, S. Tsoukali, & S. Mazzola, 2014. Habitat selection response of small pelagic fish in different environments. Two Examples from the oligotrophic Mediterranean Sea. PLoS ONE 9(7): e101498. https://doi.org/10.1371/journal.pone.0101498

Bonanno, A., M. Barra, G. Basilone, S. Genovese, P. Rumolo, S. Goncharov, S. Popov, B.B. Nardelli, G. Procaccini, S. Aronica, B. Patti, G. Giacalone, R. Ferreri, I. Fontana, G. Tranchida, S. Mangano, M. Pulizzi, A. Gargano, A. di Maria & S. Mazzola, 2016. Environmental processes driving anchovy and sardine distribution in a highly variable environment: the role of the coastal structure and riverine input. Fisheries Oceanography 25: 471–490. http://dx.doi.org/10.1111/fog.12166.

Browne, M.A., P. Crump, S.J. Niven, E. Teuten, A. Tonkin, T. Galloway & R. Thompson, 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environmental Science & Technology 45: 9175–9179. http://dx.doi.org/10.1021/es201811s.

Capone, A., M. Petrillo & C. Misic, 2020. Ingestion and elimination of anthropogenic fibers and microplastic fragments by the European anchovy (*Engraulis encrasicolus*) of the NW Mediterranean Sea. Marine Biology 167: 166. https://doi.org/10.1007/s00227-020-03779-7

Cedervall T., L.A. Hansson, M. Lard, B. Frohm & S. Linse, 2012. Food chain transport of nanoparticles affects behaviour and fat metabolism in fish. PLoS One 7: e32254

Claessens, M., S.D. Meester, L.V. Landuyt, K.D. Clerck & C.R. Janssen, 2011. Occurrence and distribution of microplastics inmarine sediments along the Belgian coast. Marine Pollution Bulletin 62: 2199–2204.

Clarke, K.R. & R.M. Warwick, 2001. Changes in marine communities: an approach to statistical analysis and interpretation. 2nd edition, PRIMER-E, Plymouth

Collignon, A., J.-H. Hecq, F. Galgani, P. Voisin, F. Collard & A. Goffart, 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Marine Pollution Bulletin 64: 861–864. https://doi.org/10.1016/j.marpolbul.2012.01.011

Compa, M., A. Ventero, M. Iglesias & S. Deudero, 2018. Ingestion of microplastics and natural fibres in *Sardina pilchardus* (Walbaum, 1972) and *Engraulis encrasicolus* (Linnaeus, 1758) along the Spanish Meiterranean coast. Marine Pollution Bulletin 128: 89-96.

Davison, P. & R.G., Asch, 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Marine Ecology - Progress Series 432: 173–180.

de Sá, L.C., L.G. Lús, & L. Guilhermino, 2015. Effects of microplastics on juveniles of the common goby (*Pomatoschistus microps*): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. Environmental Pollution 196: 359–362.

Deudero. S. & C. Alomar, 2015. Mediterranean marine biodiversity under threat: Reviewing influence of marine litter on species. Marine Pollution Bulletin 98: 58–68.

Drinkwater, K.F., A. Belgrano, A., Borja, A. Conversi, M. Edwards, C.H. Greene, G. Ottersen, A.J. Pershing & H. Walker, 2003. The response of marine ecosystems to climate variability associated with the North Atlantic Oscillation, in: Hurrell, J.W., Y. Kushnir, G. Ottersen, & M. Visbeck (eds), The North Atlantic Oscillation. Climatic significance and environmental impact. Geophysical Monograph, American Geophysical Union, Washington DC: 134.

Enders, K., R. Lenz, C.A. Stedmon & T.G. Nielsen, 2015. Abundance, size and polymer composition of marine microplastics ≥10 μm in the Atlantic Ocean and their modelled vertical distribution. Marine Pollution Bulletin 100(1): 70-81. doi: 10.1016/j.marpolbul.2015.09.027.

Enfrin, M., J., Lee Y. Gibert, F. Basheer, L. Kong & L.F. Dumée, 2020. Release of hazardous nanoplastic contaminants due to microplastics fragmentation under shear stress forces. Journal of Hazardous Materials 384: 121393 https://doi.org/10.1016/j.jhazmat.2019.121393.

Eriksen, M., L.C.M. Lebreton, H.S. Carson, M. Thiel, C.J. Moore, J.C. Borerro, F. Galgani, P.G. Ryan & J. Reisser, 2014. Plastic Pollution in the World's Oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9. https://doi.org/10.1371/journal.pone.0111913

Fernández de Puelles, M. L. & J. C. Molinero, 2007. North Atlantic climate control on plankton variability in the Balearic Sea, western Mediterranean, Geophysical Research Letters 34: L04608, doi:10.1029/2006GL028354.

Fernández de Puelles M.L., F., Alemany & J., Jansá, 2007. Zooplankton time-series in the Balearic Sea (Western Mediterranean): variability during the decade 1994–2003. Progress in Oceanography 74: 329–354.

