The variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lakes

Fu-Liu Xu\textsuperscript{a,}\textsuperscript{*}, Jun-Jun Wang\textsuperscript{a}, Bin Chen\textsuperscript{b}, Ning Qin\textsuperscript{a}, Wen-Jing Wu\textsuperscript{a}, Wei He\textsuperscript{a}, Qi-Shuang He\textsuperscript{a}, Yin Wang\textsuperscript{a}

\textsuperscript{a} College of Urban & Environmental Sciences, MOE Laboratory for Earth Surface Process, Peking University, Beijing 100871, China
\textsuperscript{b} School of Environment, Beijing Normal University, Beijing 100875, China

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Abstract
Taking 29 Chinese lakes and 29 Italian lakes as two separate case studies, the paper presented the variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lakes. The exergies (Ex) and structural exergies (Exst) were calculated based on phytoplankton biomass (BA) and zooplankton biomass (BZ). A trophic state index (TSI) scaling from 0 to 100 was developed to classify trophic status for Chinese and Italian lakes based on three indicators, chlorophyll-a concentration (Chl-a, in mg/m\textsuperscript{3}), total phosphorus (TP in mg/m\textsuperscript{3}) and transparency in Secchi disk depth (SD in m). The relationships between TSI and Ex, Exst, total biomass, BZ/BA ratios were analyzed. The following results were obtained: (1) with the increase of TSI in Chinese and Italian lakes, there is an increasing trend for Ex, and a decreasing trend for Exst, generally. The obvious negative correlations exist between TSI and Exst, at the significant level of 0.01 for Italian lakes, and 0.05 for Chinese lakes. The obvious positive correlations exist between TSI and Ex, at the significant level of 0.01 for Chinese lakes, and for Italian lakes in Spring, Autumn and the all-year. (2) The structural exergy is more dependent on the ratio of phytoplankton biomass to zooplankton biomass (BZ/BA) than the exergy, and the exergy is more dependent on total biomass than the structural exergy. (3) The phytoplankton biomass (BA) and zooplankton biomass (BZ) are increased with the increasing TSI in Chinese and Italian lakes, and phytoplankton biomass (BA) increases more rapidly then zooplankton biomass (BZ) does. This results in the definite decrease of BZ/BA ratio with the increasing trophic status index. Such changes of BA, BZ and BZ/BA ratio could explain successfully the variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lakes. From the two separate case studies of Chinese lakes and Italian lakes, it could be concluded that exergy and structural exergy are feasible to serve as the system-level ecological indicators to give appropriate information on the trophic status of different lakes.

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1. Introduction

Since the 1960s, a number of attempts to evaluate quantitatively the trophic status of lakes applying single-variable trophic indices and multi-parameter approaches have been made (Xu, 2008). The relatively simple single-variable trophic state criteria represent only subjective judgments, and may be limited spatially (Therriault and Platt, 1978; Reckhow and Chapra, 1983; Powell et al., 1989; Boyle et al., 1990; Danilov and Ekelund, 1999). Comparatively, multi-parameter approaches are more robust than single-variable trophic indices, because of the multidimensional nature of the eutrophication phenomenon in water bodies (Shannon and Brezonik, 1972; Carlson, 1977; Cruzado, 1987; Xu, 1997, 2008). Further, it would be difficult to describe the continuous changes of a lake's trophic state or to study quantitatively the eutrophication mechanism using such descriptive classifications for lake trophic states as oligotrophic, mesotrophic and eutrophic (Shannon and Brezonik, 1972; Carlson, 1977; Yoshimi, 1987; Xu, 1997, 2008). In order to characterize the multidimensional nature of eutrophication and to eliminate effectively the subjective labeling associated with the use of oligotrophic, mesotrophic and eutrophic states as indicators, the trophic state indices (TSI), especially the Carlson-type TSIs, have been proposed by some researchers (e.g. Carlson, 1977; Walker, 1979; Porcella et al., 1980; Swanson, 1998; Aizaki et al., 1981; Jin et al., 1990; Xu, 1997, 2008). These TSIs offer a 0–100 scale providing continuous numerical classes of lake trophic states and a rigorous foundation for quantitative studies of the mechanisms behind eutrophication. TSI method has been proved as the most suitable and acceptable method for trophic classifications of lakes (Xu, 1997, 2008).

