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Modelling the interplay of environment, economy and resources in Marine Protected Areas. A case study in Southern Italy

Pier Paolo Franzese*, Giovanni Fulvio Russo, Sergio Ulgiati

*Department of Environmental Sciences, Parthenope University of Naples,
Centro Direzionale – Isola C4, (80143) Napoli, Italy
corresponding author, e-mail: pierpaolo.franzese@uniparthenope.it

Abstract. In order to improve environmental management and policy making based on the principles of sustainable development it is necessary to explore both ecological and economic dynamics interacting in human-dominated ecosystems. A way to perform such an integrated assessment is provided by the Emergy Synthesis method that allows to account for mass, energy and money flows supporting a given ecosystem. In this paper Geographical Information System and Emergy Synthesis methods were combined to model the interplay of environment, economy, and resources in the Site of Community Interest named *Parco Marino di S. Maria di Castellabate* and located in Southern Italy. The GIS allowed to organize and explore data dealing with several environmental features while the emergy modelling and accounting provided a characterization of the energy metabolism of the study area.
The solar transformity of the net primary production of the marine system resulted in $4.86 \cdot 10^4$ seJ Joule^{-1}. The emergy cost for fish and mollusk (two of the main products of the fishing sector) resulted in $1.05 \cdot 10^7$ seJ Joule^{-1} and $2.43 \cdot 10^7$ seJ Joule^{-1}, respectively. These emergy-based indicators provided information about the environmental performance of the marine ecosystem and its fishing economic sector by relating the input emergy invested into the processes with the generated outputs.
The solar transformities calculated in this case study (one of the first ever performed in Italy by adopting this methodological approach) will provide a benchmark for future comparison with similar marine systems in Italy and abroad.
In conclusion, the combined use of GIS and Emergy Synthesis methods resulted a promising approach able to provide a deeper understanding of human-managed ecosystems and their dynamics.

Key words: GIS Analysis; Emergy Synthesis; Ecological Modelling, Marine Protected Areas.

1. Introduction

Ecological systems are complex, adaptive, hierarchical systems, highly interrelated by a web of matter and energy flows. These features translate into non equilibrium, irreversible phenomena, and non linear dynamics (De Groot & Mazur 1962; von Bertalanffy 1968; Kondepudi & Prigogine 1998).

Economic-productive systems, supplied with raw materials and ecosystem services by natural ecosystems, are usually run like linear systems according to materials economy and growth ethic paradigms.

The idea to indefinitely run a linear system on a finite planet has led human society to ecological overshoot, exploiting natural resources faster than their natural rate of regeneration (Odum & Odum 2000, 2001). For this reason, landscape and marine protected areas have been planned and instituted worldwide to prevent the loss of habitats, biodiversity and ecological functions (Groom et al. 2006; Carleton Ray & McCormick-Ray 2003).

In spite of the effort promoted by Biological Conservation to properly manage and value natural resources, natural capital and ecosystem services have been often underestimated or even excluded by economic assessment frameworks, mainly due to the idea that they have no market value and are unlimitedly available.

Ecological Economics, a new branch of Economics that focuses on how to operate an economy within the ecological constraints of earth's natural resources, provides a theoretical framework to assess the *economic value* of natural capital and ecosystems services (Costanza et al. 1997, 2000; Cleveland & Ruth 1997; Farber et al. 2002; Patterson 1998, 2002). Ecological Economics can be considered an anthropocentric evaluation approach as it assesses values related to the use that humans do of natural resources. In so doing, it performs what can be defined a "user-side approach".

This approach, although incomplete, has the merit to consider natural capital like a factor of production function, together with human labor and money capital. This is an important shift from Neoclassical Economics as it relates the growth of economic systems with the availability of natural resources, pointing out that natural capital is the real limiting factor for the economic development.

