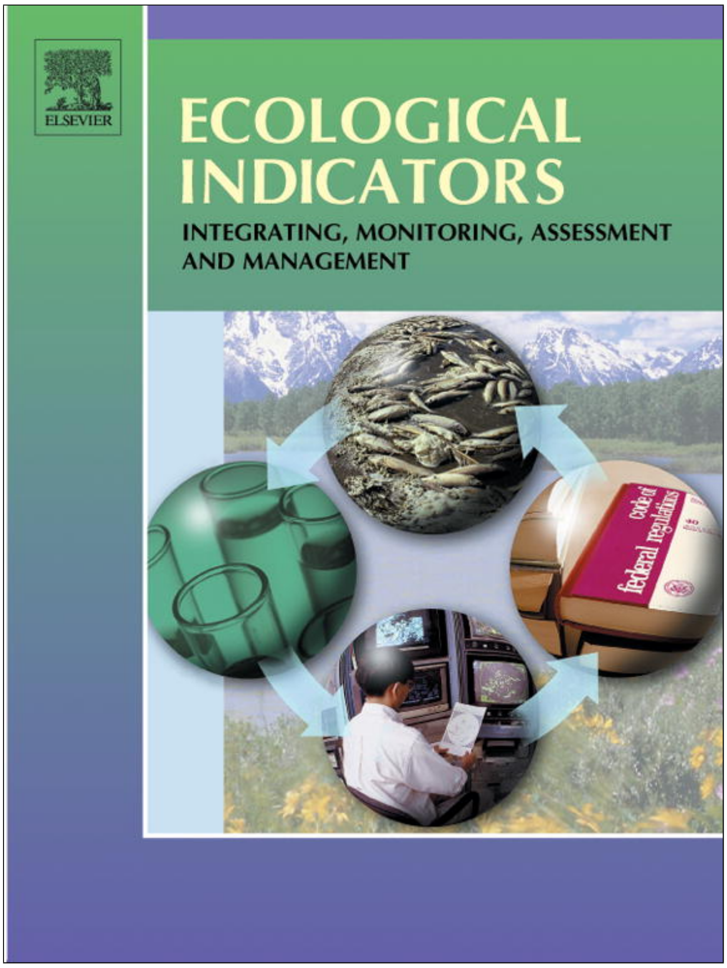
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Thermodynamic oriented ecological indicators: Application of Eco-Exergy and Specific Eco-Exergy in capturing environmental changes between disturbed and non-disturbed tropical reservoirs

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ABSTRACT

Effective assessment of ecological quality in aquatic ecosystems has become an important issue for researchers and environmental managers worldwide. The potential of thermodynamic oriented ecological indicators in environmental assessment and management was tested and compared with diversity measures in three tropical reservoirs located in the basin of the Paraopeba River, Minas Gerais State-Brazil. We computed Eco-Exergy based indices (Eco-Exergy and Specific Eco-Exergy) and the Margalef and Shannon–Wiener indices and tested differences in their responses to change in benthic communities across reservoirs characterised by different degrees of anthropogenic disturbance. Indices were estimated based on biotic descriptors (macrofauna biomass, composition, and abundance) and their values analysed against abiotic descriptors (pH, conductivity, transparency, turbidity, nutrients concentration, dissolved oxygen, chlorophyll *a*, and total dissolved solids). The Margalef index showed significant differences between reference and impacted sites, with the highest values in the former type of sites, (Pseudo $F_{2.719}$ = 24,506, p = 0.001), while the Shannon–Wiener index values showed no significant differences between reference and impacted sites. Eco-Exergy values were significantly higher at stations located in more disturbed sites (Pseudo $F_{2.719}$ = 80.319, p = 0.001), but Specific Eco-Exergy did not show really significant differences between disturbed and non-disturbed sites, although values were higher in the non-disturbed sites type. This might be explained by the fact that opportunistic tolerant species present high biomass values in polluted sites, since Eco-Exergy values may vary due to changes in biomass or information. On the other hand, differences in information between disturbed and non-disturbed sites were more subtle (although the number of species was higher in the less disturbed sites, it was not clearly reflected in Specific Eco-Exergy values). Our results suggest that thermodynamic oriented indicators can capture coherent structural changes in biological communities, highlighting its indicator potential for assessing the ecological condition/integrity of highly modified water bodies, such as reservoirs.

1. Introduction

Reservoirs are highly modified ecosystems, built to meet the demands of economic growth. These systems caused significant changes in the prevailing hydrological and ecological conditions of rivers and watersheds (Tundisi, 2006). The impact of impoundment coupled with perturbations induced by urbanisation, agricultural and industrial activities result in higher instability and lower resilience of the aquatic communities (Fore et al., 1994; Klemm et al., 2003).

Large river reservoir systems are some of the most difficult aquatic ecosystems to assess because they are essentially artificial and, consequently, it is hard to find minimally disturbed sites that can be used to determine as comparable reference conditions. This reservoir type, characterised by a low retention time is essentially a transitional system between rivers and lakes (Terra and Aráujo, 2011).