Exergy, a thermodynamic concept, was first applied to ecology in the late 1970s (Jørgensen and Mejer, 1977, 1979). Owing to a
good theoretical basis in thermodynamics, close relation to information theory, rather high correlation with other goal functions, and relative easiness of computation (Jørgensen, 1994), exergy has been widely used as a goal function in ecological models to account for changes in the composition of organisms (e.g. Jørgensen, 1986, 1988, 1992a; Jørgensen and de Bernardi, 1997, 1998; Nielsen, 1994, 1995; Zhang et al., 2003, 2004; Gurkan et al., 2006), and as a holistic indicator for assessing the eco-health of lake ecosystems (e.g. Jørgensen, 1995a; Xu, 1996; Xu et al., 1999a,b, 2001a,b) and marine ecosystems (e.g. Marques et al., 1997; Jørgensen, 2000; Fonseca et al., 2002). Moreover, as a system-level indicator, exergy has been applied to describe quantitatively the ecological conditions (e.g. Jørgensen, 1995b) and the trophic status of lakes (e.g. Xu, 1997; Ludovisi and Poletti, 1999, 2003), as well as the influence of toxic pollutants on lake ecosystems (e.g. Silow, 1999; Xu et al., 2002). However, the contrary results have been concluded in some studies on lake eutrophication and exergy changes. Along increasing trophic status, exergies increase in some studies (e.g. Salomonsen, 1992; Jørgensen, 1995b), and decrease in other studies (e.g. Xu, 1997; Ludovisi and Poletti, 1999). It is, therefore, necessary to explore the relationships between trophic status and exergy changes using more lake data.

The objectives of present research, taking 29 Chinese lakes and 29 Italian lakes as two separate case studies, are: (1) to develop a TSI scaling from 0 to 100 for describing trophic statuses of Chinese and Italian lakes, respectively; (2) to calculate exergies and structural exergies of Chinese and Italian lakes respectively; (3) to analyze the variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lakes; and (4) to discuss the relationships between exergies, structural exergies and lake ecological structure with changing trophic status of lake ecosystems.

2. Methods

2.1. Study areas

In order to meet the major purpose to analyze the variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lakes, the lakes with different trophic states from the oligotrophic to the eutrophic have to be selected for the study. Also, the lakes should be phytoplankton-responded to eutrophic states expressed by high concentration of total phosphorus (TP). This means that the lakes are dominated by phytoplankton in the case of eutrophic states. The macrophyte-responded lakes with eutrophic states are not selected for the study, since the macrophytes domination is quite different in biological structure to the phytoplankton domination in eutrophic lakes. However, it should be pointed out that the lakes with oligotrophic states expressed by low TP concentration might be often dominated by macrophytes, especially submerged vegetation. Such lakes with macrophytes domination in the case of oligotrophic states could also be regarded as the phytoplankton-responded lake. In shallow lakes, the macrophytes domination at oligotrophic state and the phytoplankton domination at eutrophic state are two different stable states that may shift catastrophically following the changes of nutrient loading (Scheffer, 1990; Scheffer et al., 2001).

Study areas include 29 Chinese lakes (Fig. 1) and 29 Italian lakes (Fig. 2, Table 1). It can be seen from Fig. 1 that 29 Chinese lakes distribute in different regions in China. Their surface areas range from 3.7 km² (Lake Xuanwu-Hu) to 4200 km² (Lake Qinghai-Hu), with trophic status varying from oligotrophic (e.g. Lake Qinghai-Hu) to extremely hypertrophic (e.g. Lake Luhua-Hu, Lake Dongshan-Hu and Lake Dong-Hu) (see Jin et al., 1990 for details). 29 Italian lakes are located in the Sicily Island. About 70% lakes are used for irrigation; while 30% lakes are used for drinking. Their surface


\[ \text{Ex} = R \times T \times \sum_{i=0}^{n} C_i \times \ln \left( \frac{C_i}{C_i^0} \right) \]  

(1)
where \( R \) is the gas constant, \( T \) is the absolute temperature, \( C_i \) is the concentration in the ecosystem of component \( i \), index 0 indicates the inorganic components of the considered element and \( C_i^{eq} \) is the corresponding concentration of component \( i \) at thermodynamic equilibrium.

The problem related to the assessment of \( C_i^{eq} \) has been discussed and a possible solution proposed in Jørgensen et al. (1995). According to classical thermodynamics and probability, Jørgensen et al. (1995) deduced step by step the following equation for the exergy calculation of ecosystem components:

\[
\text{Ex} = \left[ \mu_i - \mu_i^{eq} \right] \times \sum_{i=1}^{N} \left( \frac{C_i}{C_i^{eq}} \right) - \sum_{i=2}^{N} C_i \times \ln |P_{i,a}| \tag{2}
\]

where \( \mu \) indicates the chemical potential and index 1 is for dead organic matter. The difference \( \mu_i - \mu_i^{eq} \) is known for organic matter, e.g., detritus, which is a mixture of carbohydrates, fats and proteins. \( P_{i,a} \) is the probability for producing the considered component \( i \) at thermodynamic equilibrium, and it can be found from the number of permutations among which the characteristic amino acid sequence for the considered organism. Living organisms use 20 different amino acids and each gene determines the sequence of on average 700 amino acids. So, \( P_{i,a} \) can be calculated by the following equation:

\[
P_{i,a} = 20^{-700} \times g \tag{3}
\]

where \( g \) is the number of genes (see Table 2 and Jørgensen et al., 1995 for details).

