Use of Thermodynamic and Network Oriented Indicators for the Health Assessment of the Coastal Benthic Marine Environment

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The application of a Thermodynamic and a Network oriented analysis on the micro and meio-benthic community at a wide number of coastal zones in the Mediterranean Sea allowed to assess different states of ecosystem health and to identify useful descriptors of the environmental quality employing a holistic approach. The analysis of micro and meiobenthic subsystem 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. 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 1980 (Azam *et al.*, 1983). 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 (Boyd *et al.*, 2000). In particular, organic matter and bacteria are considered as powerful tools for assessing the trophic state and quality of the benthic marine environment (Vezzulli *et al.*, 2002). Temporal and spatial variability of the holistic indicators were evaluated using benthic measures collected at different times for different environments in the north western Mediterranean Sea (Ligurian Sea and south Adriatic Sea). The analyzed systems displayed great variability in respect to the organic matter load changing from extremely oligotrophic to hypertrophic conditions. Within this great variability the indicators considered in this study displayed different reciprocal behaviour let us supposing that it is by the comparative analysis of many indicators that the environmental state could be detected.

The performed Thermodynamic analysis is based on the determination of Exergy and Specific Exergy. The calculation of these indicators has been performed following Jørgensen's approach (Meyer and Jørgensen, 1979) that is based on the multiplication of the concentrations of different groups and the corrispective weighting factor based on Exergy detritus equivalent according to Marques *et al.* (2003). Exergy links the chemical energy of the various groups of the ecosystem to the information embodied in DNA. If it is necessary to consider only variations in structural complexity of the biomass Specific Exergy has to be taken in account and it is obtained by dividing the Exergy of the system for the total biomass (Fabiano *et al.*, 2004).

The analysis of networks of ecological trophic transfers is a useful complement to simulation modelling in the quest for understanding whole-ecosystem dynamics (Ulanowicz, 2004). In order to assess a complete network analysis of the considered systems a simulation of the micro and meiobenthic community has been performed using the dedicated software ECOPATH with ECOSIM 5.0 (http//www.ecopath.org). Systems that display increase in network indicators are generally considered systems in evolution with increasing functionality and efficiency in resources exploitation.

The calculation of the holistic indicators was made by using data on organic matter, bacteria, microphytobenthos and meiofauna collected from 84 stations in the southern Adriatic Sea continental shelf (Italian and Albanian coast) (Fabiano *et al.*, 2004) and 40 stations along the Ligurian coast (north-western Mediterranean) (Vassallo *et al.*, submitted). The first dataset is regarding an area that is considered oligotrophic with low human impact and anthropogenic pressure; on the other hand, along the Ligurian coast there is a wide range of human pressure with some of the considered stations placed in strongly eutrophic areas such as near the outlet of a city river or under an inshore fish farm installation.

In oligo-mesotrophic conditions Ascendency and Exergy increased at increasing Biopolymeric Carbon (BPC) concentration in the sediment. This trend is even more evident during spring when there is a strong detritus production with higher percentage of labile compounds that allow a great possibility of BPC exploitation confirming a strong and rapid benthic pelagic coupling for the micro and meio benthic community. In intermediate condition of trophic enrichment it resulted that both structure (i.e. Exergy) and functionality (i.e. Ascendency) of the micro and meiobenthic community increased at increasing resources availability. Nevertheless the micro and meiobenthic subsystem displayed the highest efficiency in resources exploitation when the resources availability was low displaying the highest values of biological complexity (Specific Exergy) and ability in exploiting and cycling resources detected as Finn Cycling Index (FCI) values. On the contrary these latter indices displayed a decrease in areas characterised by a stronger anthropogenic impact (i.e. near main urban centres) probably depending upon the origin and biochemical composition of the organic matter. This is intriguing and will need future investigations since specific Exergy and FCI might be considered as candidate indices for the assessment of health when the ecosystem is far below the hypertrophic conditions.

On the other hand if systems that we can consider reaching hypertrophic conditions are considered (Ligurian Coastal zones) different behaviours are detectable. The Ascendency displayed two different trends in function of Organic Matter (OM) load to the benthos: below 10 kg m^{-2} of OM we did not observe a significant increase in Ascendency values, while over this level we observed a rapid increase. This behaviour is related to the increase in the system activity due to an increase in the number and magnitude of fluxes that are directed to and from the detritus group. The Ex values increased with increasing OM concentrations confirming strongly the dependence of Ex on total biomass and in particular for these systems on detritus when calculated for the micro and meiobenthic subsystem. 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 kg m^{-2}. 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 of the living biomass at increasing OM concentrations.

For conditions with high trophic level Exergy resulted completely dominated by detritus contribution to the calculation and doesn’t give any more significant information. If we consider on the same scale of organic matter load (Fig. 1) both Ascendency that represents the system functionality and specific Exergy that represents the system structural complexity it is clear that over a certain threshold of OM enrichment there is an uncoupling phenomenon characterised by a decrease in structural complexity (Specific Exergy) followed by a sudden increase in the functional component and activity (Ascendency) that could identify the buffer capacity of the microbenthic loop subsystem in tolerating organic matter enrichment.

