Temporal and spatial change of exergy and ascendency in different benthic marine ecosystems

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Abstract

Holistic indicators such as exergy and ascendency have been widely employed to assess the health of ecosystems given by their structure, function and organization. In this study we calculate the exergy, specific exergy and ascendency for the microbenthic loop that represents a major sub-system within the marine food chain. The analysis of the microbenthic loop investigated in terms of organic matter, bacteria, microphytobenthos and meiofauna reflected changes occurring in the trophic state of benthic ecosystems and provided a tool for comparison between different environments. Temporal and spatial variability of the holistic indicators were evaluated using benthic measures collected at different times for different environments in the Mediterranean Sea. Exergy was strongly correlated with the organic contents of the sediments, and did not provide a useful description of the investigated system. In contrast, specific exergy resulted related to the microbenthic loop structure and complexity while Ascendency mostly reflected its activity and organization. Temporal analysis showed that in natural ecosystems specific exergy and ascendency showed convergence and follow similar seasonal trends. On the contrary in strongly eutrophicated systems an uncoupling between the two indicators occurred indicating a malfunctioning of the microbenthic loop that become strongly dissipative.

As a result specific exergy and ascendency calculated within the microbenthic loop appeared to be sensitive to changes in environmental conditions and trophic state and may be proposed as useful tools for the health assessment of marine benthic ecosystems.

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1. Introduction

Many researchers have suggested operational definitions and indicators of ecosystems health [1–4]. Unfortunately, there are several methods of measuring or quantifying the particular symptoms of distress potentially resulting in an inordinate number of ecosystem health indicators [4]. Qualitative alterations in the ecosystems (biomass, species composition, activity) could be detected by exergy [5–9] and ascendency [10,11] that measure the ecosystem structure, its function and organization. Exergy and specific exergy are two thermodynamic indicators derived from ecosystem theory. The exergy index (Ex) was first applied to ecological study in the late 1970s [12]. Exergy considers, besides the free energy of biomass as fuel, the information embodied in the biomass structure. The thermodynamic definition of exergy is the amount of work the system can perform by being brought into equilibrium with its environment [6]. As ecological indicator, exergy was used to assess the health and ecological condition of aquatic ecosystems [6,8,13].

Ascendency is a network oriented indicator and its ecological application was first proposed by Ulanowicz [11]. Ulanowicz [11] defines ascendency as an index that quantifies both the level of system activity and the degree of its organization whereby it processes material in autocatalytic fashion.

Several studies aimed at the comparison of different ecosystems using exergy and ascendency as ecological indicators of health [5,7,13–16]. However, in all these studies the ecosystem was mostly investigated in a broader sense (i.e. ecosystem as a whole) and to our knowledge no attempts have been made to focus attention on particular sub-systems whose structure and organization may be of particular interest for the definition of ecosystem health relative to a specific disturbance.

In this study, we focus on the trophic state of the benthic marine environment to provide a tool for the comparison and assessment of the benthic health of ecosystems. We investigate at a new approach to assessing the ecosystem health based on the use of the microbenthic loop for the calculation of exergy and ascendency.

The microbenthic loop is a major sub-system within the marine food chain and its role in affecting ecosystem function has raised increasing interest since it was first described in 1983 [17]. The microbenthic loop encompasses organic matter, bacteria, microphytobenthos, protozoa and meiofauna and the state of its structure and dynamics, have been recently proposed as sensitive indicators of the changes occurring in marine ecosystems [18,19]. In particular, organic matter and bacteria are considered as powerful tools for assessing the trophic state and quality of the benthic marine environment [20,21].

In order to investigate the trophodynamics of the benthic ecosystem we combine past observations and more recent data in an integrative manner, providing an interpretation of the biological responses within the microbenthic loop as a function of different ecological scenarios. To capture the state of the systems we make use of the mentioned holistic indicators. In particular we evaluate the spatial and temporal changes of exergy, specific exergy and ascendency within the microbenthic loop system in different benthic environments.

2. Methods

The calculation of exergy, specific exergy and ascendency within the microbenthic loop was made by using data on organic matter, bacteria, microphytobenthos and meiofauna for 52 stations located in eight different environments (see Section 3 for details on the stations and the benthic environments employed in the study). Identification of meiofauna taxonomic groups reaches a taxon level resolution according to the weighting factors for the calculation of exergy [22]. Major meiofauna taxa employed in the calculation were nematodes, polychaetes, copepods and turbellarians. Nematodes were further identified in four nutritional groups following microscope examination of the feeding apparatus (selective deposit feeders, unselective deposit feeders, epigrowth feeders and omnivorous feeders).