Eqs (2) and (3) can be applied to calculate exergy for important ecosystem components according to the number of genes stored in organisms (see Table 2 and Jørgensen et al., 1995 for details). If we consider only detritus, we know that the free energy released per g of organic matter is about 18.5 kJ/g. It is 8.4 J/mol and the average molecular weight of detritus is assumed to be 100,000 (Jørgensen et al., 1995). The following contribution of exergy by detritus per liter of water can be gotten, when the unit g/l for the concentration is used (Jørgensen et al., 1995):

\[
\text{Ex}_{\text{detritus}} = 18.5 \times C_i \text{kJ/l} \quad \text{or} \quad \frac{\text{Ex}_{\text{detritus}}}{RT} = 7.34 \times 10^5 \times C_i \text{g/l} \tag{4}
\]

A typical algae has about 850 genes. The contribution of exergy by algae per liter of water, using g/l as concentration unit would be:

\[
\frac{\text{Ex}_{\text{algae}}}{RT} = 7.34 \cdot 10^5 C_i - C_i \ln(20^{-700} \times 850) \approx 25.2 \cdot 10^5 \times C_i \text{g/l} \tag{5}
\]

Average number of genes for zooplankton is about 50,000. The contribution of exergy by zooplankton per liter of water, using g/l

\[
\begin{table}[h]
\centering
\caption{Basic limnological characteristics for Italian lakes.}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Lake name & Cond. (mS/cm) & TP (\mu g/l) & N-NH4 (\mu g/l) & N-NO3 (\mu g/l) & SiO2 (mg/l) \\
\hline
Ancipa & 0.18 & 30.66 & 12 & 77 & 2.0 \\
Arancio & 0.72 & 166.65 & 667 & 676 & 4.8 \\
Biviere di Cesro & 0.08 & 46.02 & 31 & 76 & 0.6 \\
Biviere di Gela & 2.72 & 45.15 & 22 & 78 & 2.3 \\
Castello & 0.96 & 109.88 & 775 & 263 & 2.9 \\
Cimia & 2.15 & 40.57 & 199 & 803 & 3.4 \\
Dirillo & 0.53 & 60.54 & 60 & 514 & 4.1 \\
Disueri & 1.21 & 1093.43 & 684 & 2226 & 3.6 \\
Fanaco & 0.53 & 54.34 & 199 & 1143 & 3.3 \\
Gammauta & 0.49 & 183.07 & 154 & 446 & 2.7 \\
Garcia & 0.77 & 51.36 & 22 & 1165 & 3.6 \\
Gorgo & 4.51 & 80.87 & 33 & 65 & 6.1 \\
Guadalani & 0.42 & 38.89 & 111 & 459 & 0.3 \\
Nicoletti & 1.42 & 33.18 & 46 & 66 & 1.5 \\
Ogliastro & 2.72 & 40.87 & 173 & 1710 & 2.9 \\
Olivo & 0.91 & 38.00 & 71 & 69 & 1.6 \\
Pergusa & 33.65 & 87.97 & 788 & 157 & 1.6 \\
Piana degli Albanesi & 0.37 & 46.77 & 349 & 412 & 0.4 \\
Piano del Leone & 0.41 & 46.85 & 160 & 546 & 2.4 \\
Poma & 0.74 & 51.11 & 73 & 994 & 1.4 \\
Pozzillo & 1.13 & 49.38 & 91 & 355 & 1.6 \\
Prizzi & 0.46 & 52.99 & 86 & 503 & 2.5 \\
Rubino & 1.05 & 28.94 & 18 & 711 & 1.0 \\
San Giovanni & 1.49 & 80.56 & 658 & 283 & 2.7 \\
Santa Rosalia & 0.42 & 55.81 & 125 & 279 & 3.4 \\
Scanzano & 1.50 & 61.65 & 300 & 1283 & 2.3 \\
Soprano & 0.85 & 2962.96 & 7671 & 57 & 12.7 \\
Trinità & 1.86 & 83.24 & 26 & 417 & 3.8 \\
Vasca Ogliastro & 0.32 & 106.69 & 28 & 177 & 3.4 \\
Villarosa & 2.27 & 64.06 & 524 & 276 & 1.0 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{The approximate number of information genes and conversion factors for some organisms.}
\begin{tabular}{|c|c|c|}
\hline
Organisms & Average genes number & Weighting factors \(^a\) \( (W) \) \( (W) \) \\
\hline
Bacteria & 600 & 19.9 \times 10^5 & 2.7 \\
Algae & 850 & 25.2 \times 10^5 & 3.4 \\
Yeast & 2,000 & 49.3 \times 10^5 & 5.8 \\
Fungus & 3,000 & 70.3 \times 10^5 & 9.5 \\
Sponges & 9,000 & 196.1 \times 10^5 & 26.7 \\
Zooplankton & 50,000 & 1058.1 \times 10^5 & 144 \\
Worms & 100,000 & 2104.4 \times 10^5 & 287 \\
Fish & 120,000 & 2521.8 \times 10^5 & 344 \\
Mammals & 140,000 & 2943.2 \times 10^5 & 404 \\
\hline
\end{tabular}
\end{table}

\(^a\) Please see text for the meaning and calculation of two weighting factors; based on number of information genes and the exergy content of the organic matter in the various organisms, compared with the exergy contained in detritus has about 18 kJ exergy (see Jørgensen et al. (1995) for details).