Ferreira, G.V.B., M. Barletta, A.R.A. Lima, S.A. Morley & M.F. Costa, 2019. Dynamics of marine debris ingestion by profitable fishes along the estuarine ecocline. Scientific Reports 9: 13514. https://doi.org/10.1038/s41598-019-49992-3.

Fossi, M. C., C., Panti, C. Guerranti, D. Coppola, M. Giannetti, L. Marsili & R. Minutoli, 2012. Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*). Marine Pollution Bulletin 64: 2374–2379. https://doi.org/10.1016/j.marpolbul.2012.08.013

Froese, B.R., 2006. Cube Law, Condition Factor and Weight – Length Relationships: History, Meta-analysis and Recommendations. 22: 241–253. http://dx.doi.org/ 10.1111/j.1439-0426.2006.00805.x.

Gago, J., O. Carretero, A.V. Filgueiras & L. Viñas, 2018. Synthetic microfibers in the marine environment: A review on their occurrence in seawater and sediments. Marine Pollution Bulletin 127: 365–376.

Hartline, N.L., N.J. Bruce, S.N. Karba, E.O. Ruff, S.U. Sonar & P.A. Holden, 2016. Microfiber masses recovered from conventional machine washing of new or aged garments. Environmental Science & Technology 50: 11532‑11538. http://dx.doi.org/10.1021/acs.est.6b03045.

James, A.G., T. Probyn, & J. Seiderer, 1989. The relationship between respiration rate, swimming speed and feeding behaviour in the cape anchovy *Engraulis capensis* Gilchris. Journal of Experimental Marine Biology and Ecology 131: 81-100.

Jiang, Y., F. Yang, Y. Zhao & J. Wang, 2020. Greenland Sea Gyre increases microplastic pollution in the surface waters of the Nordic Seas. Science of the Total Environment 712: 136484 https://doi.org/10.1016/j.scitotenv.2019.136484.

Jovanović, B., 2017. Potential consequences of fish ingestion of microplastic. Integrated Environmental Assessment and Management 13: 510-515. doi: 10.1002/ieam.1913.

Kanhai, L.D.K., K. Gårdfeldt, O. Lyashevska, M. Hassellov, R.C. Thompson & I. O'Connor, 2018. Microplastics in sub-surface waters of the Arctic Central Basin. Marine Pollution Bulletin 130: 8–18. https://doi.org/10.1016/j.marpolbul.2018.03.011.

Lacroix, G.J., N.P. Nezlin & S. Djenidi, 2001. Ecosystem response to the atmospheric forcing in the Southern Ligurian Sea in 1997–1999. Rapp. Comm. Int. Mer Medit. 36: 72.

Ladewig, S.M., S. Bao & A.T. Chow, 2015. Natural fibers: a missing link to chemical pollution dispersion in aquatic environments. Environmental Science & Technology 49: 12609−12610. http://dx.doi.org/10.1021/acs.est.5b04754.

Lebreton, L.C.M., J. van der Zwet, J.-W. Damsteeg, B. Slat, A.L. Andrady, & J. Reisser, 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611. https://doi.org/10.1038/ncomms15611.

Lima, A.R.A., M.F. Costa & M. Barletta, 2014. Distribution patterns of microplastics within the plankton of a tropical estuary. Environmental Research 132: 146–155. https://doi. org/10.1016/j.envres.2014.03.031.

Lima, A.R.A., M.D. Silva, F.E. Possatto, G.V.B. Ferreira & A.P. Krelling, 2020. Plastic contamination in Brazilian Freshwater and coastal environments: a source-to-Sea transboundary approach. Handbook of Environmental Chemistry, pp. 1–12. https://doi.org/10.1007/698_2020_514.

Lima, A.R.A., G.V.B. Ferreira, A.P.W. Barrows, K.S. Christiansen, G. Treinish & M.C. Toshack, 2021. Global patterns for the spatial distribution of floating microfibers: Arctic Ocean as a potential accumulation zone Journal of Hazardous Materials 403: 123796

Lleonart, J. & F. Maynou, 2003. Fish stock assessments in the Mediterranean: state of the art. Scientia Marina (suppl. 1): 37–49.

Lusher, A.L., M. McHugh & R.C. Thompson, 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Marine Pollution Bulletin 67: 94–99.

Lusher, A.L., V. Tirelli, I. O'Connor & R. Officer, 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Scientific Reports 5, 1–9. https://doi.org/10.1038/srep14947.

Marshall, J., Y. Kushnir, D. S. Battisti, P. Chang, J. Hurrell, M. McCartney, R. Saravanan & M. Visbeck, 2002. North Atlantic climate variability: phenomena, impacts and mechanisms. International Journal of Climatology 15: 1863–1898. https://doi.org/10.1002/joc.693

Misic, C., M. Castellano & A. Covazzi Harriague, 2011. Organic matter features, degradation and remineralisation at two coastal sites in the Ligurian Sea (NW Mediterranean) differently influenced by anthropogenic forcing. Marine Environmental Research 72: 6-74.