Benthic measures and groups used for the calculation of exergy and ascendency within the microbenthic loop system are reported in Table 1. Units of measure for each group were standardized to ton km^{-2} = g m^{-2}.

2.1. Exergy

The exergy index was calculated as the concentration of different groups c_i multiplied by weighting factors β_i, based on exergy detritus equivalents according to Marques and Jørgensen [22] (Table 1). Exergy links the chemical energy of the various groups of the ecosystem to the information embodied in DNA as explained by the following equation:

$$Ex = \sum_i \beta_i * X_i, \tag{1}$$

where β_i are the weighting factors and X_i are the concentrations of each group in the system.

Unit exergy detritus equivalents are expressed in g m^{-2} and can be converted to kJ m^{-2} by a factor of 18.7 corresponding to the approximate average energy content of 1 g of detritus [7].

A variation in exergy values could be due to variations of biomass or to variations of the structural complexity of the biomass. This latter assess for the information embedded in the

Table 1
Values of the "qualities" of the biomass expressed by the weighing factors [22]. The weighing factors values are based on the number of information genes. The exergy content of organic matter in the various organisms is compared with the exergy contained in detritus

Organisms	Weighing factors β
Detritus	1
Bacteria	3
Algae	3.9
Annelid	50
Crustacean zooplancton	30–46
Crustacean (decapods)	230
Fish	287–344
Amphibians	800
Reptiles	1000
Birds	1100

DNA and could be called the specific exergy or exergy per unit of biomass. Specific exergy is given by:

$$Ex_{sp} = Ex/\text{Total biomass} \tag{2}$$

2.2. Ascendency

Ulanowicz and Abarca-Arenas [23] assert that ascendency incorporates aspects of both a system's size and constitutive nature. T, the total system throughput, gauges the level of overall system activity; the index I measures the organization by which exchanges among components are transacted. The ascendency (AS) is calculated as the product of T and I. An increase of AS is linked to the growth and development of the system [11].

Computation of ascendency used the following equations:

$$T = \text{TST} = \sum_i T_i \tag{3}$$

$$I = k \sum_{i=1}^{n} \sum_{j=1}^{n} (T_{ij}/T) \log(T_{ij} B^2 / B_i B_j T) \tag{4}$$

where k is constant, T_{ij} is the flux out of i-group and going in j-group, T is the sum of all the fluxes in the system and B_i is the biomass of i-group.

$$\text{AS} = T * I = \sum_{i=1}^{n} \sum_{j=1}^{n} T_{ij} \ \log(T_{ij} B^2 / B_i B_j T) \tag{5}$$

Ascendency was calculated using the software Ecopath with Ecosim [24].

2.3. Basic modelling approach

The models for each study area were created using Ecopath 5.0 software which for each group (array of species with similar ecological attitude) uses a set of linear equations in order to balance the flows (in and out) of each compartment [24].

For a basic parameterization the model's routine uses a system of linear equations, which can be expressed for an arbitrary time period by:

$$B_i * \left(\frac{P}{B}\right)_i * \text{EE}_i = C_i + \sum_{j=1}^{n} \left[B_j * \left(\frac{Q}{B}\right)_j * \text{DC}_{ij} \right] \tag{6}$$

Consequently the software needs five parameters for each group: biomass (B), production/biomass ratio (P/B), consumption/biomass ratio (Q/B), ecotrophic efficiency (EE) and diet composition input (DC_{ij}). If one of these parameters is not available it could be calculated by four additional parameters: unassimilated/consumption (GS), net migration rate (E), biomass accumulation (BA) and catch mortality (Y).

In this study ecotrophic efficiency was always estimated considering E, BA and Y null for each simulation.
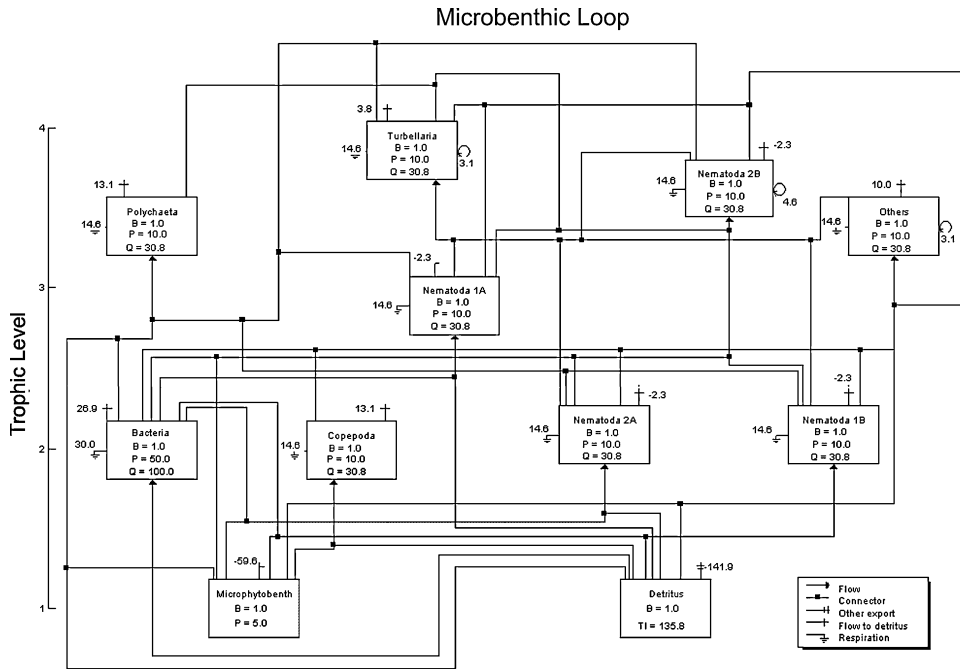
Microbenthic Loop