\(^b\) When the unit g/l is used for concentration (see Eqs. (4)–(8)).

\(^c\) When the unit g detritus/l is used for concentration (see Eq.(9)).
Table 3
Relations between trophic status index (TSI) and exergy (Ex), structural exergy (Exst) in Chinese and Italian lakes.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Time</th>
<th>Relations</th>
<th>Person correlation coefficient</th>
<th>Significance test (2-tailed)</th>
<th>Number of lakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chinese lakes</td>
<td>Yearly average</td>
<td>TSI-Ex</td>
<td>0.681**</td>
<td>0.000</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-Exst</td>
<td>−0.414*</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>Italian lakes</td>
<td>Spring</td>
<td>TSI-Ex</td>
<td>0.664**</td>
<td>0.000</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-Exst</td>
<td>−0.617**</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>TSI-Ex</td>
<td>0.304</td>
<td>0.108</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-Exst</td>
<td>−0.473**</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>TSI-Ex</td>
<td>0.559**</td>
<td>0.002</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-Exst</td>
<td>−0.636**</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>TSI-Ex</td>
<td>0.288</td>
<td>0.130</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-Exst</td>
<td>−0.602**</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>All-year</td>
<td></td>
<td>TSI-Ex</td>
<td>0.360**</td>
<td>0.000</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-Exst</td>
<td>−0.563**</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

As concentration unit would be:

$$\text{Ex}_{\text{zooplankton}} = 7.34 \cdot 10^5 C_i - C_i \ln(20^{-700} \times 50000)$$

$$= 1055.8 \cdot 10^5 \times C_i \text{ g/l}$$ (6)

Average number of genes for fish is about 120,000. The contribution of exergy by fish per liter of water, using g/l as concentration unit would be:

$$\text{Ex}_{\text{fish}} = 7.34 \cdot 10^5 C_i - C_i \ln(20^{-700} \times 120000)$$

$$= 2523.8 \cdot 10^5 \times C_i \text{ g/l}$$ (7)

If a considered ecosystem consists of phytoplankton (P), zooplankton (Z), fish (F) and detritus (D), the exergy for this ecosystem can be calculated using above related values:

$$\text{Ex} = P \times (25.2 \cdot 10^5) + Z \times (1055.8 \cdot 10^5) + F \times (2523.8 \cdot 10^5)$$

$$+ (P + P + Z + F) \times (7.34 \cdot 10^5) \text{[g/l]}$$ (8)

The contributions from phytoplankton, zooplankton and fish to the exergy of the entire ecosystem are significant and far more than corresponding to the biomass. Note that the unit of Ex/RT is g/l. Exergy can always be found in Joules per liter, provided that the right units for R and T are used. Eq. (8) can be rewritten by converting g/l to g detritus/l by dividing by (7.34 \times 10^5):

$$\text{Ex} = P \times (3.4) + Z \times (144) + F \times (344) + (D) \text{[g detritus/l]}$$ (9)

Later, Jørgensen (1995a,b) presented a general equation for the calculation of exergy of an ecosystem:

$$\text{Ex} = R \times T \times \sum_{i=1}^{n} (C_i \times W_i)$$ (10)

where $C_i$ is the concentration of i-th organic component in the ecosystem using g/l or g detritus/l as unit, $W_i$ is the conversion factor of i-th organic component. For certain organisms, $W_i$ can be computed from the information stored in genes (see Table 3).

Structural exergy (Exst) can be calculated by following equation (Jørgensen, 1995a,b):

$$\text{Exst} = R \times T \times \sum_{i=1}^{n} \left( \frac{C_i}{C_j} \right) \times W_i$$ (11)

where $C_i$ is the total biomass concentration (the sum of all the $C_j$).

As can be seen from the equations, exergy is dominated by the contributions coming from information, originated from the genes of the organisms. The total exergy of an ecosystem cannot be calculated exactly, as we cannot measure the concentrations of all the components of an ecosystem, but we can calculate the contributions from the dominant components (Jørgensen et al., 1995). Compared with dominant organisms such as phytoplankton, zooplankton and fish, detritus with the lowest weighting factor can be neglected in the calculation of exergy and structural exergy (Jørgensen, 1995a,b; Xu, 1996, 1997; Marques et al., 1997; Ludovisi and Poletti, 1999, 2003; Xu et al., 2001a, 2002). According to data availability for Chinese and Italian lakes, phy...
toplankton and zooplankton are used to calculate exergy and structural exergy.