To evaluate the ecological condition of these aquatic ecosystems, a panoply of ecological indicators has been used in environmental assessment studies. Nevertheless, most ecological indicators take into consideration only a few ecosystem components and result from non-universal theoretical approaches. Some

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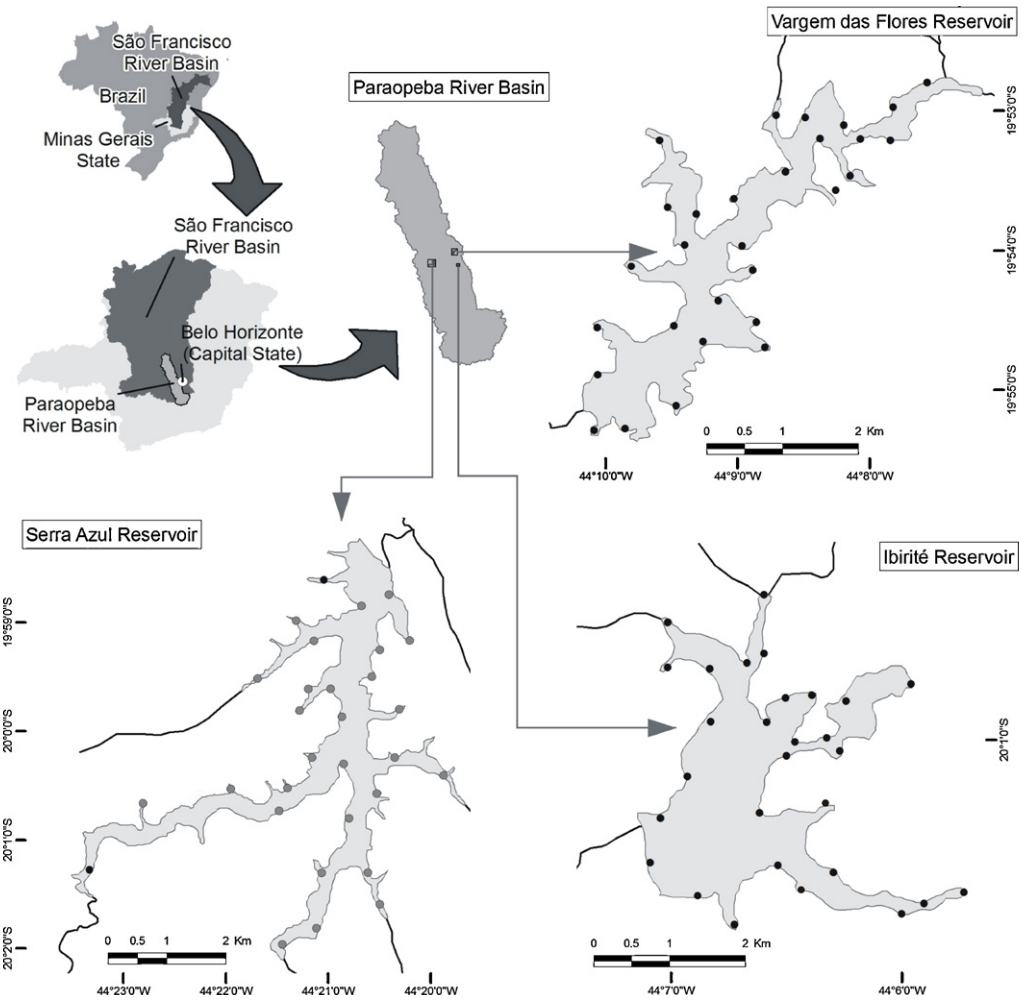

Fig. 1. Location of the reservoir Vargem das Flores, Ibirité and Serra Azul in the Paraopeba River catchment, Minas Gerais, Brazil and distribution of the sampling sites: maximum ecological potential (reference sites) (●) and impacted sites (●) in the reservoirs.

of these approaches are based on the presence/absence of indicator species, and others take into account the ecological strategies of different organisms while diversity measures consider communities composition, abundance and equitability. Another group of ecological indicators is either thermodynamically oriented or based on network analysis, capturing information on the ecosystem from a more holistic perspective (Salas, 2002; Salas et al., 2006; Marques et al., 2009).

The characteristics that define a good ecological indicator are easy handling, a unimodal response to small variations of specific types of pollution, independence of reference states, and applicability across extensive geographical areas (Salas, 2002).

Salas et al. (2005) and Marques et al. (2009) considered that excellent indicators are those that are based on the more general properties of populations, communities and processes involved in ecosystem function. Eco-Exergy (Jørgensen et al., 1995; Marques et al., 1997, 2003) is one of the mathematical functions that has been proposed as a holistic ecological indicator over the last two decades: (a) to express emergent properties of ecosystems arising from self-organisation processes as part of their development and (b) to act as a goal function in model development (Marques et al., 1998). Such proposals have resulted from a wider application of theoretical concepts, based on the assumption that it is possible to develop a theoretical framework able to explain ecological observations, rules and correlations based on an accepted pattern of ecosystem theories (Marques and Jørgensen, 2002; Patrício et al., 2006).

Eco-Exergy is a concept derived from thermodynamics, a measure of the maximum amount of work that an ecosystem can perform when it is brought into thermodynamic equilibrium with their environment. Eco-Exergy is a measure of the distance between the ecosystem in its present state and what it would be if it was at equilibrium with the surrounding abiotic environment, i.e. a measure of its thermodynamic potential. Eco-Exergy of an ecosystem at thermodynamic equilibrium would be zero. This means that, during ecological succession, Eco-Exergy is used to build up biomass, which in turn stores Eco-Exergy; Eco-Exergy therefore represents a measure of the structural biomass and the information embedded in the biomass (Jørgensen and Mejer, 1979; Jørgensen, 2002; Xu et al., 2005).