Fig. 1. Standard flow diagram for the microbenthic loop sub-system based on the starting diet matrix with all the biomass forced to 1.

The model compartments consist of 11 different groups: one primary producer, nine consumers and one non-living group (detritus compartment).

The software routine gives an error message if the model output is not realistic. In particular it checks if the ecological efficiency is <1.0 for all compartments. If inconsistencies were detected, the diet matrix was slightly adjusted until the simulation procedure can perform. Fig. 1 shows a standard flow diagram that has been employed for the microbenthic loop sub-system based on the starting diet matrix with all the biomass forced to 1.

3. Marine benthic ecosystems

Eight marine ecosystems were selected for the study of spatial and temporal changes of exergy and ascendency. In each system a minimum of 2 to a maximum of 13 stations were selected. For each station the same benthic measures were employed for the calculation of the ecological indicators (Table 2).

3.1. Prelo Bay (Ligurian Sea)

Prelo station is located in the Gulf of Tigullio in the Ligurian Sea (Fig. 2A). The bay is sheltered and is characterised by an extended seagrass bed of *Posidonia oceanica* located at 0.4–9 m

Table 2
Benthic parameters and groups expressed as ton km^{-2} utilised for the calculation of exergy and ascendency within the microbenthic loop system

Benthic parameters	Groups	References
Chlorophyll-*a*	Microphytobenthos	Plante-Cuny [25]
Bacteria biomass	Bacteria	Meyer-Reil [26]
	Nematodes (selectives deposit-feeders)	Wieser [27]; Warwick and Price [28]; Romeyn and Bowman [29]
	Nematodes (non selective deposit-feeders)	Wieser [27]; Warwick and Price [28]; Romeyn and Bowman [29]
	Nematodes (epigrowth-feeders)	Wieser [27]; Warwick and Price [28]; Romeyn and Bowman [29]
Meiofauna	Nematodes (predators-feeders)	Wieser [27]; Warwick and Price [28]; Romeyn and Bowman [29]
	Copepods	Wieser [30]; Warwick and Price [28]
	Polychaeta	Wieser [30]; Warwick and Price [28]
	Turbellaria	Wieser [30]; Warwick and Price [28]
	Others	Wieser [30]; Warwick and Price [28]
Total organic matter	Detritus	Parker [31]

of depth [32]. Sampling was carried out at monthly interval from January 1991 to January 1992 in the middle of the bay. Sampling depth ranged from 8 to 10 m.

3.2. Zoagli Coast (Ligurian Sea)

Zoagli station is located east of Prelo Bay in the Tigullio Gulf (Fig. 2B). The area has an average depth of 10 m and is characterised by soft bottom sediments with the presence of interstitial infauna.

As for Prelo, sampling was carried out on a monthly basis from January 1991 to January 1992. The sampling station was located 50 m offshore and was close to the Entella river estuary. The area is exposed to southerly winds and to the main Ligurian current re-suspending the sediments within the 10 m bathymetric contour [32].

3.3. Paraggi Bay (Ligurian Sea)

Paraggi station is located near the headland of Portofino (protected area) and is in a natural inlet surrounded by dense Mediterranean vegetation (Fig. 2C). Sampling was carried out in January and July 2001 at a depth of 1.5 m [33]. Organic matter content of the sediment is comparable to oligotrophic areas of the Mediterranean Sea [32].