2.3. Calculation of trophic state index

The indicators for calculating TSI are composed of basic and additional indicators. Basic indicators have the consanguineous relationships to lake trophic status; while additional indicators have the less important relationships to lake trophic status. A lake trophic status can be evaluated mainly on the base of basic indicators; while, the classification by additional indicators can be considered as the remedies of results by basic indicators (Xu, 2008).

The concentrations of Chl-a (Chl-a) and phytoplankton biomass (BA) are two of the more obvious symptoms of eutrophication (Rast and Holland, 1988; Ryding and Rast, 1989; Cooke et al., 1993). The higher BA or Chl-a concentration in a lake is, the more trophic the lake trophic status is. Therefore, BA and Chl-a can service as two basic indicators. According to data availability for Italian and Chinese lakes, Chl-a (in mg/m³) is selected as a basic indicator; while total phosphorus (TP in mg/m³), transparency in Secchi disk depth (SD in m) are applied as additional indicators.

In order to quantitatively assess the trophic status of a lake ecosystem, a TSI with a scale from 0 to 100 was developed. The equation for TSI calculation is as follow:

\[
TSI = \sum_{i=1}^{n} W_i \cdot TSI_i
\]

where TSI is a synthetic trophic index, TSIᵢ is the ith trophic state index for the ith indicator, and Wᵢ is the weighting factor for the i-th indicator, n is the total number of assessment indicators. In the present study, the method of relation-weighting index (Jin et al., 1990) is used to determine the weighting factors for all indicators.

![Fig. 4. The variations of exergy along eutrophication gradients in Italian lakes.](image)
i.e. the relation ratios between the basic indicator and other additional indicators can be used to calculate the weighting factors for all indicators. The equation is as follows:

$$W_i = \frac{r_{i1}^2}{\sum_{i=1}^{n} r_{i1}^2}$$  \hspace{1cm} (13)

where $W_i$ is the weighting factor for the $i$-th indicator; $r_{i1}$ is the relation coefficient between the $i$-th indicator and the basic indicator; and $n$ is the total number of assessment indicators. According to data availability for Chinese lakes (Jin et al., 1990) and Italian lakes (Calvo et al., 1993), the statistic correlative coefficients of $(Chl-a)-(Chl-a)$, $(Chl-a)-TP$ and $(Chl-a)-SD$ for Italian lakes are computed as 1.0, 0.57 and $-0.50$, while that for Chinese lakes as 1.0, 0.84 and $-0.83$. Based on these statistic correlative coefficients between basic indicator $(Chl-a)$ and additional indicators (TP and SD), weighting factors for $Chl-a$, TP, SD can be calculated by equation (13) as 0.635, 0.206, 0.159 for Italian lakes, and 0.418, 0.293, 0.289 for Chinese lakes, respectively.

2.3.1. Calculating sub-TSIs for Italian lakes

There are two main steps to calculate sub-TSIs for all selected indicators. The first step is to calculate $TSI(Chl-a)$ for the basic indicator, $Chl-a$. The second step is to calculate $TSI(TP)$ and $TSI(SD)$, for the additional indicators, TP and SD, respectively. After the $TSI(Chl-a)$ for the basic indicator being obtained, the sub-TSIs including $TSI(TP)$ and $TSI(SD)$ for the additional indicators can be deduced according to the relationships between the basic indicator $(Chl-a)$ and the additional indicators (TP, SD).

For $TSI(Chl-a)$ calculation, it is assumed that, $TSI(Chl-a) = 0$ if $Chl-a$ is lowest, and that $TSI(Chl-a) = 100$ if $Chl-a$ is highest. Referring Carlson’s studies on TSI (Carlson, 1977), the relationship between trophic status and $Chl-a$ concentrations in a lake ecosystem can be described as logarithmic normal distribution. So, $TSI(Chl-a)$ can be calculated by the following equation:

$$TSI(Chl-a) = 100 \times \frac{\ln C_x - \ln C_{min}}{\ln C_{max} - \ln C_{min}}$$  \hspace{1cm} (14)

Fig. 5. The variations of structural exergy along eutrophication gradients in Italian lakes.
Table 4

<table>
<thead>
<tr>
<th>Lake</th>
<th>Time</th>
<th>Relations</th>
<th>Person correlation coefficient</th>
<th>Significance test (2-tailed)</th>
<th>Number of lakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chinese lakes</td>
<td>Yearly</td>
<td>Ex-TB</td>
<td>0.910**</td>
<td>0.000</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ex-BZ/BA</td>
<td>−0.017</td>
<td>0.931</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exst-TB</td>
<td>−0.158</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TSI-BZ/BA</td>
<td>0.872</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Italian lakes</td>
<td>Spring</td>
<td>Ex-TB</td>
<td>0.878</td>
<td>0.000</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ex-Ln (BZ/BA)</td>
<td>−0.125</td>
<td>0.517</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exst-TB</td>
<td>−0.437</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exst-Ln(BZ/BA)</td>
<td>0.989**</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>Ex-TB</td>
<td>0.189</td>
<td>0.326</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ex-Ln (BZ/BA)</td>
<td>0.211</td>
<td>0.272</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Exst-TB</td>
<td>−0.517</td>
<td>0.004</td>
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<tr>
<td></td>
<td></td>
<td>Exst-Ln(BZ/BA)</td>
<td>0.932**</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
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<td>Winter</td>
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<tr>
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<td>Exst-Ln(BZ/BA)</td>
<td>0.956**</td>
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* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