Another way to give a value to natural capital and ecosystem services is to assess their *energy value*. In the 1980s H. T. Odum developed the so-called Emergy Synthesis: a biophysical accounting method based on the concepts of energy quality (Odum 1988, 1994, 1996, 2007). Emergy Synthesis can be considered a geocentric evaluation method as the evaluation is based on a "donor-side approach", focusing on the work done by the biosphere to generate good and services (Brown & Ulgiati 1999, 2001, 2004a, b, Franzese et al. 2005, 2008a; Tilley & Swank 2003).

In this paper we combine the use of Geographical Information System (GIS) and Emergy Synthesis methods to model the interplay of economy, environment and resources in the Marine Protected Area (MPA) named *Parco Marino di S. Maria di Castellabate* and located in Southern Italy.

2. Materials and methods

2.1. The area of study

The area of study is the Site of Community Interest (SCI) n. IT8050036, named *Parco Marino di S. Maria di Castellabate*. It is located in Southern Italy (E 14°55' – N 40°17') and has a total area of 50.2 km^2 (Fig. 1).

This MPA, established in 2006 in the framework of the "Habitats Directive" (92/43/EEC), is an important ecological system for the Mediterranean biogeographical region. The "Habitats Directive" on the conservation of natural habitats and wild fauna and flora forms, together with the "Birds Directive" (79/409/EEC), the cornerstone of Europe's nature conservation policy.

The MPA has a coastline length of 21.5 km and it is bordered by two small municipalities with low density population: Castellabate and Montecorice. Geographically, the MPA is bordered by a watershed with a total area of 52.1 km^2.

The marine ecosystem is characterized by oligotrophic waters, sandy and muddy seabed with widespread prairies of the endemic seagrass *Posidonia oceanica*. The importance of the study area is mainly due to the presence of habitats as marine seagrass (*Posidonia oceanica*) and bioconstructions of the Coralligenous, and species as fishes (among which, *Alosa fallax*, *Epinephelus caninus*,

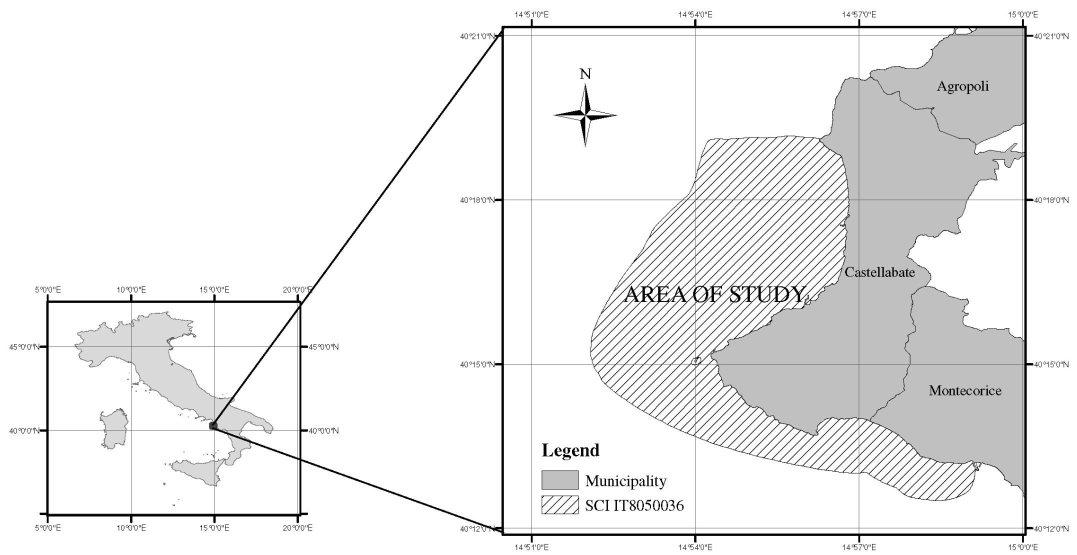

Figure 1. Area of study: Site of Community Interest n. IT8050036 *Parco Marino di S. Maria di Castellabate* (Southern Italy)

Epinephelus alexandrinus), reptils (*Caretta caretta*), birds (among which *Larus audouinii*), and cetacean mammals (*Tursiops truncatus*). The main threats to the area are related to overfishing and traffic of motor boats (Russo & Di Stefano 2003, 2005).