3.4. La Spezia Bay (Grazie Basin—Ligurian Sea)

La Spezia station is located beneath a fish farm in a semi-enclosed bay in the Gulf of La Spezia (Ligurian Sea, NW Mediterranean Sea) (Fig. 2D). The farm has been used for approx-
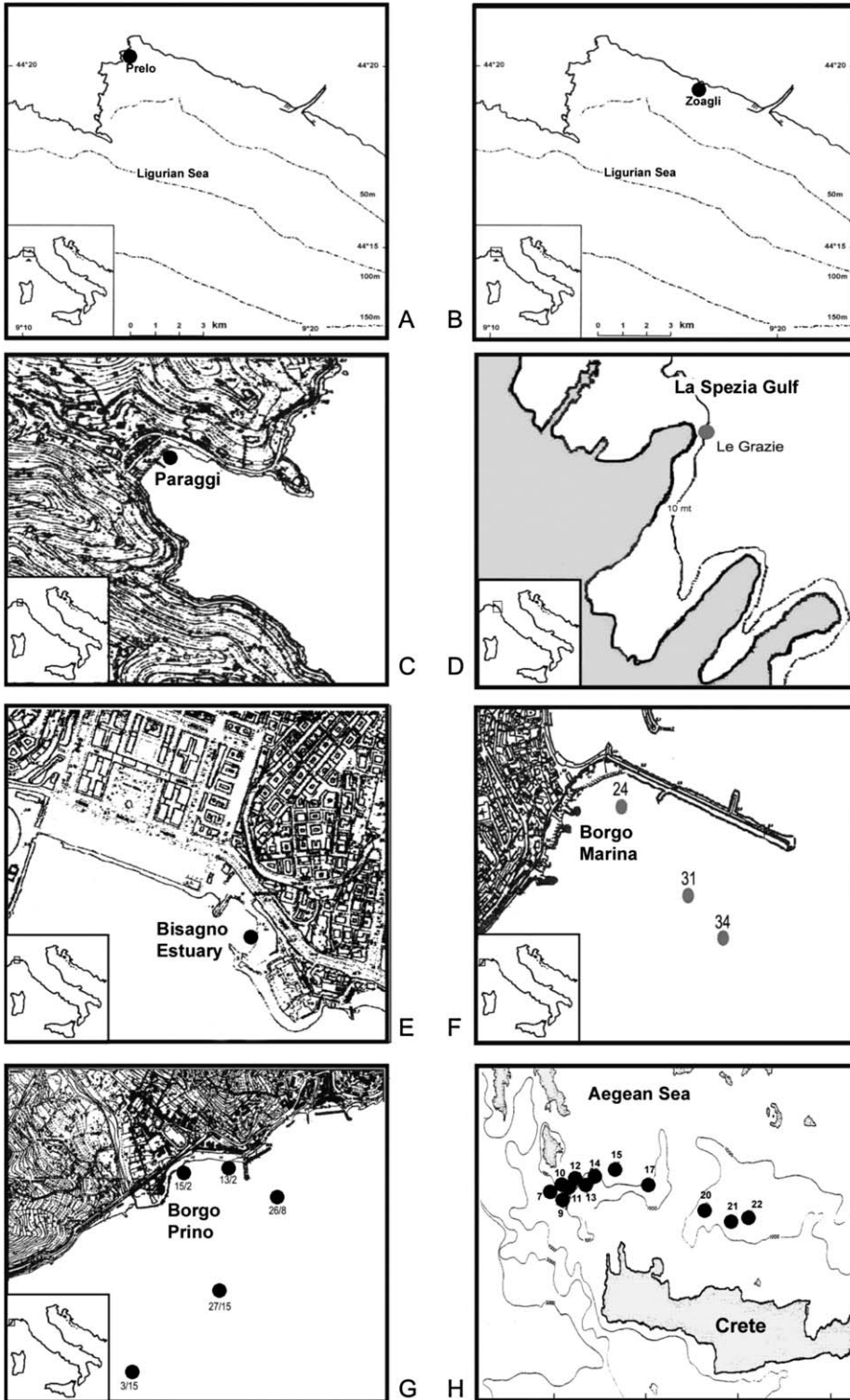
Fig. 2. Sampling stations.

imately 15 years for the commercial rearing of the gilthead sea bream (*Sparus aurata*), and, at the time of study, contained a biomass of 16 ton of fish. The study area (water depth 10 m) is sheltered and characterised by a low circulation regime. Sediment is mostly composed of mud. Dominant current flow in the NE–NW direction, following the cyclonic circulation of the NW Mediterranean Sea. Sampling was carried out in June and February 2001. Sediments are characterised by extremely elevated concentrations of organic matter compared with concentrations found in highly eutrophicated coastal areas [21,34].

3.5. Bisagno Estuary (Ligurian Sea)

Bisagno Estuary station is located near the water treatment plant of Genoa not far from the city harbour (Fig. 2E). Samples were taken a depth of 1.5 m in January and July 2001 [33]. Organic matter (OM) content of the sediment is comparable to typical OM concentrations in estuaries [35].