where TSI(Chl-a) is sub-TSI for basic indicator, Chl-a; $C_x$ is the measured Chl-a value; $C_{\text{min}}$ is the measured lowest Chl-a value; $C_{\text{max}}$ is the measured highest Chl-a value.

Eq. (5) can be predigested as the following format:

$$\text{TSI(Chl-a)} = 10(a + b \ln C_x)$$ (15)

where: $a$ and $b$ are constants, and they can be computed by the following equation:

$$\begin{align*}
a &= -10 \times \frac{\ln C_{\text{min}}}{\ln C_{\text{max}} - \ln C_{\text{min}}} \\
b &= 10 \times \frac{1}{\ln C_{\text{max}} - \ln C_{\text{min}}}
\end{align*}$$ (16)

According to the measured data for 29 Italian lakes (Calvo et al., 1993), $C_{\text{min}} = 0.12$ (mg/m³), $C_{\text{max}} = 560$ (mg/m³). Then, $a = 2.51$, $b = 1.18$. Thus, the expression for calculating TSI(Chl-a) for 29 Italian lakes can be obtained as follows:

$$\text{TSI(Chl-a)} = 10 \times (2.51 + 1.18 \times \ln(\text{Chl-a}))$$ (17)

It can be seen that the equation for calculating TSI(Chl-a) can be deduced from the Chl-a measured data by logarithmic expression for differences between extremum values.

The sub-TSIs for additional indicators, TSI(TP) and TSI(SD), can be calculated according to the relationships between the basic indicator (Chl-a) and the additional indicators (TP and SD). According to the measured data (Calvo et al., 1993), their relationships are as follows:

$$\ln(\text{Chl-a}) = -0.60 + 0.66 \times \ln(\text{TP}), (N = 87, R = 0.57, P < 0.0001)$$ (18)

$$\ln(\text{Chl-a}) = 2.16 - 1.14 \times \ln(\text{SD}), (N = 87, R = -0.50, P < 0.0001)$$ (19)
Thus, the equations for calculating TSI(TP) and TSI(SD) can be deduced from Eqs. (17)–(19):

\[
\text{TSI}(\text{TP}) = 10 \times (1.802 + 0.779 \times \ln(\text{TP}))
\]

\[
\text{TSI}(\text{SD}) = 10 \times (7.219 - 2.485 \times \ln(\text{SD}))
\]

2.3.2. Calculating sub-TSIs for Chinese lakes

According to the above-mentioned steps, the equations to calculate TSI(Chl-a), TSI(TP) and TSI(SD) for Chinese lakes are obtained as follows (Jin et al., 1990):

\[
\text{TSI}(\text{Chl-a}) = 10 \times (2.5 + 1.086 \times \ln(\text{Chl-a}))
\]

\[
\text{TSI}(\text{TP}) = 10 \times (9.436 + 1.624 \times \ln(\text{TP}))
\]

\[
\text{TSI}(\text{SD}) = 10 \times (5.118 - 2.117 \times \ln(\text{SD}))
\]

3. Results and discussions

3.1. The variations of exergies and structural exergies along eutrophication gradients

Exergy (Ex), structural exergy (Exst), and TSI have been computed by expressions (10), (11) and (12), (17), (20)-(21), (22)-(23), respectively, using the measured data for Italian and Chinese lakes. The variations of exergy and structural exergy along eutrophication gradients in Chinese and Italian lakes are presented in Figs. 3–5, respectively. The relations between TSI and Ex, Exst in Chinese and Italian lakes are tabulated in Table 3.

It can be seen from Fig. 3 that, with the increase of TSI in Chinese lakes, an increasing trend exists for Ex, and a decreasing trend for Exst, generally. The pearson correlation coefficients of a positive
relation between TSI and Ex, and a negative relation between TSI and Exst are 0.681 and −0.414, respectively. The correlations are significant at the 0.01 level between TSI and Ex, and at the 0.05 level between TSI and Exst (Table 3).

Fig. 4 shows that the Ex in Italian lakes increases in general with the increase of trophic state index in four seasons and the all-year around. The obvious positive correlations exist between TSI and Ex in Spring, Autumn and the all-year; and the correlations are all significant at the 0.01 level, with a pearson correlation coefficient of 0.664, 0.559 and 0.360 in Spring, Autumn and the all-year, respectively. However, the correlations between TSI and Ex in Summer and Winter are not significant (Table 3).