2.2. GIS Analysis

Geographical Information Systems (GIS) are a new information technology representing one of the most relevant tools for the transition towards the so-called "intelligent cartography". Several definitions of GIS have been developed in order to describe such a useful tool able to integrate digital cartography and conventional thematic databases. Among them, according to Cowen (1988), a GIS system can be defined as *a decision support system involving the integration of spatially referenced data in a problem solving environment*.

By definition ecosystems are characterized by a large number of highly interconnected components and variables (von Bertalanffy 1968; Odum 1994). The spatial and temporal multi-layer structure of a GIS allows to explore and integrate environmental features of natural and human-dominated ecosystems. More specifically, a GIS system makes the analyst capable of integrating multiple environmental features by overlapping layers and attributes to produce new information. Exploring raw data using GIS turns data into more complex information, adding new insight to the existing knowledge about the system (Burrough & McDonnell 1998).

A GIS system of the study area was implemented in this study by using ArcGIS 9.0 (http://www.esri.com/software/arcgis/index.html) to explore the main environmental features characterizing the MPA.

2.3. Emergy Synthesis

Emergy Synthesis (Odum 1988, 1996, 2007) is an energy evaluation method rooted in irreversible thermodynamics (De Groot & Mazur 1962) and systems thinking (von Bertalanffy 1968). It aims at calculating indicators of environmental performance and sustainability accounting for both natural and economic resources used by natural, human-dominated and man-made ecosystem (Brown & Ulgiati 1999, 2001; Franzese et al. 2005, 2008a; Tilley and Swank 2003).

Emergy is defined as "the total amount of available energy of one kind (most often of the solar kind) that is used up directly or indirectly in a process to deliver an output product, flow, or service" (Odum 1996). According to the emergy theory different forms of energy, materials, human labour and economic services are all evaluated on the common basis of biosphere by converting them into equivalents of only one form of energy (the solar kind) expressed as solar equivalent Joule (seJ). The ratio of the available energy previously used up to make a product to the actual energy content of such a product provides a measure of the hierarchical position of the item within the thermodynamic scale of the biosphere (a kind of production cost of the item measured in "biosphere currency"). Such a ratio is expressed as solar equivalent Joules per Joule (seJ/J) or per gram (seJ/g), termed solar transformity and specific emergy, respectively (Brown & Ulgiati 2004a, b; Franzese et al. 2008b).

3. Results and discussion

3.1. The GIS system of the MPA *Santa Maria di Castellabate*

A GIS system of the study area was implemented to organize and integrate environmental data dealing with ecological and human-related features characterizing the MPA. The GIS system was then utilized in support to the emergy accounting of the MPA.

After georeferring raster maps of the study area, several thematic layers were derived, such us: administrative boundary, coastline, zonation, bathymetry, bionomic map, fishing area, rivers, watershed.

The GIS provided the spatial information useful to quantitatively assess the energy inputs to the MPA dealing with solar radiation, geothermal flow, wind, rain, tide, ocean current, watershed, runoff rate, and the net primary production of the marine ecosystem.

In particular, the watershed area bordering the marine system, the related runoff rate and its chemical potential, were calculated by deriving surface characteristics from a digital terrain model (D.T.M.). The model of the surface was built using ArcGIS tools for Kriging, an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with *Z* values. This method weighs the surrounding measured values to derive a prediction for an unmeasured location. The general formula for the interpolators is formed as a weighed sum of the data:

$$Z(p_0) = \sum_{i=1}^{N} \lambda_i Z(p_i) \qquad \text{Equation 3.1}$$

where: $Z(pi)$ is the measured value at the i^{th} location; λ_i is an unknown weight for the measured value at the i^{th} location, p_0 is the prediction location, N is the number of measured values.