Nadal, M.A., C. Alomar & S. Deudero, 2016. High levels of microplastic ingestion by the semipelagic fish bogue *Boops boops* (L.) around the Balearic Islands. Environmental Pollution 214: 517–523.

Neves, D., P. Sobral, J.L. Ferreira & T. Pereira, 2015. Ingestion of microplastics by commercial fish off the Portuguese coast. Marine Pollution Bulletin 101: 119–126.

Pedá, C., L. Caccamo, M.C. Fossi, F. Gai Andaloro, L. Genovese, A. Perdichizzi, T. Romeo & G. Maricchiolo, 2016. Intestinal alterations in European sea bass *Dicentrarchus labrax* (Linnaeus 1758) exposed to microplastics: preliminary results. Environmental Pollution 212: 251–256.

Pesce, M., A. Critto, S. Torresan, E. Giubilato, M. Santini, A. Zirino, W. Ouyang &, A, Marcomini, 2018. Modelling climate change impacts on nutrients and primary production in coastal waters. Science of the Total Environment 628–629: 919–937. https://doi.org/ 10.1016/J.SCITOTENV.2018.02.131.

Politikos, D.V., G. Triantafyllou, G. Petihakis, K. Tsiaras, S. Somarakis, S.-I. Ito & B.A. Megrey, 2011. Application of a bioenergetics growth model for European anchovy (*Engraulis encrasicolus*) linked with a lower trophic level ecosystem model. Hydrobiologia 670: 141-163.

Remy, F., F. Collard, B. Gilbert, P. Compère, G. Eppe & G. Lepoint, 2015. When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodetritus. Environmental Science & Technology 49: 11158–11166. http://dx.doi.org/10.1021/acs.est.5b02005.

Rios-Fuster, B., C. Alomar, M. Compa, B. Guijarro & S. Deudero, 2019. Anthropogenic particles ingestion in fish species from two areas of the western Mediterranean Sea. Marine Pollution Bulletin 144: 325-333.

Rumolo, P., A. Bonanno, M. Barra, E. Fanelli, M. Calabrò, S. Genovese, R. Ferreri, S. Mazzola & G. Basilone, 2016. Spatial variations in feeding habits and trophic levels of two small pelagic fish species in the central Mediterranean Sea. Marine Environmental Research 115: 65-77.

Sillanpää, M. & P. Sainio, 2017. Release of polyester and cotton fibers from textiles in machine washings. Environmental Science and Pollution Research International 24: 19313-19321. https://doi.org/10.1007/s11356-017-9621-1.

Suaria, G., C.G. Avio, A. Mineo, G.L. Lattin, M.G. Magaldi, G. Belmonte, C.J. Moore, F. Regoli & S. Aliani, 2016 The Mediterranean Plastic Soup: synthetic polymers in Mediterranean surface waters. Scientific Reports 6(1):37551.

Tanaka, K. & H. Takada, 2016. Microplastic fragments and microbeads in digestive tracts of planktivorous fish from urban coastal waters. Scientific Reports 6: 34351.

Turner, A., 2019. Trace elements in laundry dryer lint: A proxy for household contamination and discharges to waste water. Science of the Total Environment 665: 568–573

Van Sebille, E., C. Wilcox, L. Lebreton, N. Maximenko, B. D. Hardesty, J. A. van Franeker, M. Eriksen, D. Siegel, F. Galgani & K.L. Law, 2015. A global inventory of small floating plastic debris. Environmental Research Letters 10: 124006. https://doi.org/: 10.1088/1748-9326/10/12/124006

Vignudelli, S., G.P. Gasparini, M. Astraldi & M.E. Schiano, 1999. A possible influence of the North Atlantic Oscillation on the circulation of the Western Mediterranean Sea. Geophysical Research Letters 26: 623-626.

Yu, F., C. Yang, Z. Zhu, X. Bai, & J. Ma, 2019. Adsorption behavior of organic pollutants and metals on micro/nanoplastics in the aquatic environment. Science of the Total Environment 694: 133643 https://doi.org/10.1016/j.scitotenv.2019.133643.

Zhu, L., H. Bai, B. Chen, X. Sun, K. Qu, & B. Xia, 2018. Microplastic pollution in North Yellow Sea, China: observations on occurrence, distribution and identification. Science of the Total Environment 636: 20–29. https://doi.org/10.1016/j.scitotenv.2018.04.182.

Zuur, A.F., E.N. Ieno & G.M. Smith, 2007. Analysing ecological data. Springer, New York.

## Captions to figures

**Fig.1**. NW Mediterranean: Ligurian Sea and northern Tyrrhenian Sea. Arrows denote the Eastern Corsica Current (ECC), the Western Corsica Current (WCC) and the Ligurian Current (Lig. C). The black star indicates the area where the samplings took place.

