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Characterizing Ecological Exergy as an Ecosystem Indicator in Streams Using a Self-Organizing Map

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Abstract – Benthic macroinvertebrate communities were collected at six different sampling sites in the Musucheon stream in Korea from July 2006 to July 2007, and ecological exergy values were calculated based on five different functional feeding groups (collector-gatherer, collector-filterer, predator, scrapper, and shredder) of benthic macroinvertebrates. Each sampling site was categorized to three stream types (perennial, intermittent and drought) based on the water flow condition. Exergy values were low at all study sites right after a heavy rain and relatively higher in the perennial stream type than in the intermittent or the drought stream type. Self-Organizing Map (SOM), unsupervised artificial neural network, was implemented to pattern spatial and temporal dynamics of ecological exergy of the study sites. SOM classified samples into four clusters. The classification reflected the effects of floods and droughts on benthic macroinvertebrate communities, and was mainly related with the stream types of the sampling sites. Exergy values of each functional feeding group also responded differently according to the different stream types. Finally, the results showed that exergy is an effective ecological indicator, and patterning changes of exergy using SOM is an effective way to evaluate target ecosystems.

Key words : ecological exergy, thermodynamics, ecological indicator, functional feeding groups, Self-organizing map (SOM), ecological assessment, stream types

INTRODUCTION

Disturbance has been regarded to be changes in ecosystem, community or population structure in response to relatively discrete events altering resources or physical environments (Sousa 1984; White and Pickett 1985), and has been also considered by many stream ecologists because of playing a central role in determining the structure of stream communities (e.g., Resh *et al.* 1988; Lake 1990; Fisher and Grimm 1991; Poff 1992; Giller 1996). Especially, floods, low flows and droughts are the major events which influence to lotic ecosystems as environmental conditions are changed.

Floods are usually pulse disturbances which are short-term and sharply delineated disturbances. They alter the abiotic environment of the floodplain and the channel and it subsequently leads to changes in the composition of the biota. During floods, benthic macroinvertebrates are influenced by water velocity (Hart *et al.* 1996; Holomuzki and Biggs 1999, 2000) and by physical scouring once bed movement is initiated (Newbury 1984; Cobb *et al.* 1992; Biggs *et al.* 2001). Generally, benthic macroinvertebrate communities respond to floods with reduction of the density and taxonomic richness (Gjerlov *et al.* 2003). However, floods should be considered through their magnitude, duration, frequency, predictability, the rate of change of their hydrograph, and the shear forces that they exert on sections of the streambed (Poff *et al.* 1997).

Meanwhile, the impacts of low flows on benthic macro-

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invertebrate communities were not studied as much as the impacts of floods (Boulton 2003; Wood and Armitage 2004). As flows decrease, there is generally a reduction in habitat space (Stanley *et al.* 1997; Brasher 2003) and often a reduction in invertebrate density (Cowx *et al.* 1984). Droughts are ramp disturbances where the strength of the disturbance steadily increases over time (Lake 2000). Thus, droughts cause the direct effects such as loss of water and indirect effects, generated by the loss of water volume, that affect water quality and resource availability that in turn affect the biota (Matthews 1998; Gasith and Resh 1999; Lake 2000; Boulton 2003; Matthews and Marsh-Matthews 2003).

Stable environment contains more species and more niches because a more stable environment involves a higher degree of organization and complexity of the food web (Margalef 1958). Consequently, according to environmental conditions, energy (quantity and quality) transfer processes will be affected, in addition to interactive changes among internal populations (e.g. trophic relations) (Søndergaard *et al.* 1990; Zhou *et al.* 1996; Marques *et al.* 1997; Jørgensen and Nielsen 1998). Several goal functions such as maximum power (Odum 1960), biomass (Straškraba 1980), exergy (Jørgensen 1982), ascendency (Ulanowicz 1986), and entropy (Schneider 1988; Aoki 1989) have been proposed to describe the direction of the ecosystem development. Among them, Jørgensen (1994) showed that exergy has a good theoretical basis in thermodynamics, a close relation to information theory and good correlation to other goal functions. Exergy is defined as the amount of work a system can perform when it is brought to thermodynamic equilibrium with its environment. The environment or reference state could be represented as the inorganic soup of the system without life (Jørgensen 1997). With this reference state the exergy measures directly the distance between the present state of the considered ecosystem and the thermodynamic equilibrium (Jørgensen 1992, 1997; Jørgensen *et al.* 1995). Therefore, exergy may be an effective measurement to represent the changes of accumulated energy through the effects of disturbances such as flooding, low water levels and drought of target ecosystems.