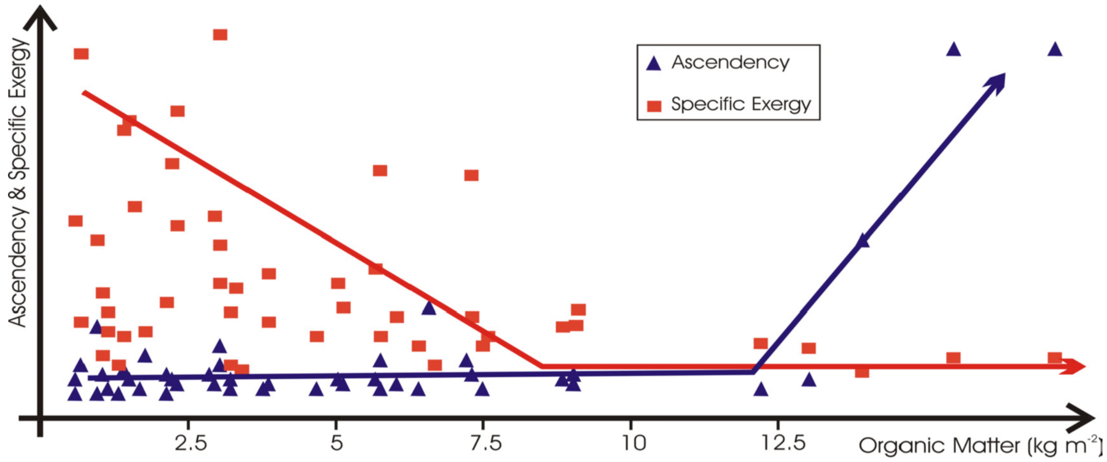
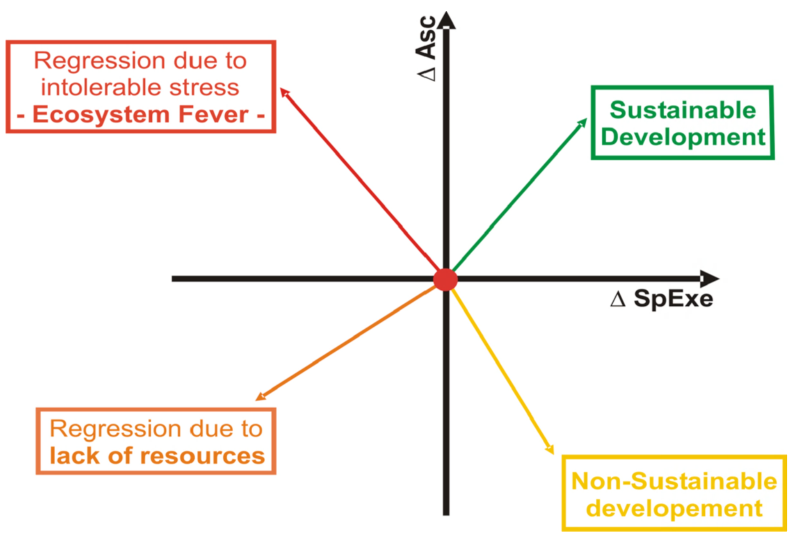


Figure 1. *Ascendency and Specific Exergy trend across the threshold of hypertrophy.*

In conclusion, regarding the thermodynamic and network oriented analysis of benthic marine environment it is possible to summarize that the holistic approach allows a general point of view in assessing changes in structure and functionality of benthic marine environment; the comparison between different indicators permits a better comprehension of the reacting strategy of the considered system and that thus it is by the comparative analysis of more than one indicator that we can draw the best information on the health of the system. Following these conclusions a schematic approach for the health assessment of the benthic marine environment could be presented. It is based on the comparative analysis of variations of two holistic indicators that better represent variations in benthic environment: Ascendency and Specific Exergy (Fig. 2). If in a spatial or temporal pattern we can observe a variation in the system that leads to an increase both in specific Exergy and in Ascendency then we can reasonably suppose that the system is developing in the right way increasing its structure, consequently its complexity and functionality to support the development. Otherwise if only Exergy increases but Ascendency decreases probably the system is just developing with a little delay in functionality increase or it is going toward a non-sustainable development where biomass and complexity are not supported by functionality increase.

Obviously if both the indicators are subjected to a decrease the system is going backwards probably due to a lack of resources. Finally if we can observe a strong increase in functionality and a contemporaneous decrease in complexity then we are attending a regression due to an intolerable stress that bring the system to try to remove the source of disturbance by increasing its activity but not using this activity to build new complex structure but dissipating energy and matter. That is what we call *ecosystem fever*.

Figure 2. *Health assessment schematic approach for benthic coastal marine systems*



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