3.6. Borgo Marina (Imperia Coast—Ligurian Sea)

Borgo Marina station is located east of Borgo Prino along the Imperia Coast (Fig. 2F). Sampling was carried out in June 2000 within 15 m of depth [33].

3.7. Borgo Prino (Imperia coast—Ligurian Sea)

Borgo Prino station is located along the Imperia Coast in the Ligurian Sea. The site is characterised by sand and rocky shores and by the presence of the Prino River outlet (Fig. 2G). As for Borgo Marina, sampling was carried out in June 2000 within 15 m of depth [33].

3.8. Cretan Sea (Aegean Sea)

In the Aegean Sea 12 stations were sampled along a East–West transect near $36°$ N in September 1989. The sampling depth ranged from 110 to 1840 m. This site is one of the more oligothrophic areas of the Mediterranean Sea [36] (Fig. 2H).

4. Results and discussion

The evaluation of the sensitivity of Ex, Ex_{sp} and AS as a function of the considered environmental constraints (Table 3) let us to verify that:

- Exergy is strongly influenced by OM concentration and often results are not meaningful for the study of the microbenthic loop sub-system.
- Specific exergy shows a great sensitivity with respect to the structural variations in the microbenthic sub-system such as biomass composition, complexity and recruitment events.
- Variations in ascendency are strongly related to the functionality of the microbenthic loop in particular with the decomposition activity and with the capacity for resource exploitation.

Table 3
Efficacy of the holistic indicators as a function of the considered environmental variables

		Environmental constrains			
		Temporal variability	OM variability	Depth variability	Variations in hydro-dynamic features
Holistic indicators	Exergy	–	–	–	+
	Specific Exergy	+	+	+	+
	Ascendency	+	+	O	–

(+) Good variability and significant responses; (−) responses not relevant; (O) responses that need succesive confirmations.

Furthermore, it is of particular interest that comparative analysis of the three indicators reveals the trophic adaptation of the system at different levels of environmental disturbance.

4.1. Temporal variability

To assess the temporal variability of exergy and ascendency within the microbenthic loop in marine sediments, we considered the stations of Prelo and Zoagli where the sampling was carried out on a monthly basis for a whole year; differences between the two sites are due to the presence of a large seagrass bed of *P. oceanica* in Prelo Bay. In this site the seasonal variation of total OM are strongly influenced by *P. oceanica* and in particular by the leaf fall occurring in late summer [32]. Detritus of *Posidonia* is mostly refractory [35,37] and represents the major component of OM in the studied environment.

In Prelo, where Posidonia was present, the OM showed a seasonal variation characterised by a stepwise increase from June to March up to a maximum value of $14\,043$ ton km^{-2} followed by a decrease up to the minimum value of 5890 ton km^{-2} in July. In contrast, in Zoagli, OM showed a less marked trend and an increase was only observed from November (3547 ton km^{-2}) to February (8751 ton km^{-2}).

The exergy in Prelo displayed an increasing trend from summer to winter and ranged from a minimum value of $834\,405$ kJ m^{-2} in June to maximum of $1\,926\,738$ kJ m^{-2} in January (Fig. 3). In Zoagli the exergy variation displayed a less marked increase ranging from a minimum value of $530\,128$ kJ m^{-2} in June to a maximum of $1\,141\,346$ kJ m^{-2} in February (Fig. 4). The seasonal trend in exergy values resulted in strong correlation with OM variations both in Prelo and Zoagli ($n = 13$, $p < 0.05$ in Prelo; $n = 13$, $p < 0.05$ in Zoagli) and this might be explained by the high OM concentrations having a great influence on the calculation of exergy within the microbenthic loop at the two sites.

In contrast, specific exergy displayed a different trend. In Prelo Ex_{sp} showed a stepwise increase from 1.056 in April to 1.404 in October with peak values observed in October–November (Fig. 3). In Zoagli an increase in Ex_{sp} was also observed from 1.075 in February to 1.312 in November and two maxima were observed in April (1.520) and November (1.312) (Fig. 4). In the area of Prelo, Danovaro [32] reported an increase of meiofaunal biomass and diversity during leaf fall related to the high input of OM. Meiofauna was also the main biotic component displaying
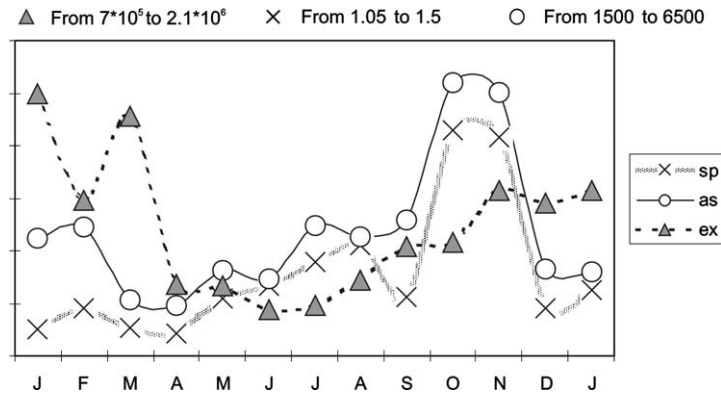
△ From 7*10⁵ to 2.1*10⁶   ✕ From 1.05 to 1.5   ○ From 1500 to 6500