If the total biomass in the system remains constant then Eco-Exergy variations will rely upon its structural complexity. Specific Eco-Exergy is defined as total Eco-Exergy divided by total biomass. Both Eco-Exergy and Specific Eco-Exergy may be used as indicators in environmental assessment and management and it is advisable to use them complementarily (Marques et al., 1997, 2003).

Salas et al. (2005) indicated that higher values of Eco-Exergy and Specific Eco-Exergy are concordant with higher biodiversity, higher functional redundancy, higher buffer capacity and resilience and more complex systems. This is the reason why the Eco-Exergy and the Specific Eco-Exergy have been used as indicators of ecological condition in a number of European lakes (Jørgensen, 2000; Jørgensen et al., 1995; Nielsen, 1994; Ludovisi and Poletti, 2003; Jørgensen and Ulanowicz, 2009; Xu et al., 2005, 2011), coastal lagoons (Salas et al., 2005), freshwater systems and estuaries (Marques et al., 1997, 2003; Jørgensen and Padisak, 1996; Patrício et al., 2009) and coastal areas (Patrício et al., 2006; Salas et al., 2006).

The main aim of the present study is to test the Eco-Exergy and Specific Eco-Exergy as indicators of ecosystem condition, in three tropical reservoirs in order to assess whether they can differentiate areas with maximum ecological potential (taken as reference for comparisons) from impacted sites. We compared the Eco-Exergy and Specific Eco-Exergy estimations with the values of the Shannon–Wiener and Margalef indices in order to assess the degree of their coherence in describing ecosystem ecological condition, based on benthic macroinvertebrate communities.

2. Materials and methods

2.1. Study sites

We sampled three reservoirs (Ibirité, Vargem das Flores and Serra Azul) located in the Paraopeba river (a tributary of the São Francisco River) catchment, in Minas Gerais, South-eastern Brazil. The region climate is tropical sub-humid (Cwb), with summer rains (November–April) and a dry winter (May–October). The average annual temperature is 20 °C (Moreno and Callisto, 2006) (Fig. 1).

The Ibirité reservoir (20°01′13.39S; 44°06′44.88″W), was built in 1968 at an altitude of 773 m. This reservoir has an area of 2.8 km^2, a volume of 15,423,000 m^3 and an average depth of 16 m. Land use around the reservoir basin not only consists predominantly of Eucalyptus plantations, but also includes a large condominium, small farms, and several industrial plants (Pinto-Coelho et al., 2010; Molozzi et al., 2011).

The Vargem das Flores reservoir (19°54′25.0622″S; 44°09′17.78″W), built in 1971, is located at 838 m. Main uses are potable water supply for the cities of Contagem and Belo Horizonte and leisure for population of approximately 100,000 people living around the reservoir (COPASA, 2004) (Companhia de Saneamento de Minas Gerais). The Vargem das Flores reservoir has a surface area of 4.9 km^2, contains 37,000,000 m^3 of water and has a maximum depth of 18 m. The maximum height of sill spillway is 838 m and the reservoir has a hydraulic retention time of 365 days. An area of about 12.3 ha of the area around the reservoir was transformed into a state environmental protection area in 2006 (Decree 20.793 on 07/08/80).

The Serra Azul reservoir (19°59′24.92″S; 44°20′46.74″W), built in 1981, is located at an altitude of 760 m, has a water surface of 7.5 km^2, a water volume of 88,000,000 m^3, and a maximum depth of 40 m. The maximum height of sill spillway is 760 m and the reservoir has a hydraulic retention time of 351 days. The reservoir is surrounded by an environmental protected area of 27,000 ha established in 1980. Within the protected area, 3.2 ha situated around the reservoir are property of COPASA (2004), the industry that manages the reservoir (Decree 20.792 on 08/07/80); no tourism or fisheries are allowed in this area.

2.2. Sampling stations

Ninety sampling stations were sampled in the three reservoirs at sites representative of the different biocenoses at minimally disturbed reference sites and the principal polluted areas. Samples were collected every three months, in March, June, September and December, in 2008 and 2009.

Twenty-eight different stations located at the Serra Azul reservoir were considered as having maximum ecological potential (MEP) in a previous work (Molozzi et al., 2012), and therefore classified as reference sites in the present study.

2.3. Environmental parameters

For each sampling occasion, and at each sampling site the following water physical and chemical parameters were measured in situ using an YSI Model Multiprobe: oxygen dissolved, conductivity, turbidity, total dissolved solids (TDS) and pH. Sub-surface water samples were collected with a Van Dorn type bottle for subsequent analysis of total nitrogen (TN), total phosphorus (TP) and orthophosphates (PO_4), in accordance with "Standard Methods for the Examination of Water and Wastewater" (APHA, 1992). The concentration of chlorophyll *a* (Chla) was determined according to Golterman et al. (1978). Transparency was estimated using a Secchi disc, and water column depth was estimated using a portable sonar.