Fig. 5 reveals that the Exst in Italian lakes decreases in general with the increase of trophic state index in four seasons and the all-year around. The obvious negative correlations exist between TSI and Exst in four seasons and the all-year; and the correlations are all significant at the 0.01 level, with a pearson correlation coefficient of −0.617, −0.473, −0.636, −0.602 and −0.563 in Spring, Summer, Autumn, Winter and the all-year, respectively (Table 3).

It can be seen from above analyses that, in both Chinese lakes and Italian lakes, there is a significant positive correlation between TSI and Ex, and a significant negative correlation between TSI and Exst, i.e. Ex increases and Exst decreases with the increasing TSI.

3.2. Relations between Ex, Exst and total biomass (TB), BZ/BA ratio

The relations between Ex, Exst, and total biomass (TB), BZ/BA ratio in Chinese and Italian lakes are presented in Figs. 5–8, respec-
Fig. 6 shows that, in Chinese lakes, with the increase of total biomass, the exergy increases, and the structural exergy decrease in general. However, the opposite trends of exergy and structural exergy exist following the increase of BZ/BA ratios, i.e. the exergy decreases generally, and the structural exergy increases obviously (Fig. 7). Table 4 demonstrates that, for Chinese lakes, there are distinct positive correlations at the significant level of 0.01, with the pearson correlation coefficient of 0.910 between exergy (Ex) and total biomass (TB), and 0.878 between structural exergy (Exst) and the ratio of phytoplankton biomass to zooplankton biomass (BZ/BA), respectively.

Fig. 8 illustrates that, in Italian lakes, in general, with the increase of total biomass, the exergy shows an increase trend, and the structural exergy shows a decrease trend in four seasons and the all-year around. The pearson correlation coefficients between exergy and total biomass in Spring, Summer, Autumn, Winter and the all-year are 0.878, 0.189, 0.703, 0.373, and 0.399, respectively. The correlation is significant at the 0.01 level in Spring, Autumn and the all-year, and at the 0.05 level in Winter; however, not significant in Summer (Table 4). The pearson correlation coefficients between structural exergy and total biomass in Spring, Summer, Autumn, Winter and the all-year are −0.437, −0.517, −0.503, −0.466, and −0.361, respectively. The correlation is significant at the 0.01 level in Summer, Autumn and the all-year, and at the 0.05 level in Spring and Winter (Table 4).

Fig. 9 manifests that structural exergy in Italian lakes increases significantly with the increase of the ratio of phytoplankton biomass to zooplankton biomass in four seasons and the all-year around; however, there is no obvious trend for exergy. The pearson correlation coefficients between structural exergy and Ln(BZ/BA) in Spring, Summer, Autumn, Winter and the all-year are 0.989, 0.932, 0.975, 0.965, and 0.956, respectively. The correlation is significant at the 0.01 level in four seasons and the all-year (Table 4). However, the pearson correlation coefficients between exergy and Ln(BZ/BA) in Spring, Summer, Autumn, Winter and the all-year are −0.125, 0.211, −0.127, 0.389, and 0.164, respectively. The correlation is significant at the 0.05 level in Winter, and not significant in other seasons and the all-year (Table 4).

From above analysis on the change trends of exergy and structural exergy with the changes of total biomass and the ratio of phytoplankton biomass to zooplankton biomass, as well as on their correlation relationships in Chinese and Italian lakes, it can be seen that the structural exergy is more dependent on the ratio of phytoplankton biomass to zooplankton biomass (BZ/BA) than the exergy, and that the exergy is more dependent on total biomass than the structural exergy. These results are in accordance with the findings for the similar study on Lake Chaohu, a eutrophic Chinese lake (Xu, 1997), and also with the studies for 41 ecosystem models (see Christensen, 1994). Many model studies (Jørgensen, 1992b) and ecological studies (Weiderholm, 1980) show clearly that decreased trophic state means that there is higher probability of a better utilization of the available resources. A better utilization of all ecological niches is accompanied by a higher biodiversity. A development towards more complex organism (with more genes) will also result in a higher structural exergy (Jørgensen, 1995b).

3.3. The variations of BA, BZ and BZ/BA ratio along eutrophication gradients

According to the Eqs. (10) and (11), the exergies and structural exergies in lake ecosystems are depended on biological structure (Jørgensen, 1995b; Xu, 1997). In order to explain the variations of exergies and structural exergies in Chinese and Italian lakes, it is necessary to analyze the changes of BA, BZ and BZ/BA ratio along eutrophication gradients. The relationship between trophic status and phytoplankton biomass (BA), zooplankton biomass (BZ) and BZ/BA ratios in Chinese and Italian lakes are presented in Figs. 9–12, respectively. Their correlation coefficients and significances are tabulated in Table 5.

