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Effects of eutrophication and exotic crayfish on health status of two Spanish lakes: a joint application of ecological indicators

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ABSTRACT

Lake Sentiz and Lake Chozas are two small water bodies in the Province of León (NW Spain). The former is mesotrophic and the latter went from oligotrophic to turbid in 1997, due to introduction of an invasive allochthonous crayfish *Procambarus clarkii* (Rodríguez et al., 2003, 2005; Marchi et al., 2011a,b). We set out to study health status of the two ecosystems by the joint use of different but correlated ecological indicators, supplementing the values obtained by monitoring campaigns. We examine three scenarios: (1) Lake Sentiz, (2) Lake Chozas before and (3) Lake Chozas after the biological invasion. We evaluate eco-exergy, emergy and eco-exergy–empower ratio, three holistic ecological indicators based on the thermodynamics of far-from-equilibrium systems. When structural changes take place in ecosystems it is recommended to apply holistic thermodynamic indicators as presented in Jørgensen et al. (2010a,b). We propose their joint application for a complete overview of the monetary value of natural capital, because they provide information added to statistical analysis and direct measurement. The aim is to determine which of these indicators best represents the effects of eutrophication and perturbations caused by alien species in the two freshwater systems. The eco-exergy–empower ratio gives the best results, since it clearly indicates lake efficiency in transforming direct and indirect solar energy inputs into organization. The eco-exergy (work capacity) results are used to estimate ecosystem services and quantify the economic value of lake natural capital. Calculation of ecosystem services on an eco-exergy basis provides good indications of monetary gains or losses possible in perturbed systems, including eutrophic or invaded ecosystems. This is not surprising, because work capacities include all possible services offered by ecosystems, not only the services actually used by humans. Eco-exergy and the eco-exergy–empower ratio can be guidelines for the calculation of ecosystem services, although they give only a partial indication of the environmental costs and benefits of a given level of information. The present results suggest political and economic considerations and solutions, and are a useful example for organisations involved in environmental management of pollution and biological invasions by exotic species.

1. Introduction

The damage caused by alien species all over the world has been estimated at more than $1400 trillion or 5% of the world economy (Stanley and Muir, 2010), while economic losses associated with climate change reach 5% of annual gross world product (Stern, 2006). Recent data indicates that the increase in mean annual temperature aggravates the already serious effects of invasive species, creating a destructive spiral of worsening effects, in terms of loss of biodiversity and economic value (Sachs et al., 2009; Occhipinti-Ambrogi and Savini, 2003). Moreover, eutrophication of aquatic systems lowers welfare, since it significantly affects human use of water resources (Rast and Holland, 1988).

To understand these problems we analyze the data of two lakes, monitored from 1984 to 2001. The two systems are Lake Sentiz and Lake Chozas, both small water bodies in León (NW Spain). The lakes have many similar characteristics, with the difference that Lake Chozas was invaded by the Louisiana red swamp crayfish, *Procambarus clarkii* (Girard, 1852), in 1997. The crayfish was introduced into Spain in 1974 for aquaculture (Gutiérrez-Yurrita and Montes, 1999) and is recognized for its high invasive capacity in Mediterranean freshwater ecosystems. Indeed, its flexibility to

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abiotic changes and the damage it causes to indigenous communities have earned it the name “killer” crayfish (Gherardi and Holdich, 1999).

Lake Sentiz, a shallow and mesotrophic water body (4.51 ha; volume 30,400 m^3; mean depth 0.75 m), is analyzed as control lake by virtue of the absence of exotic crayfish (first scenario). Lake Chozas, a similar ecosystem (5.37 ha; volume 17,551 m^3; maximum depth 1.8 m) in the same district, is studied before and after 1997, the year of the accidental crayfish invasion (second and third scenario, respectively). The alien crustacean feeds on most underwater vegetation, causing an increase in nutrients and triggering mechanisms promoting water turbidity. For this reason, Chozas Lake saw the breakdown of its ecological equilibria, going from oligotrophic to eutrophic. As confirmed by field observations (Rodríguez et al., 2003, 2005) and models (Marchi et al., 2011a,b), biodiversity was lost, biogeochemical cycles were altered and the food web was simplified.

To highlight the variations in the ecological complexity of Lake Chozas after the biological invasion, we apply three systemic ecological indicators able to, approximately, estimate the health status of the two Spanish lakes by quantifying how far they are from thermodynamic equilibrium:

1. eco-exergy, the thermodynamic distance of an ecosystem from equilibrium with the surrounding environment (Jørgensen, 1982);
2. emergy, an indicator of the flow of natural resources necessary to sustain system complexity, expressed in solar energy equivalent (Odum, 1996);
3. the eco-exergy–empower ratio, or system efficiency in converting the energy cost of available inputs, expressed in solar energy equivalent, into ecosystem organization (Bastianoni et al., 2006).