2.4. Biological samples

Macroinvertebrates were sampled at 90 sites in the littoral zone of the three reservoirs using an Eckman-Birge dredge (0.0225 m^2). Samples were fixed in 70% formalin and carried to the laboratory for processing. Invertebrates collected were almost always identified to the family level (Merritt and Cummins, 1996; Fernandez and Domingues, 2001; Costa et al., 2006; Mugnai et al., 2010). However, Chironomidae larvae were treated with 10% lactophenol solution and identified to the genus level, under a microscope (400×), according to Trivinho-Strixino (2011) and Epler (2001). After taxonomic identification, organisms were dried in an oven at 60 °C for 48 h and weighed (precision 10^{-4} mg) for biomass determination, the Mollusca, which after drying were burned in furnace at 450 °C for 4 h to estimate ash free dry weight.

2.5. Ecological indicators computation

2.5.1. Eco-Exergy estimations

Eco-Exergy can be computed from (Jørgensen, 2010) (Eq. (1)):

$$\sum_{i=n}^{i=0} \beta_i ci \tag{1}$$

where β_i are weighting factors applicable to the various components (i) of the ecosystem, reflecting the Exergy that those various components possess as a function of their chemical energy and the information embodied in their genome (Jørgensen, 2010). β_i values based on Exergy detritus equivalents have been found for various species (Fonseca et al., 2000; Jørgensen et al., 2005). The unit Exergy detritus equivalents expressed in g m^{-2} can be converted to kJ/m^{-2} by multiplying by 18.7, corresponding to the approximate average energy content of 1 g of detritus.

Over time, the variation of Eco-Exergy in an ecosystem will be due to the variation of the quantity of biomass (g m) and the information embodied in each unit of biomass (expressing the quality of the biomass) (Marques et al., 1997) (Eq. (2)):

$$\Delta EX_{\mathrm{tot}} = \Delta \mathrm{Biom} \times \beta_i \times \Delta\beta_i \times \mathrm{Biom} \tag{2}$$

If the total biomass (B_{tot}) in a system remains constant through time, then the variation of Eco-Exergy (EX_{tot}) will be only a function of changes in the information embodied in the biomass.

Such information is called Specific Eco-Exergy (SpEx), expressing Eco-Exergy per unit of biomass (Eq. (3)):

$$SpEx = \frac{Ex_{tot}}{Biom_{tot}} \quad (3)$$

Values of Eco-Exergy and Specific Eco-Exergy were calculated from the biomass of the different organisms ($g\,m^{-2}$) through the use of weighting factors able to discriminate different 'qualities' of biomass. Taking into account the available set of weighting factors, data on organisms' biomass were pooled as a function of higher taxonomic levels (Marques et al., 1997). An overview of the major taxonomic groups contributing to the exergy in this system is provided in Table 1.

2.5.2. Diversity measures

We estimated the Margalef and the Shannon–Wiener indices in order to compare them with the values of Eco-Exergy and Specific Eco-Exergy. Our aim was to assess the degree of their coherence in describing ecosystem condition.

The Margalef index (Margalef, 1969) is given by (Eq. (4)):

$$D = \frac{S-1}{\log_e N} \quad (4)$$

where S is the number of species and N is total number of individuals.

The Shannon–Wiener index (Shannon and Weaver, 1963) is given by (Eq. (5)):

$$H' = -\sum p_i \log_2 p_i \quad (5)$$

where p_i is the proportion of the individuals found in the species i. In the sample, the real value of p_i is unknown, but it is estimated through the ratio Ni/N, where Ni is the number of individuals of the species i, and N is the total number of individuals.

2.6. Data analysis

A previous work (Molozzi et al., 2012) carried out in the same study areas showed no significant differences in the communities between different periods of the year (e.g. rainy season vs. dry season) (Table 2), and therefore, there was no reason for separately analysing the data collected quarterly over the two-year study period (2008 and 2009) data underwent square root transformation.

In order to examine the similarity between communities from reference (28 sites, with maximum ecological potential at Serra Azul reservoir) and impacted sites (62 sites at Serra Azul, Ibirité and Vargem das Flores reservoirs) (see Molozzi et al., 2012), multivariate analysis was performed using the PRIMER 6 software

Table 1
Exergy/biomass conversion factors (β) for benthic communities, based on Jørgensen et al. (2005).

Organism	Exergy conversion factor (β)	Organism	Exergy conversion factor (β)
Virus	1.01	Kinorhynch	165
Minimal cell	5.8	Gastrotric, MetI	76
Bacteria	8.5	Rotifera	163
Algae	20	Gnahostom	143
Archaea	13.8	Gastrotric, MetII	116
Protists	21	Ctenophora	167
Diatoms	66	Entoprocta	165
Yeast	17.4	Nematoda (Worms)	133
Fungi	61	Nematina	76
Protozoa, Amoebe	31–46	Mollusc	310
Prolifera	97	Gastropods	312
Angiosmperm	147	Bivalve	297
Rhodophyta	92	Annelida (f.i. leeches)	133
Bryophyta	173	Brachiopods	109
Pteridophyta	146	Sea squirt	191
Psilophyta	170	Crustacean	232
Pinus mono	314	Coleoptera (Beetles)	156
Mustard weed	147	Diptera (Flies)	184
Rice	275	Hemiptera	159
Eudicot	268	Hymenoptera	267
Monocot	393	Lepidoptera	221
Placozoa	35	Phasmida	43
Cnidaria	91	Mosquito	322
Platyhelminthes	120	Chordata	246
Mesozoa	30	Fish	499

Table 2
Results of ANOSIM pair wise tests between the samples of Serra Azul, Vargem das Flores, and Ibirité reservoirs; ns indicates p values >0.05 (Molozzi et al., 2012).