Finally, the total area of the watershed delivering a runoff input to the marine system was evaluated in $5.21 \cdot 10^7$ m^2 (Fig. 2), while the chemical potential of the runoff resulted in $1.07 \cdot 10^{14}$ J year $^{-1}$, equivalent to $7.37 \cdot 10^{18}$ seJ year $^{-1}$ (Tab. 1).

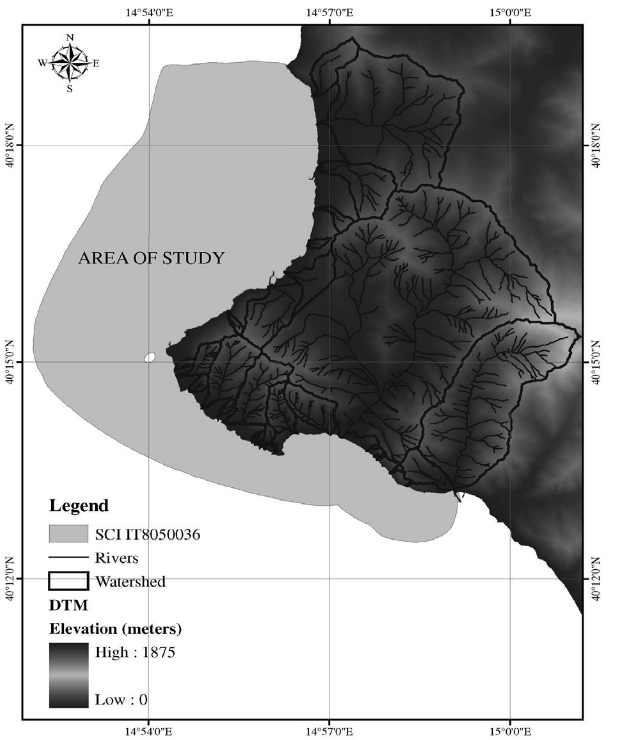

Figure 2. Digital Terrain Model, river patterns, and watershed of the MPA *Santa Maria di Castellabate*, Southern Italy

3.2. The Emergy Synthesis of the MPA *Santa Maria di Castellabate*

The Emergy Synthesis of the main natural and human-driven resource flows used by the MPA in the year 2006 was implemented to model the interplay of environment, economy and resources, with special reference to the net primary production of the marine system and its fishing economic sector. Finally, emergy-based indicators of environmental performance were calculated.

The main steps of the Emergy Synthesis were:

Identification of the boundaries (spatial and temporal) of the study area.

Modelling of the MPA by means of a model of emergy flow (Fig. 3).

Calculation of the main matter, energy and money flows supporting the ecological system of the MAP and its fishing economic sector.

Conversion of matter, energy and money flows into solar emergy unit by means of suitable transformity values.

Calculation of the total emergy used by the MPA in the year 2006.

Calculation of emergy-based indicators of environmental performance for the net primary production, and the main products of the fishing activities (fish and mollusk).

The spatial boundary of the study area corresponds to its administrative boundary (Fig. 1), while all the data accounted for were evaluated on a yearly base (year 2006). In Figure 3 the model of emergy flow implemented for the