**Fig. 2**. PCA for the climatic variables (monthly NAO index and NAO index averages) and meteorological variables (minimum air temperature of the sampling day: Tmin, maximum air temperature of the sampling day: Tmax, cumulative rainfall for the 4 days before sampling: rainfall) in the NW Mediterranean for the springs of 2011-2014. The 32 observations (sampling days) are reported with different markers: 2011 full black circle, 2012 empty triangle, 2013 full black square, 2014 empty circle.

**Fig. 3**. Values of the NAO index. A: average values for the cold/winter period before each sampled spring (data from https://crudata.uea.ac.uk/cru/data/nao/values.htm). B: monthly NOA index values (data from: www.cpc.ncep.noaa.gov) for the sampled months.

**Fig. 4**. Meteorological variable trends in the period 2011-2014 in the NW Mediterranean. Minimum air temperature of the sampling day: Tmin, maximum air temperature of the sampling day: Tmax, cumulative rainfall for the 4 days before sampling: rain.

**Fig. 5**. Anchovy characteristics (A: length, B: weight, C: Fulton’s condition factor, and D: gonadosomatic index GSI) averaged for each month in the four years. Bars denote standard deviations, only positive standard deviations are reported to simplify the figures. Lines are descriptive trends of each variable for each year.

**Fig. 6**. Fibre and fragment abundances per individual in the 32 sampling dates. To simplify the figure, standard deviations are not reported for each sampling date, but they are available in Appendix - Table 1.

**Fig. 7**. Triplot for the RDA results. The explanatory variable vectors (monthly NAO index, winter/cold season NAO index averages, Tmin, Tmax, and rainfall) are reported with bold lines. The response variable vectors (incidence of contaminated fish, fibres per individual, fragments per individual, fish length and weight, Fulton’s condition factor, and gonadosomatic index GSI) are reported with thin lines. The 32 observations (sampling days) are reported with different markers: 2011 full black circle, 2012 empty triangle, 2013 full black square, 2014 empty circle.