Months	Serra Azul (R, p)	Vargem das Flores (R, p)	Ibirité (R, p)
March/08–March/09	0.08, 0.0004	0.18, 0.001	0.21, 0.001
March/08–June/08	0.04, ns	−0.01, ns	0.04, 0.04
March/08–June/09	0.09, 0.002	0.04, 0.05	0.07, 0.007
March/08–September/08	0.02, ns	0.03, ns	0.09, 0.001
March/08–September/09	0.09, 0.001	0.06, 0.015	0.39, 0.001
March/08–December/08	0.04, 0.025	0.06, 0.015	0.21, 0.001
March/08–December/09	0.15, 0.001	0.10, 0.001	0.31, 0.001
March/09–June/08	0.05, 0.018	0.20, 0.001	0.20, 0.001
March/09–June/09	0.02, 0.094	0.22, 0.001	0.14, 0,001
March/09–Setember/08	0.05, 0.025	0.13, 0.003	0.10, 0.001
March/09–Setember/09	−0.01, ns	0.25, 0.001	0.13, 0.005
March/09–December/08	0.08, 0.004	0.14, 0.001	0.07, 0.005
March/09–December/09	0.02, ns	0.34, 0.001	0.20, 0.001
June/08–June/09	0.06, 0.015	0.1, 0.001	0.07, 0.007
June/08–September/08	0.05, 0.023	0.01, ns	0.05, 0.03
June/08–September/09	0.04, 0.035	0.15, 0.001	0.22, 0.001
June/08–December/08	0.03, 0.038	0.07, 0.015	0.21, 0.001
June/08–December/09	0.10, 0.002	0.21, 0.001	0.26, 0.001
June/09–September/08	0.04, 0.029	0.09, 0.004	0.11, 0.001
June/09–September/09	0.03, 0.054	−0.02, ns	0.17, 0.001
June/09–December/08	0.08, 0.002	0.12, 0.001	0.25, 0.001
June/09–December/09	0.04, 0.036	0.01, ns	0.22, 0.001
September/08–September/09	0.05, 0.014	0.13, 0.004	0.11, 0.003
September/08–December/08	0.01, ns	0.02, ns	0.09, 0.006
September/08–December/09	0.10, 0.001	0.18, 0.001	0.23, 0.001
September/09–December/08	0.06, 0.008	0.16, 0.001	0.18, 0.001
September/09–December/09	−0.01, ns	0.001, ns	0.06, 0.007
December/08–December/09	0.10, 0.001	0.16, 0.001	0.35, 0.001

package (Plymouth Marine Laboratory, UK). Data (species abundance and biomass) underwent square root transformation. A Bray Curtis similarity matrix was calculated and used to generate two-dimensional plot using the non-metric Multi-dimensional Scaling analysis (nMDS) technique (Clarke and Warwick, 2001; Clarke and Gorley, 2006). Stress values were computed for each nMDS plot to indicate the goodness of representation of differences among samples. PERMANOVA tests (Permutational Multivariate Analysis of Variance; Anderson, 2001a,b; Anderson and Braak, 2003; Anderson et al., 2008; software package PERMANOVA + for PRIMER, 2006) considering 999 permutations were applied to see which of the proposed groups were significantly distinct with regard to biomass and abundance data (species abundance and biomass) underwent square root transformation, using Bray Curtis similarity matrix was calculated). Differences between reference and impacted sites based on results from the Margalef and Shannon–Wiener indices, Eco-Exergy and Specific Eco-Exergy values were assessed with a PERMANOVA test and graphically presented by Box–Whisker plots (Software Statistica 7.0).

Pearson's correlations ($p \leq 0.05$) were estimated to assess relationships between indicator values and environmental parameters (Software Statistic 7.0). The correlation coefficient itself, rather than its probability, is more critical as far as measuring agreement between parameters is concerned, because the coefficient reflects the ratio of covariance between different variables (Willby and Birk, 2010). Thus, a minimum value for r of 0.4–0.5 is required to consider a correlation between indicators and environmental parameters as significant.

3. Results

3.1. Benthic communities' response to pressures

Results obtained from the nMDS multivariate analysis for biomass and abundance data on the biological communities are illustrated in Fig. 2. Stress values computed were relatively high (0.19 and 0.20, respectively), and therefore the reliability of the graphic representations' detail had to be taken into account carefully.

Nevertheless, PERMANOVA shows significant differences in biomass (Pseudo $F_{1.89} = 43.05$, $p = 0.001$) and abundance (Pseudo $F_{1.89} = 61.50$, $p = 0.001$) between the reference sites and impacted sites. Taxa such as *Melanoides tuberculatus*, Oligochaeta and *Chironomus* occurred in higher proportions at impacted sites (25.47%, 24.83% and 9.27%, respectively) and lower proportions at reference sites (2.62%, 3.42%, and 1.05%, respectively). However, taxa such as *Fissimentum*, Philopotamidae, Hydrobiosidae and *Procladius* occurred in higher proportions in reference sites (5.45%, 0.04%, 0.04% and 3.16%, respectively), but were present in much lower proportions or absent from impacted sites (0.24%, 0%, 0%, and 0.09%, respectively) (Molozzi et al., 2012).The highest biomass