Fig. 10 reveals that phytoplankton biomass (BA) and zooplankton biomass (BZ) are increased with the increasing trophic status index (TSI) in Chinese lakes, and that phytoplankton biomass (BA) increases more rapidly then zooplankton biomass (BZ) does. This results in the decrease of BZ/BA ratio with the increasing trophic status index (Fig. 11). It can be seen from Table 5 that there are obvious positive correlations between TSI and BA, BZ at the significant level of 0.01 with pearson correlation coefficients of 0.852 and 0.669, respectively; while, there is an obvious negative correlation between TSI and BZ/BA ratio at significant level of the 0.05 with pearson correlation coefficient of −0.443.

Fig. 12 presents that, with the increasing TSI in Italian lakes in four seasons and the all-year around, phytoplankton biomass (BA) is increased significantly, and zooplankton biomass (BZ) is increased slightly. This causes the obvious decrease of BZ/BA ratio with the increasing trophic status index in four seasons and the all-year around (Fig. 13). Table 5 shows that there are obvious pos-
itive correlations between TSI and BA at the significant level of 0.01 with pearson correlation coefficients of 0.704, 0.768, 0.783, 0.707 and 0.641 in Spring, Summer, Autumn, Winter and the all-year, respectively. For the relationships between TSI and BZ, there are obvious positive correlations at the significant level of 0.01 with pearson correlation coefficients of 0.651, 0.489 and 0.276 in Spring, Autumn and the all-year, respectively; however, the correlation is not significant in Summer and Winter. The evident negative correlations at the significant level of 0.01 between TSI and BZ/BA ratio can also be found in Table 5, with pearson correlation coefficients of $-0.610$, $-0.640$, $-0.643$, $-0.598$ and $-0.614$ in Spring, Summer, Autumn, Winter and the all-year, respectively.

Above-mentioned changes of BA, BZ and BZ/BA ratio could explain the variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lakes. From the
information stored in the non-repetitive genes (see Jørgensen, 1995a,b), the number of information genes in zooplankton organisms is much higher than in phytoplankton organisms. Therefore, zooplankton has larger contributions to exergy than phytoplankton. If the biomass concentration of zooplankton changes as phytoplankton, exergy change caused by zooplankton biomass change is 42.35 times that caused by phytoplankton biomass change. Large exergy changes indicate thereby changes in ecosystem structure or in species composition. The most serious eutrophication is often accompanied by too much phytoplankton biomass (BA) (algal bloom) and less zooplankton biomass (BZ) as well as lower BZ/BA ratio, which may not cause obvious exergy changes, however results in definitely the decrease of structural exergy. This may be the reason why the structural exergy is more
sensitive to the trophic state and the changes of phytoplankton and zooplankton biomass (Xu, 1997).

Lake eutrophication ranks as one of the most pervasive water quality problems around the world, especially in China. An efficacious measure for eutrophication control is the application of bio-manipulation, such as growing macrophytes in eutrophic waters (Reed et al., 1988; Brix and Schierup, 1989). It was found by many researchers that macrophytes growing in eutrophic lakes could decrease phytoplankton biomass, increase Secchi Disc depth (Van Donk et al., 1989; Scheffer et al., 1994; Li and Yan, 1995) and stabilize the ecosystem by taking up nutrients, allelopathy and offering a shelter to zooplankton and piscivorous fish (Van Donk et al., 1989; Grimm, 1994; Moss et al., 1996). In our previous modeling study on the effects of macrophyte restoration to a typical eutrophied Chinese lake (the Lake Chaohu), two ecological models were developed (Xu et al., 1999b). The model 1 describes the nutrient-food web dynamics before the restoration of macrophytes, and the model 2 describes the food web after the restoration of macrophytes. Exergy, structural exergy, ratio of zooplankton to phytoplankton biomass and Secchi disc transparency are used as ecosystem indicators in the two models. The modeling results show that, compared with ecosystems without macrophytes, ecosystems with macrophytes have higher exergy, higher structural exergy, higher transparency and higher zooplankton/phytoplankton ratio, and that, an increase of initial macrophyte biomass from 2 to 5, 10 mg/m² causes an increase of exergy, structural exergy, transparency, fish biomass and zooplankton/phytoplankton ratio and a decrease in phytoplankton biomass. These imply that macrophyte restoration can significantly improve lake ecosystem health (see Xu et al., 1999b for details).

4. Conclusions

An analysis of the variations of exergies and structural exergies along eutrophication gradients in Chinese and Italian lake has been done. The findings reveal that it is feasible for exergy and structural exergy to serve as the system-level ecological indicators to give appropriate information on the trophic status of different lakes. The increasing exergy or decreasing structural exergy indicates the development of the lake ecosystem towards higher trophic status expressed by larger TSI, namely the increasing lake eutrophication. The changes of exergy or structural exergy can express the changes of ecosystem structure or ecosystem components, since different components are with different information genes.

Acknowledgements

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References

Jørgensen, S.E., 1988. Use of models as an experimental tool to show the structural changes are accompanied by increased exergy. Ecol. Model. 41, 117–126.

Table 5

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<th>Lake</th>
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* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.