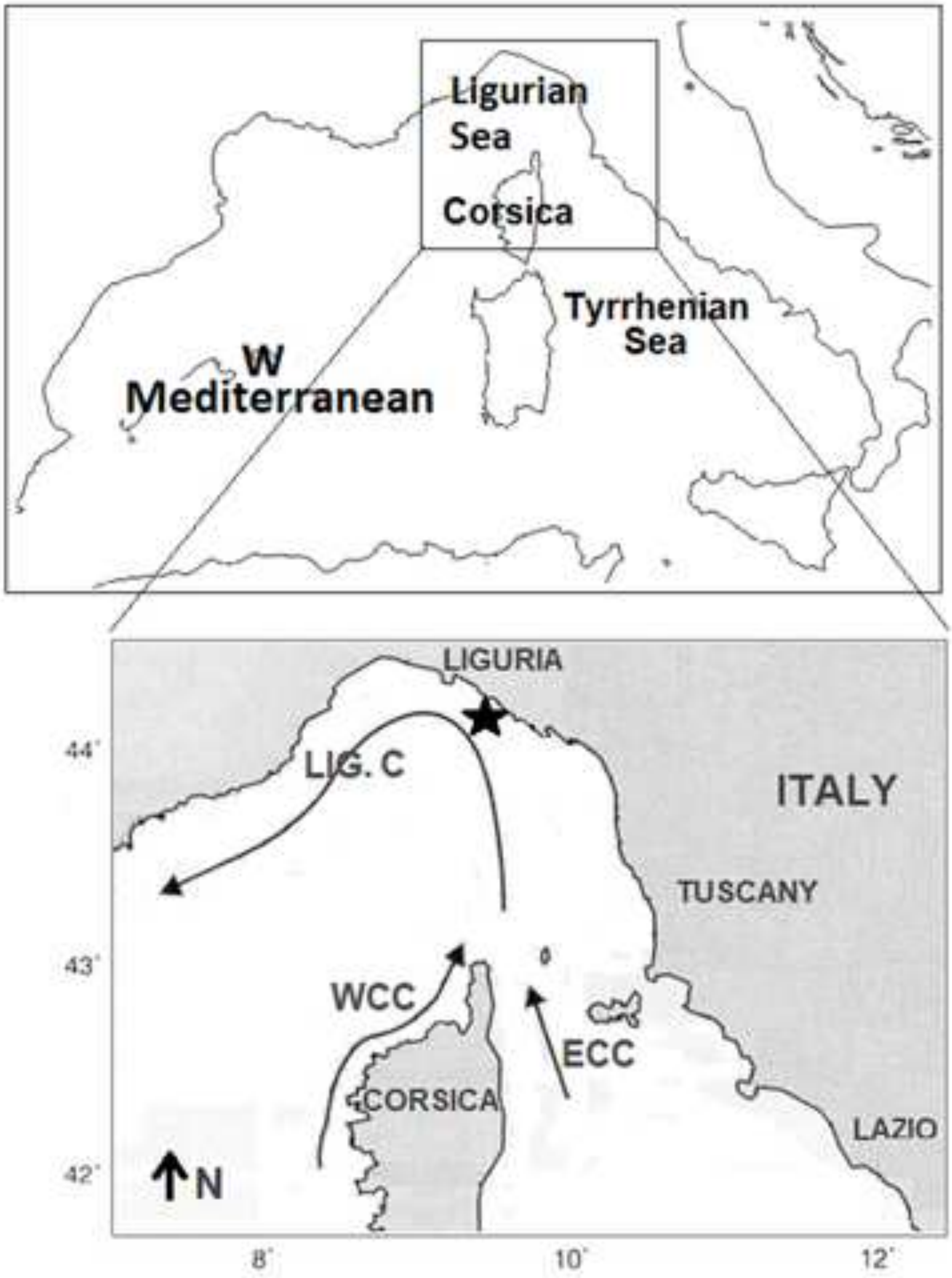
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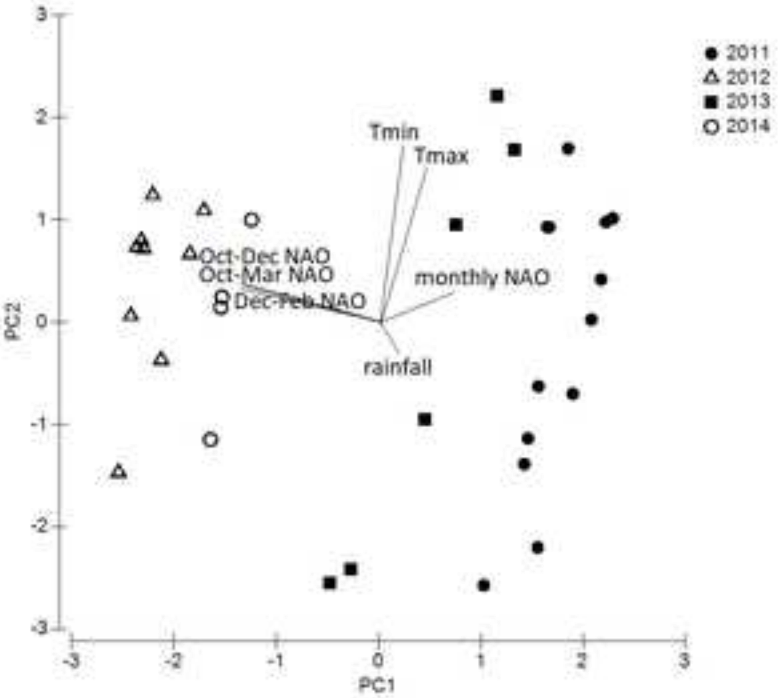
Figure 2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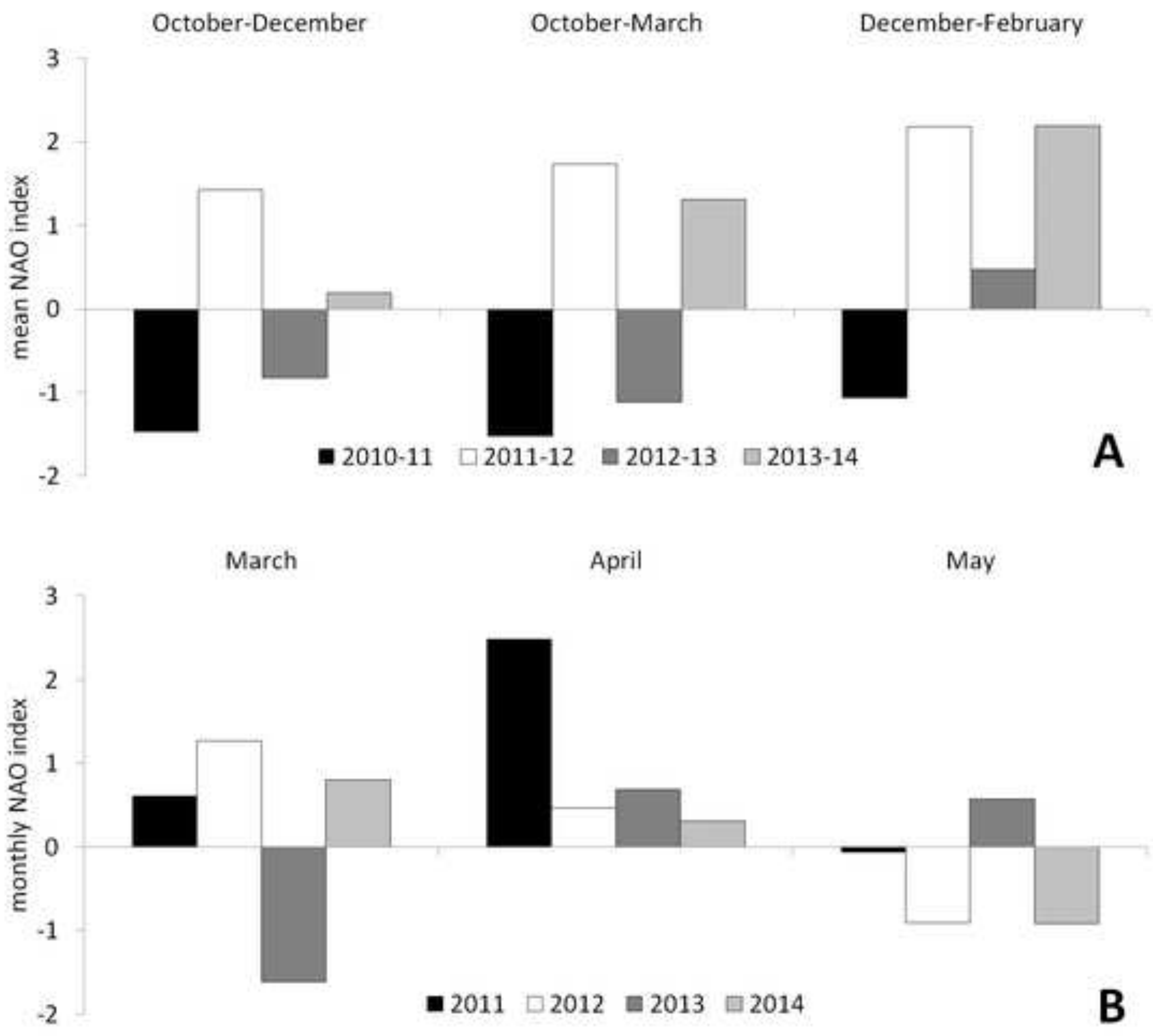
△ 2012
■ 2013
○ 2014