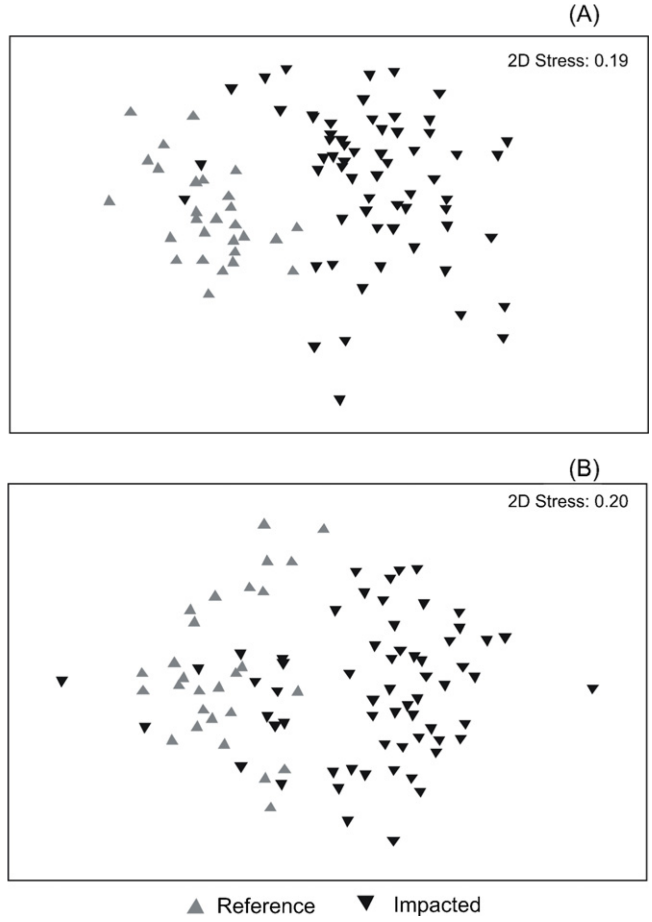

Fig. 2. nMDS ordination plot based on macrobenthic biomass data (A) and abundance data (B) from 90 sites located in the studied reservoirs.

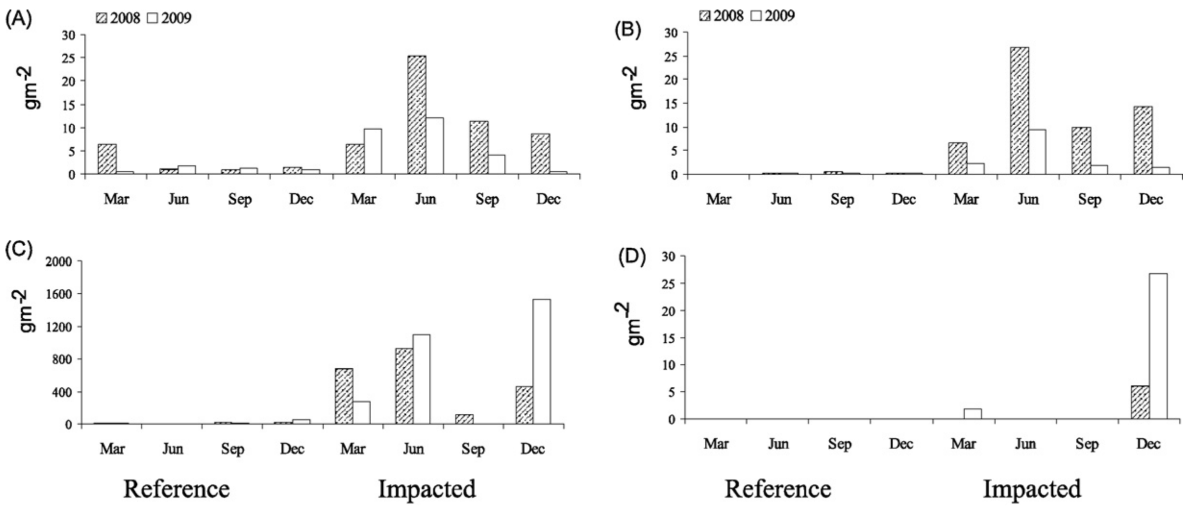

Fig. 3. Temporal and spatial variation of biomass of the groups used the calculated Eco-Exergy index for reference sites and impacted sites: (A) Diptera, (B) Annelida, (C) Gastropoda and (D) Bivalve.