The joint use of different, but related, ecological indicators can provide quite realistic information about environmental health, to supplement the values obtained by monitoring campaigns (Jørgensen et al., 2007). The aim of this study is to determine variations in the biological and chemical information embodied in the two ecosystems, quantifying which of the three indicators best represents the effects of eutrophication and loss of biodiversity, caused by alien species.

Costanza et al. (1997) calculate and aggregate the value of all services that ecosystems provide to humans: purification of air and water, recycling, recreational services and natural resources, such as timber, fish and drinking water. Despite this, in the present study, we estimate the ecosystem services provided by the two lakes on eco-exergy basis (work capacity), as in Jørgensen (2010a). Applying eco-exergy, all major elements of the system are considered, not only the monetary flows from exploitation of good and services needed for human welfare. The results of the three scenarios are compared to obtain an overview of the monetary value of services of lakes Chozas and Sentiz. The present case study is an example of the assessment of environmental effects of eutrophication and invasions of exotic species in freshwater ecosystems.

Such considerations could be useful for formulating political and economic solutions to environmental problems.

2. Material and methods

2.1. Eco-exergy

Eco-exergy measures the sustainability of ecosystems (see Jørgensen, 2006, 2010b; Jørgensen et al., 2010b) as it expresses the work capacity indispensable for all the activities involving elements of the system. It is defined as the amount of work that a system can perform when brought to thermodynamic equilibrium with its environment (Jørgensen, 1992a,b, 1997b, 1999a). Maximum eco-exergy storage is based on the hypothesis that an ecosystem tends to move as far as possible from thermodynamic equilibrium. Total eco-exergy can be found by summing the contributions of all components. Since direct measurement of the eco-exergy of an ecosystem is impossible, Jørgensen and Mejer (1979) proposed that once the major components of an ecosystem are known, eco-exergy can be computed by Eq. (1):

$$\text{Exergy} = RT\sum_i \left[C_i \ln \left(\frac{C_i}{C_i^{eq}} \right) + (C_i - C_i^{eq}) \right] \quad (1)$$

where R is the gas constant, T absolute temperature, C_i the corresponding concentration of the ith component in the system and C_i^{eq} the corresponding concentration of this component at thermodynamic equilibrium.

Jørgensen (1997b) further proposed a relative eco-exergy index, Ex, approximated by Eq. (2):

$$Ex = \sum_{i=1}^{n} \beta_i \cdot C_i \quad (2)$$

where β_i is the weighting factor of the ith component in the system and C_i is the corresponding concentration of this component. The eco-exergy calculation counts the chemical energy in organic matter as well as the (minimum) genetic information embodied in the living organisms. The latter contribution is measured by the extremely small probability of forming living components, for instance algae, zooplankton, fish, mammals, etc., spontaneously from inorganic matter (Jørgensen et al., 2010a). Weighting factors defined as the eco-exergy content with respect to detritus are quality factors reflecting the evolutionary rank of the various groups of organisms and their contribution to eco-exergy by virtue of their information content, which is reflected in the computation (Jørgensen, 2008a,b). We normalized β-values to detritus ($i = 1$ and $\beta = 1$ for detritus). Since 1 g of detritus contains 18.7 kJ, multiplying eco-exergy by 18.7 according to Eq. (2), we obtain eco-exergy in kJ/m^3 when C_i is in g/m^3.

Eq. (2) is applied to our three cases, using β-values in Jørgensen et al. (2005a,b) and biomass concentrations recorded in the two lakes in various monitoring campaigns from 1984 to 2001. Table 1 shows the concentration of biomass in the two lakes for the three scenarios and the β-values related to every taxonomic group considered in the evaluation. Biomass concentration includes most taxonomic groups present in the lakes and is expressed in mg/m^3. The functional groups considered are phytoplankton, zooplankton, submerged vegetation, benthic and epiphytic macroinvertebrates, fish, birds and detritus, as well as *P. clarkii* in Lake Chozas after its introduction. We use the plant biomass sampling data and species catalogue in Fernández-Aláez et al. (1984, 1999, 2002) and Rodríguez et al. (2005, 2007). The biomass of phytoplankton is determined from the biovolume of single species expressed in mm^3/l, and zooplankton biomass is quantified from the concentrations of specimens by species. Sampling of benthic macroinvertebrate and macroinvertebrates associated with vegetation is carried out in transects with sampling nets and a Kornijów sampler, as in García-Criado et al. (2005) and Rodríguez et al. (2005). Fish density is evaluated in both lakes between 2000 and 2001 by the capture-marking-recapture method, also measuring the weight of individuals. The number of birds is determined from sightings and biomass is calculated from the mean body weight of coots and wild ducks (Ponton et al., 2006). The number of crayfish in Chozas after the invasion is estimated in Rodríguez et al. (2003), using a capture-marking-recapture method. The quantity of detritus in the water column and in sediment of the two ecosystems is