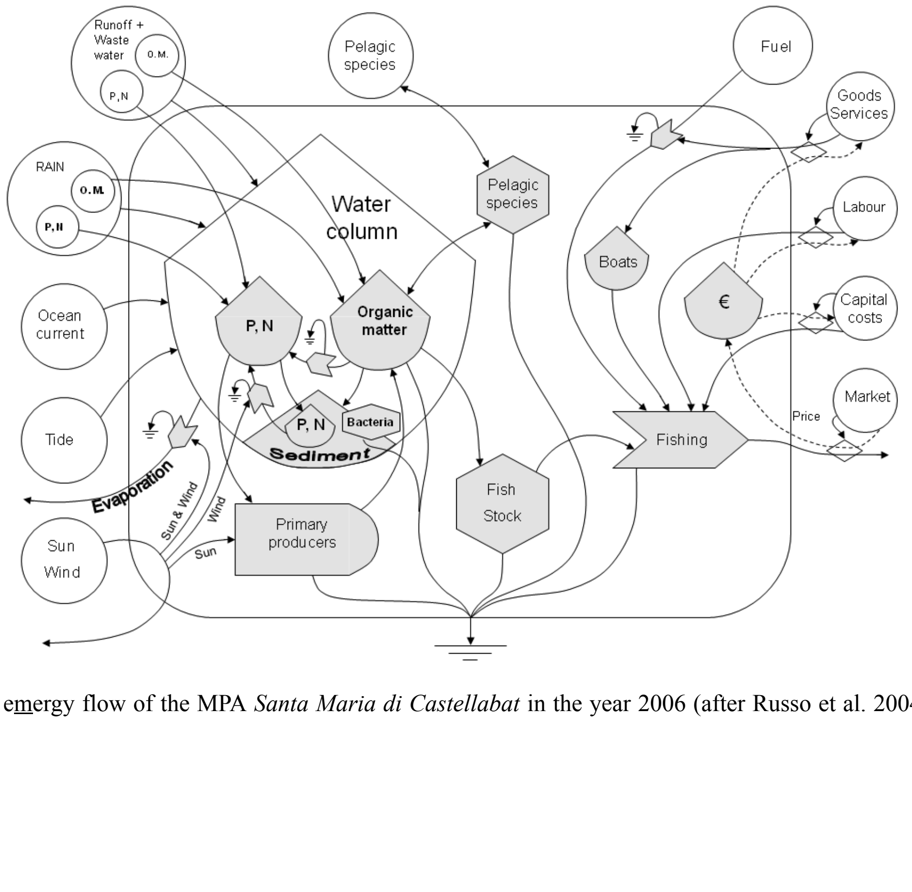

Figure 3. Model of emergy flow of the MPA *Santa Maria di Castellabat* in the year 2006 (after Russo et al. 2004)

Table 1. Emergy flows calculated for the MPA *Santa Maria di Castellabate* in the year 2006

	Item	Unit	Quantity (unit/year)	Emergy per unit (seJ/unit)	Solar emergy (seJ/yr)	Emergy %
	INPUTS					
1	**SOLAR RADIATION**	J/yr	2.72E+17	1.00E+00	2.72E+17	0.75
2	**WIND**	J/yr	4.41E+14	2.51E+03	1.11E+18	3.06
3	**RAINFALL**					
	Chemical potential	J/yr	1.79E+14	3.05E+04	5.45E+18	15.01
	Kinetic energy	J/yr	2.10E+11	1.76E+04	3.70E+15	0.01
	Inorganic Phosphor	g/yr	6.67E+05	2.98E+10	1.99E+16	0.05
	Inorganic Nitrogen	g/yr	1.61E+06	7.71E+09	1.24E+16	0.03
4	**GEOTHERMAL FLOW**	J/yr	6.32E+13	5.76E+04	3.64E+18	10.03
5	**TIDE**	J/yr	1.66E+13	2.82E+04	4.69E+17	1.29
6	**OCEAN CURRENT**					
	Geopotential	J/yr	6.05E+10	3.96E+04	2.39E+15	0.01
	Inorganic Phosphor	g/yr	3.86E+04	2.98E+10	1.15E+15	0.00
	Inorganic Nitrogen	g/yr	6.52E+05	7.71E+09	5.03E+15	0.01
7	**RUNOFF**					
	Chemical potential	J/yr	1.07E+14	6.89E+04	7.37E+18	20.32
	Inorganic Phosphor	g/yr	6.50E+05	2.98E+10	1.94E+16	0.05
	Inorganic Nitrogen	g/yr	2.38E+07	7.71E+09	1.84E+17	0.51
8	**URBAN WASTEWATER**					
	Chemical potential	J/yr	5.19E+12	6.89E+04	3.58E+17	0.99
	Inorganic Phosphor	g/yr	2.04E+06	2.98E+10	6.09E+16	0.17
	Inorganic Nitrogen	g/yr	1.53E+07	7.71E+09	1.18E+17	0.33
	TOTAL LOCAL RENEWABLE, R				**1.41E+19**	
9	Fishing boats, wood	J/yr	5.11E+12	7.37E+04	3.77E+17	1.04
10	Fishing boats, plastic	g/yr	4.40E+07	7.21E+09	3.17E+17	0.87
11	Fishing boats, metal	g/yr	1.21E+08	1.12E+10	1.36E+18	3.74
12	Fuel for fishing boats	J/yr	4.63E+13	1.11E+05	5.12E+18	14.11
13	Labour, fishing sector	work-years	95.75	6.03E+16	5.78E+18	15.92
14	Services, fishing sector	€/yr	1.30E+06	2.75E+12	3.57E+18	9.85
15	Capital costs, fishing sector	€/yr	2.43E+05	2.75E+12	6.69E+17	1.84
	TOTAL IMPORTED, F	seJ/yr			**1.72E+19**	
	OUTPUTS					
16	**Net Primary Production**	J/yr	2.90E+14	**4.86E+04**	1.41E+19	
17	**Fish**	g/yr	7.11E+08	4.40E+10	3.13E+19	
18	**Fish**	J/yr	2.98E+12	**1.05E+07**	3.13E+19	
19	**Mollusk**	g/yr	2.29E+08	1.37E+11	3.13E+19	
20	**Mollusk**	J/yr	1.28E+12	**2.43E+07**	3.13E+19	