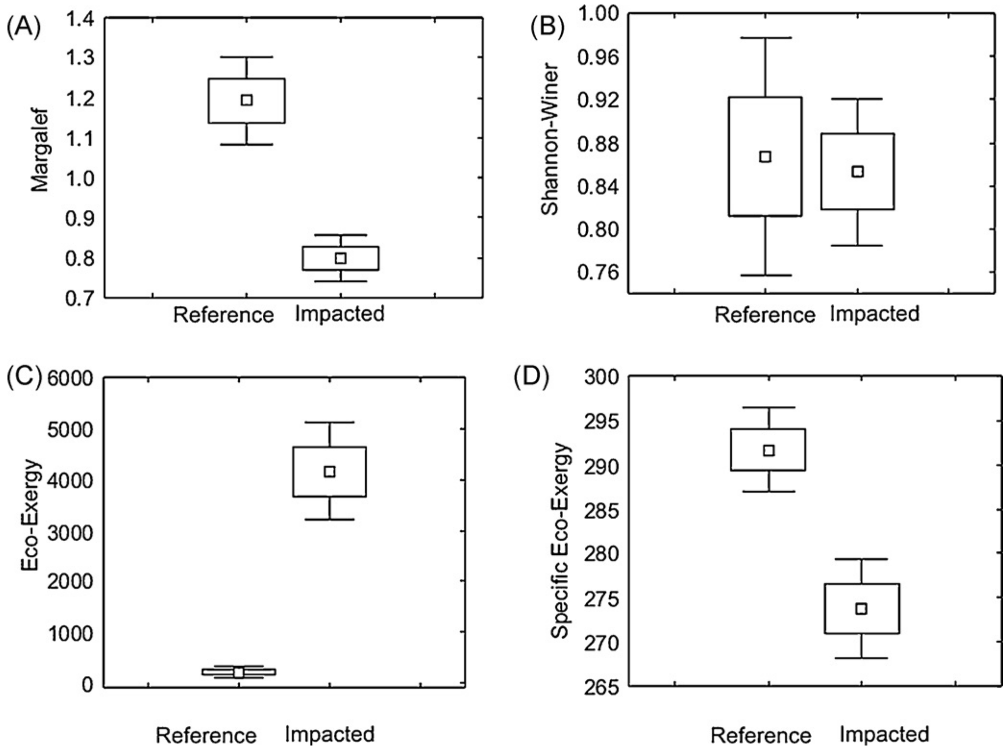

Fig. 4. Variation of the applied indices in the reference sites and impacted sites in two years: (A) Margalef index, (B) Shannon–Wiener index, (C) Eco-Exergy, (D) and Specifc Eco-Exergy.

Table 3
Mean values (±SD) Margalef, Shannon–Whiner, Eco-Exergy and Specific Eco-Exergy index, for reference sites and impacted sites in three reservoir in Brazil.

Index	Reference sites	Impacted sites
Margalef	1.16 ± 0.59	0.76 ± 0.58
Shannon–Wiener (Bits/ind)	0.86 ± 0.82	0.84 ± 0.76
Eco-Exergy (kJ m^{-2})	7541 ± 3891	92,153 ± 192
Specific Eco-Exergy (kJ g^{-1})	290 ± ±39	272 ± 67

values for all taxonomic groups occurred at impacted sites for both sampling years (Fig. 3). Gastropoda was the taxonomic group that contributed the most to total biomass, at impacted sites, due to the presence of *M. tuberculatus*, an exotic species. The total biomass of *M. tuberculatus* attained maxima of 5484.55 g m^{-2} at impacted sites, and 140.20 g m^{-2} at reference sites. Annelida (Oligochaeta and Hirudinea) biomass was also much higher at impacted sites than at reference sites (63.96 g m^{-2} and 1.11 g m^{-2}, respectively), and a similar pattern was observed for Diptera.

3.2. Eco-Exergy, Specific Eco-Exergy, and diversity measures performance

Results regarding the capability of the selected indicators to capture differences between reference sites and the impacted ones are given in Fig. 4 and Table 3.

The Margalef index (Fig. 4A; Table 3) (Pseudo $F_{2.719} = 24.50$, $p = 0.001$) showed significant differences between sites, with clearly higher values at reference sites. Eco-Exergy presented significantly higher values in stations located in impacted reservoirs (Fig. 4C; Table 3) (Pseudo $F_{2.719} = 29.82$, $p = 0.001$), while Specific Eco-Exergy and Shannon–Wiener presented no statistically significant differences between reference and impacted sites (Fig. 4D; Table 3 and Fig. 4B; Table 3), (Pseudo $F_{2.719} = 6.57$, $p = 0.92$; Pseudo $F_{2.719} = 4.76$, $p = 0.83$, respectively).

The analysis of the values of the four tested indicators and environmental parameters usually associated with impacts showed, in some cases, significant but not clearly interpretable correlations:

The Margalef index showed significant negative correlations with conductivity and TDS, usually associated with poor quality waters (Table 4).

Eco-Exergy showed a significant positive correlation with conductivity and pH, Specific Eco-Exergy was positively correlated with water transparency and depth, and negatively correlated with conductivity and TN.

4. Discussion

The occurrence of high values of biomass of a reduced number of species at impacted sites found in the present study has also been observed in other tropical eutrophic reservoirs in Brazil. This is probably a result of high secondary productivity due to excess availability of organic matter (Takahashi et al., 2008). The same biomass distribution pattern as a function of eutrophication has also been detected in lakes (Callisto et al., 2002).

Chironomidae constitute the dominant benthic group in reservoirs, attaining particularly higher biomasses at eutrophic sites, or sites impacted by other types of pollution (Vos et al., 2000). This is due to the overall tolerance of this group to strong variations in climatic, hydrological, and limnological conditions (Jorcin and Nogueira, 2008).

Vos et al. (2000) showed that detritus with high nitrogen, phosphorous, carbon, and fatty acid contents is usually associated with the presence of larger Chironomidae larvae and is therefore a controlling factor of Chironomidae population composition, abundance, and biomass. Further, increased Chironomidae biomasses appear to be associated with fine sediments with a high organic matter content that can be used for building tubes to provide refuge from predators, minimising their visibility resulting from their red

Table 4
Pearson's correlation coefficients between the different indices and the different environmental variable samples in 3 different reservoirs, Brazil.