Fig. 3. Seasonal trend of Ex, Ex_{sp} and AS in Prelo station.

seasonal variation in Prelo sediments. According to Marques et al. [38] the observed increase in specific exergy may thus be due to the increase of specific diversity within the detritus food chain. The decrease of Ex_{sp} observed from March to April is then related to unfavourable winter conditions and consequently to a decrease in meiofauna diversity [32].

In Zoagli the observed increase in Ex_{sp} can also be associated with an increase in biomass and richness within the microbenthic sub-system [39]. In addition, the maximum in Ex_{sp} values in June, at this site, is probably explained by a Polychaete recruitment event observed in the sediment [39]. Ascendency (AS) displayed a similar trend both in Prelo and in Zoagli (Figs. 3 and 4). In both systems minimum values were observed in early spring (1953.6 ton km^{-2} year^{-1} in April and 1551.2 ton km^{-2} year^{-1} in January in Prelo and Zoagli, respectively) and maximum values were observed in autumn (6210.7 and 4668.4 ton km^{-2} year^{-1} both in October in Prelo and Zoagli, respectively).

Since ascendency is a measure of the overall dynamic and organization of the system, it mostly reflects the decomposition activity that is the primary ecological role played by the microbenthic sub-system. For this reason the maximum in As values was observed in autumn
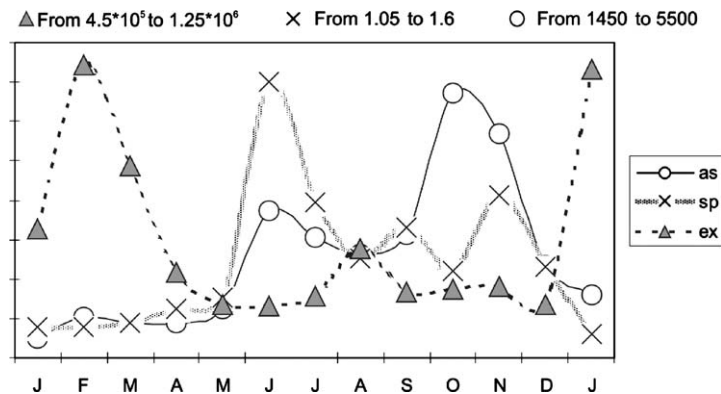
△ From 4.5*10⁵ to 1.25*10⁶   ✕ From 1.05 to 1.6   ○ From 1450 to 5500

Fig. 4. Seasonal trend of Ex, Ex_{sp} and AS in Zoagli station.

where decomposition is the principal process within the seasonal ecological dynamic of the marine benthic ecosystems [32].

In conclusion, the exergy index calculated within the detritus community highlighted a difference between Prelo and Zoagli mostly based on the presence/absence of *P. oceanica*. This was mostly due to the difference in OM content characterising the two systems having a major influence on the calculation of exergy. Therefore, exergy values are mainly determined by the variations of biomass (considered as a quantitive measure) more than structural complexity (considered as a qualitative measure) in our system. For this reason, exergy can be considered as a pure quantitative structural measure if calculated for the microbenthic sub-system.

In contrast, specific exergy seemed to provide complementary information, being more powerful in measuring the qualitative components of the system (i.e. structural complexity) more than a quantitative measure (i.e. biomass).

The ascendency index reflected the overall system activity (i.e. decomposition) and can be mostly considered as a measure of the functionality expressed by the microbenthic sub-system in the marine environment.

From these considerations it can be concluded that we observed a shift in the information provided by the three indices giving a pure structural, qualitative and mostly functional evaluation of the ecosystem by the calculation of exergy, specific exergy and ascendency calculated within the microbenthic loop in the marine environment.