Figure 3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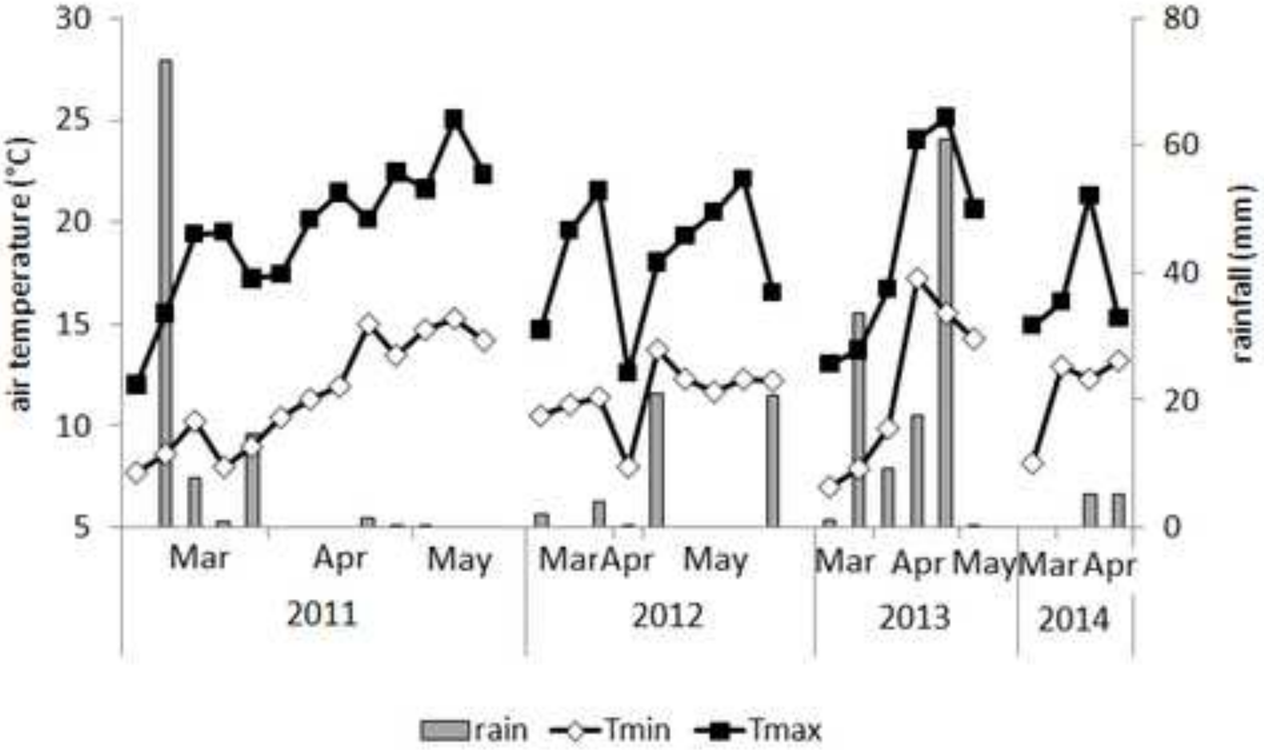
□ 2012
■ 2013
■ 2014
B