MPA is shown. It highlights: a) the main (external) natural and human-driven forces supporting both ecological and economic dynamics; b) the producers, the consumers, and the main storages within the ecosystems; c) the interactions among the components.

The input driving forces, the storages and the outputs of the MPA, were firstly evaluated in terms of mass, energy and money units.

Afterwards, by means of appropriate transformity values, they were converted into emergy unit in order to calculate the total amount of emergy used by the MAP in the year 2006.

The bar graph in Figure 4 shows all the emergy inputs to the MPA as percentage of the total emergy. This graph, called "emergy signature", summarizes the energy metabolism of the MAP, highlighting the importance of the chemical potential of rain and runoff as well as the geothermal flow as input emergy for the primary production (Fig. 4). Labour, services, and fuel resulted instead the most important emergy input to support the fishing economic sector (Fig. 4).

The accounted emergy flows were then clustered in two main categories: 1) local renewable emergy flows (*R*); 2) imported non-renewable emergy flows (*F*) (Tab. 1).

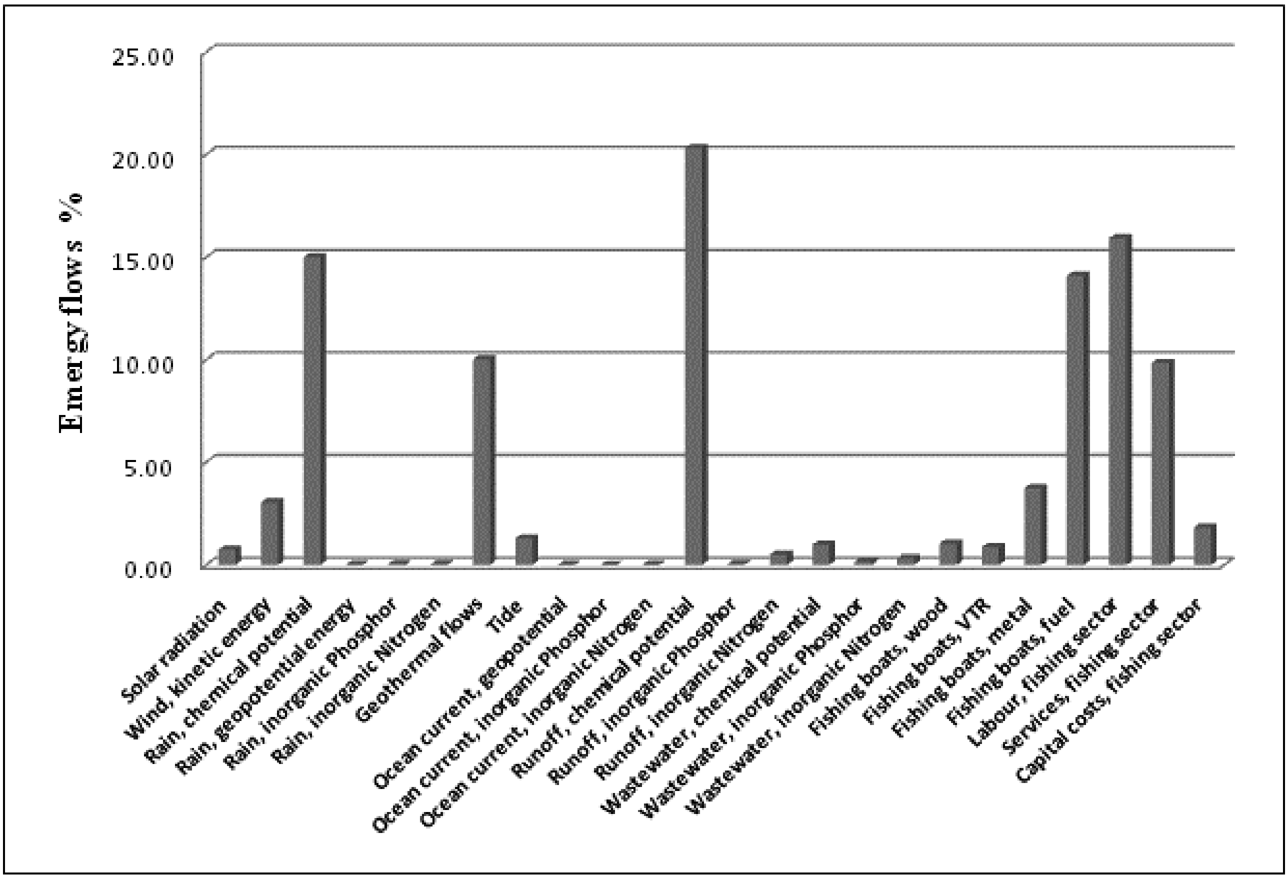

Figure 4. Emergy signature of the MPA *Santa Maria di Castellabate* in the year 2006

The ratio of the total renewable emergy (termed *R* and calculated without double counting) supporting the marine ecosystem in the year 2006 to the net primary production (NPP) generated by the system in the same year resulted in a solar transformity for the process of primary production of $4.86 \cdot 10^4$ seJ Joule^{-1} (Tab. 1). This value has to be considered as an indicator of environmental performance of the marine ecosystem as it relates the input emergy invested into the process with the generated output.

The ratio of the total (*R*+*F*) natural and human-driven emergy flows invested into the fishing economic sector to the fish and mollusk catch (expressed as Joule by considering their food calories), resulted in a value of emergy cost for fish of $1.05 \cdot 10^7$ seJ Joule^{-1} and for mollusk of $2.43 \cdot 10^7$ seJ Joule^{-1} (Tab. 1).

4. Conclusion

Emergy modelling and accounting allowed to explore the interplay of ecological properties and human activities in the area of study, providing information useful to implement strategies of natural resource management oriented to sustainable development.

This case study represents one of the first applications of this theoretical framework to a marine ecosystem in Southern Italy. Therefore, the transformity values calculated in this study for the MAP will provide a benchmark for future comparison with similar ecosystems in Italy and abroad.

In conclusion, the combined use of GIS and Emergy Synthesis methods resulted a promising approach, able to provide integrated information about natural and human-driven resources supporting ecological functions and economic activities in marine protected areas. Ecological and economic features, both managed in a GIS environment, were usefully integrated within the framework of Emergy Synthesis method, contributing to a deeper understanding of the energy metabolism of the marine ecosystem, and to the relevance of the biosphere support to the fishing economic sector.

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