4.2. Spatial variability

4.2.1. Variation of Ex and AS with respect to the organic matter concentration in the sediment

Spatial variability of exergy and ascendency has been investigated in benthic ecosystems having different concentrations of OM in the sediment. To do this, we analysed benthic parameters for the eight ecosystems studied (La Spezia, Bisagno Estuary, Paraggi, Prelo, Zoagli, Borgo Prino, Borgo Marina and the Cretan Sea) from which the samples have been collected during different times of the year.

According to Dell'Anno et al. [20], the OM content is a measure of the trophic state of the benthic ecosystem. The highest OM concentrations were found in La Spezia (17 724 and 19 694 ton km^{-2} in winter and summer, respectively) due to the presence of the fish farm. The Bisagno Estuary also displayed high OM concentrations in the sediments (16 000 and 7702 ton km^{-2} in winter and summer, respectively) especially in winter due to the river outflow. OM concentrations ranging from 5890 (winter) to 14 913 ton km^{-2} (summer) were observed in Prelo as a consequence of the presence of *P. oceanica*. Zoagli displayed a lower concentration of OM ranging from 8751 (winter) to 2789 ton km^{-2} (summer). The minimum OM concentration was found in Paraggi (3865 and 4063 ton km^{-2} in winter and summer, respectively).

The Ex values increased with increasing OM concentrations ($n = 52$, $p > 0.05$) and confirmed the dependence of Ex on detritus when calculated for the microbenthic loop system. In contrast, specific exergy showed an opposite trend and displayed a rapid decrease with increasing OM, reaching values close to 1 for OM concentrations greater than 10 000 ton km^{-2} (Fig. 5). Specific exergy of 1 is only obtained in systems characterised by the absence of living biomass where only organic detritus is present. Therefore, the value of specific exergy close to 1 observed in our study indicated a low structural complexity of the benthic system due to a progressive depletion
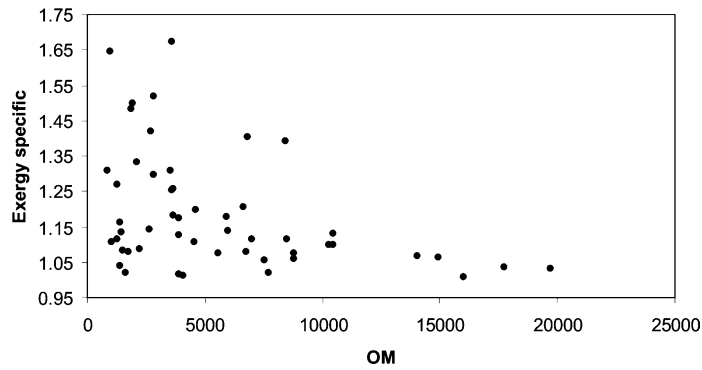
Fig. 5. Ex_{sp} variations in function of OM ammount (ton km^{-2}).

of the living biomass at increasing OM concentrations. Ultimately, the Ex_{sp} trend reflects a dystrophic stress occurring within the sedimentary system in agreement with what has been observed in other ecosystems such as lake [9] and estuaries [38].

The AS displayed an inverse trend (Fig. 6). Below 10 000 ton km^{-2} of OM we did not observe any increase in AS values, while over this level we observed a rapid increase in AS. This behaviour is strictly due to variations in throughput and not in information hence it is related to the increase in the system activity and to an increase in the number and magnitude of fluxes directed to and from the detritus group.

The study of Ex_{sp} and AS within the microbenthic loop highlighted as benthic ecosystems display different structural and functional adaptations to increasing OM. Over a certain level of organic matter we observed an uncoupling occurring between the structural and functional processes of the system characterised by a decrease in structural complexity (Ex_{sp}) followed by a sudden increase in the functional component and activity (AS).

Uncoupling phenomena between bacterial hydrolysis and the cellular scission in relation to stress due to excessive increase of OM have been found in other areas [40]. Ecosystem behaviour over an OM threshold level is thus comparable to a situation of 'ecosystem fever' where dissipation of energy is required to balance the excessive input of organic material.
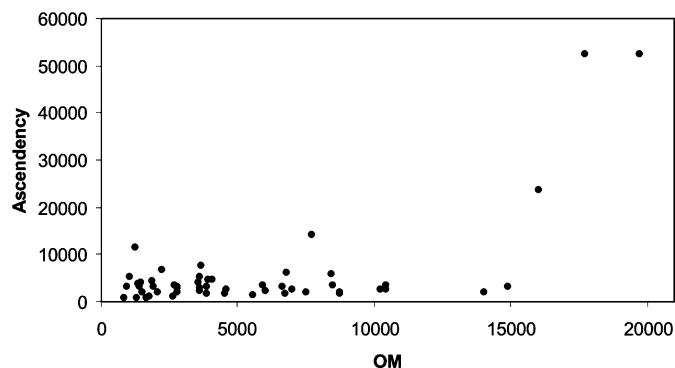

Fig. 6. Ascendency variations (ton km^{-2} $year^{-1}$) in function of OM ammount (ton km^{-2}).