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rain
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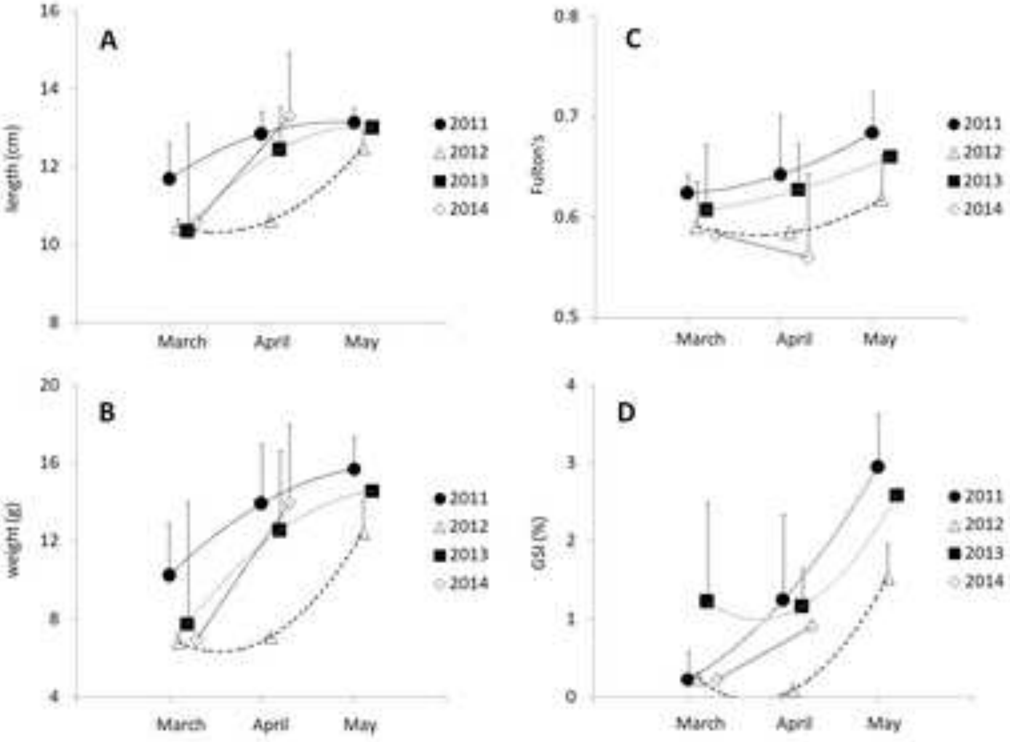
Figure 5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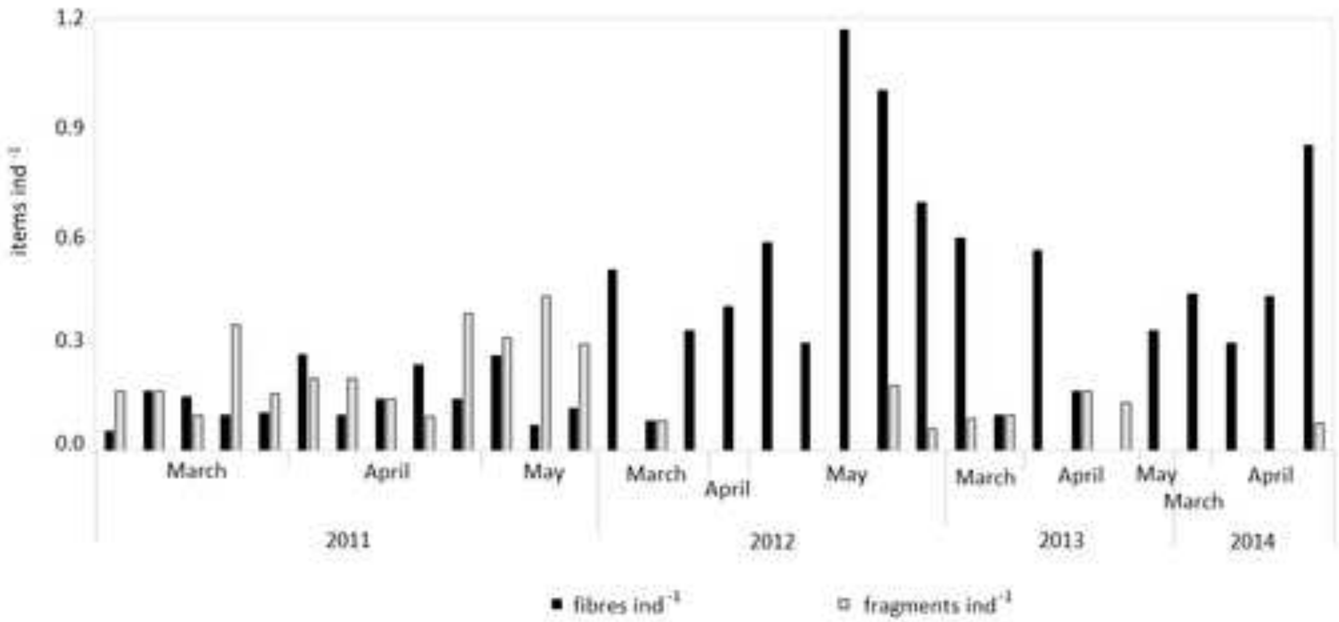
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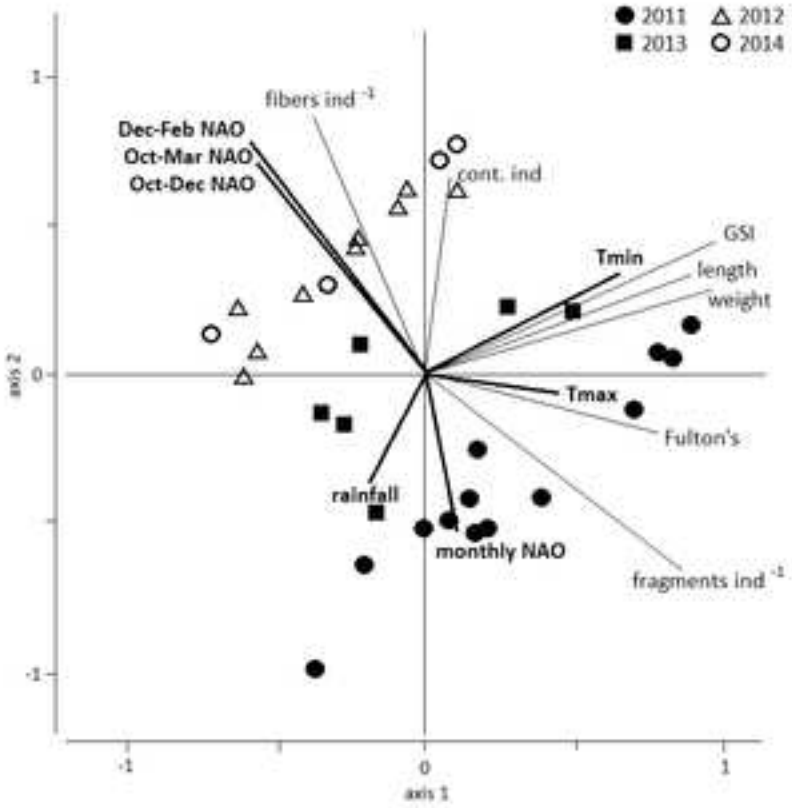
Figure 7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rainfall
monthly NAO
fragments ind -1
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1
axis 1