	Margalef	Shannon–Winer	Eco-Exergy	Specific Eco-Exergy
Margalef	1.000			
Shannon–Wiener	0.673	1.000		
Eco-Exergy	−0.280	−0.036	1.000	
Specific Eco-Exergy	0.115	−0.140	−0.116	1.000
Depth (m)	0.125	−0.137	−0.334	0.177
Secchi (m)	0.386	−0.134	−0.373	0.425*
pH	−0.360	−0.076	0.458*	−0.077
Conductivity	−0.443*	0.090	0.466*	−0.441*
TDS (mg L^{-1})	−0.525*	−0.005	0.379	−0.267
Turbidity	−0.331	0.013	0.248	−0.369
O_2 (m/L)	0.389	0.107	0.001	−0.014
Chlorophyll *a* ($\mu g\,L^{-1}$)	−0.322	−0.014	0.300	−0.120
Total nitrogen (mg L^{-1})	−0.340	0.123	0.374	−0.446*
Total phosphorus ($\mu g\,L^{-1}$)	−0.187	0.104	0.057	−0.293
Orthophosphates ($\mu g\,L^{-1}$)	−0.054	0.099	−0.064	−0.223

* $r > 0.4$.

colour (Butler and Anderson, 1990; Helson et al., 2006; Takahashi et al., 2008).

Gastropoda can be easily transported, is adaptable to all kinds of substrates and can form abundant populations with high biomass in eutrophic environments (Livishts and Fishelson, 1983). For instance, we found very high biomasses of *M. tuberculatus*, an "*r*-strategist" gastropod species with parthenogenetic reproduction and potential to maintain high population densities for long periods (Silva et al., 2010). *M. tuberculatus* has a fast growth rate during the juvenile phase, reaching sexual maturity and near maximum size within 90–279 days (Dudgeon, 1986; Livishts and Fishelson, 1983; Elkarmi and Ismail, 2007). In adverse conditions (low temperatures or lack of food) *M. tuberculatus* can slow down growth or even aestivate for long periods (Livishts and Fishelson, 1983; Supian and Ikhwanuddin, 2002), which may explain the low population densities and biomasses in oligotrophic environments.

This briefly summarises the characteristics of the benthic compartment observed in the present study, as well as in other tropical reservoirs, based on which diversity measures, Eco-Exergy, and Specific Eco-Exergy were estimated.

Values of the Margalef index behaved as one could expect against environmental pressures, with significantly higher values at reference sites and lower values at the disturbed sites (eutrophication in this case). The Margalef index showed significant and easily interpretable correlations with some of the environmental parameters usually associated to increasing eutrophication.

Eco-Exergy response was in accordance with what we should expect theoretically. Eco-Exergy values were significantly higher at more disturbed (eutrophic) sites and lower at reference sites, which can be interpreted as a response to eutrophication, namely higher biomass in association with increased concentrations of nutrients (Jørgensen et al., 1995). Thus Eco-Exergy increases as a function of variation in biomass (see Eq. (1)).

Specific Eco-Exergy showed higher values at reference sites and lower values at impacted sites. Specific Eco-Exergy normally exhibits a maximum at low levels of eutrophication, since oligotrophic lakes and reservoirs have low biomasses due to low nutrient concentrations. However, such systems have less biomass as detritus ($\beta_i = 1$), and therefore relatively more biomass of invertebrates with higher β_i values. Although differences were not statistically significant, we should expect a higher average β_i value, which is expressed in higher Specific Eco-Exergy values (Jørgensen et al., 1995; Jørgensen, 2010).

Thus, Specific Eco-Exergy was higher at reference sites due to higher organism's β_i values.

Our results were similar to those obtained in Jørgensen et al.'s (1995) study on 15 lakes where he found clear correlations between indicators and ecological eutrophication states. In our case, although Specific Eco-Exergy did not show significant statistical differences between reference and impacted sites, values were higher in reference sites. Specific Eco-Exergy is computed by dividing total Eco-Exergy by total biomass (see Eq. (3)), thus when there is less biomass there will be a higher average β value. In our case, although usually Mollusca are only moderately tolerant to pollution, occurring in less disturbed areas (Xu et al., 2011), alien mollusc populations (*M. tuberculatus*) biomasses were higher at the most impacted sites.

According to Odum (1988), ecosystem response to increasing environmental stress include a reduction in food chains, decrease in diversity, an increase in the proportion of "r-strategists", and a reduction in organism size in order to improve resource use efficiency. Our results agree with this theory, showing a reduction in diversity and an increase of "r-strategists" (which generally have lower β_i values) but although there was an increase in population density there was no reduction in organisms size resulting in a significant increase in biomass at impacted sites.

5. Conclusions

Our results support the findings of previous studies namely that when applied as ecological indicators of ecosystem condition/status, Eco-Exergy and Specific Eco-Exergy are effective in assessing reservoir water quality, but that they should be used together with other indices.

Additionally, increased eutrophication implies an increase in Eco-Exergy but a decrease in Specific Eco-Exergy; therefore these two thermodynamic oriented indicators should always be used complementarily.

As observed in previous studies, there is a need to improve the accuracy of *Bi* values, to better express biomass information content (information embodied in the genome) at more discrete taxonomic levels although higher discrimination of *Bi* values must not disregard limits of practicability in applying thermodynamic oriented holistic ecological indicators as tools in environmental quality assessment.

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