4.2.2. Variation of Ex and AS with depth

To assess the variability of exergy and ascendency with depth in coastal systems, we considered the Imperia case (eight simulations with samples collected within the first 15 m of depth) and for oceanic systems the Aegean Sea (12 simulations with samples collected at depth between 100 and 2000 m).

Ex displayed an increase with depth in both coastal and oceanic systems and this was related to the increase of OM in the sediment. However, in coastal systems the rate of increase in Ex values (ΔEx/Δdepth) was different between Borgo Marina (higher) and Borgo Prino (lower). Borgo Marina has a low circulation regime due to the near presence of a harbour seawall. The increase in the ΔEx/Δdepth may thus be related to the higher deposition rate of OM in this area. The same variation with depth was also observed for Ex_{sp} and the difference in $\Delta Ex_{sp}/\Delta$depth between Borgo Prino and Borgo Marina also suggests an increase in structural complexity in the latter (Fig. 7). In contrast, the ascendency values did not show a clear trend either in Borgo Marina and Borgo Prino.

In the Aegean Sea, the Ex_{sp} decrease at increasing depth indicated a decrease in the number and the diversity of organisms (e.g. meiofauna) according to Danovaro et al. [36]. In the Oceanic area the decrease in the living biomass [36] did not reflect any change in AS values. These results indicate that the loss in structural complexity observed with depth is not coupled with a decrease in the overall system activity and can be viewed as an increase in ecological efficiency of the deep benthic ecosystem. A possible explanation of this occurrence may be found in the increase in the number of real to possible fluxes expressed within the detritus food chain at increasing depth.

In conclusion both Ex_{sp} and AS were sensitive indicators of variation occurring with changing depth within the microbenthic loop of marine ecosystems. In particular, the change in ΔEx/Δdepth and $\Delta Ex_{sp}/\Delta$depth in the coastal area reflected a variation in OM deposition rates and in biomass composition and complexity due to the differences in physical structure such as hydrodynamic features and/or bottom morphology of the coastal ecosystem. Ascendency described an increase in ecological efficiency within the microbenthic loop at increasing depth and this was particularly evident over great depth in the benthic oceanic ecosystem.
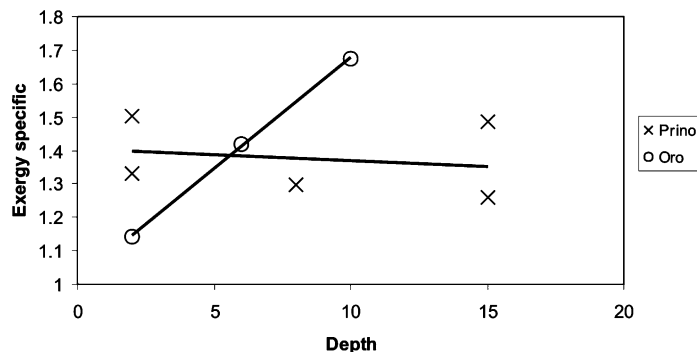

Fig. 7. Ex_{sp} variations in function of depth in Borgo Prino and Borgo Marina stations.

5. Conclusions

The analysis of the temporal and spatial changes of Ex, Ex_{sp} and AS showed the different behaviours of ecological indicators within the microbenthic loop system. Exergy was strongly correlated with the OM concentrations in the sediments, specific exergy result related to the microbenthic loop structure and complexity while ascendency mostly reflected its activity and organization. In addition, the exergy variations displayed greater seasonal variability while specific exergy and ascendency displayed similar seasonal trend when calculated for different environments. This may result from a convergence in the microbenthic loop functionality within natural benthic ecosystems. The study of the system functionality (AS) other than its structure (Ex) may thus provide a useful information for the assessment of health in different environments.

This can be further highlighted in terms of changes in exergy and ascendency with increasing OM. In particular, over a certain level of OM, we observed an uncoupling occurring between the two indices comparable to a situation of 'ecosystem fever' where dissipation of energy is required to balance the excessive input of organic material.

Both Ex and AS were sensitive indicators of variations occurring with changing depth in the marine ecosystem. An uncoupling between Ex and AS was also observed with increasing depth in the oceanic system and this was the result of natural adaptations of the benthic system to an extreme environmental condition.

In conclusion the temporal and spatial changes of exergy and ascendency within the microbenthic loop appeared to be sensitive to the changes in environmental conditions and in the trophic state and may therefore be proposed as useful tool for the health assessment of marine benthic ecosystem.

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