Table 1. ANOSIM pairwise tests among the years 2011-2014 for the environmental variables in the NW Mediterranean.

| years | R statistic | significance level (%) |
|---|---|---|
| 2011, 2012 | 0.870 | 0.1 |
| 2011, 2013 | 0.304 | 1.3 |
| 2011, 2014 | 0.692 | 0.3 |
| 2012, 2013 | 0.759 | 0.1 |
| 2012, 2014 | 0.057 | 28.7 |
| 2013, 2014 | 0.250 | 8.6 |

Table 2. Results of RDA applied on fish characteristics and ingested microparticle characteristics (response variables) using environmental characteristics as explanatory variables. Bold values indicate those explanatory variables whose variability significantly ($p<0.01$) influence the variability of the response variables.

| explanatory variables | increase total sum of eigenvalues after including new variable | F statistic and P-values of conditional effects | |
|---|---|---|---|
| | | F statistic | P-value |
| **December-February NAO index** | **0.20** | **7.336** | **0.002** |
| **Tmin** | **0.15** | **6.485** | **0.002** |
| rainfall | 0.05 | 2.757 | 0.052 |
| Tmax | 0.05 | 2.388 | 0.076 |
| monthly NAO index | 0.04 | 1.930 | 0.112 |
| October-March Nao index | 0.01 | 0.469 | 0.750 |
| October-December NAO index | 0.02 | 0.865 | 0.436 |

Table 3. Significant correlations of the environmental variables (NAO index, air temperature and rainfall) with the fish characteristics (length, weight, Fulton’s condition factor, and gonadosomatic index GSI) and the ingested microparticles (proportion of contaminated fish, number of fibres and fragments per individual). N= 32, bold p<0.01, dash: not significant.

| | length | weight | Fulton's | GSI | % cont. fish | fibre ind$^{-1}$ | fragment ind$^{-1}$ |
|---|---|---|---|---|---|---|---|
| monthly NAO index | - | - | - | - | - | - | - |
| October-December NAO index | - | - | -0.36 | - | - | **0.63** | **-0.64** |
| December-February NAO index | - | -0.35 | **-0.48** | -0.36 | - | **0.59** | **-0.75** |
| October-March NAO index | - | - | -0.44 | -0.35 | - | **0.59** | **-0.65** |
| rainfall | - | - | - | - | - | - | - |
| Tmin | **0.54** | **0.51** | - | **0.60** | - | - | - |
| Tmax | - | - | - | 0.38 | - | - | 0.43 |