Exergy was used in many studies in order to evaluate ecological health: Alessandro and Antonio (2003) used exergy and specific exergy indices to show the development state of lake ecosystems, Oh and Silow (2003) showed that the structural exergy decreases in the polluted area comparing with the clean area on lake Baikal, Salas *et al.* (2006) compared exergy with other ecological indicators to assess ecological status, and Libralato *et al.* (2006) applied exergy as an ecosystem indicator to evaluate the recovery process of marine benthic communities. In Korea, exergy was used for ecological health assessment in Nakdong River (Kim and Jørgensen 1999; Kim 2000) and for evaluating temporal dynamics of benthic macroinvertebrate communities in Suyong River (Park *et al.* 2001).

The functional feeding groups (FFGs) of benthic macroinvertebrates which are guilds of the macroinvertebrate taxa and represent getting food using similar ways, regardless of taxonomic affinities, represent not only a variety of disturbances of their habitats but also a taxonomically heterogeneous assemblage of benthic fauna. In addition, their distributions respond mostly to disturbances changing the food base of the system because they reflect the food resources available in a given area (e.g., Hart and Robinson 1990). Therefore, FFGs have offered a means of assessing the disruption of ecosystem function (Resh and Jackson 1993; Barbour *et al.* 1999).

In recent years, artificial neural networks (ANNs) have been implemented in diverse aspects (Lek and Guegan 1999; Lek *et al.* 2005). Since Chon *et al.* (1996) applied the Self-Organizing Map (SOM) to ecological data in order to pattern benthic communities, the SOM has been widely used for extracting the complexity of ecological datasets (Park and Chon 2007). In addition, the SOM was used for patterning the changes of exergy of benthic macroinvertebrate communities in streams in time (Park *et al.* 2001) and in space (Park *et al.* 2006).

Through the adaptive learning property of the SOM, in this study, we characterized the changes of exergy as an ecological indicator based on functional feeding groups of benthic macroinvertebrates as responses of environmental changes in streams according to space and time.

MATERIALS AND METHODS

1. Ecological data

Benthic macroinvertebrates were monthly collected with the Surber sampler (30 cm × 30 cm, 300 μm mesh; APHA *et al.* 1985) at six different sampling sites of the Musucheon stream, in Mt. Dobong in Seoul, Korea (Fig. 1) from July

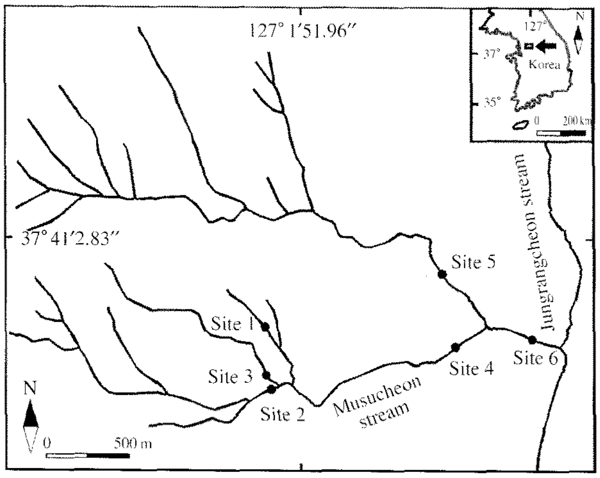

Fig. 1. Study sites in Musucheon stream, Seoul, Korea.

2006 to July 2007. On each sampling occasion, physical and chemical variables were measured at each sampling site. Water temperature (°C), dissolved oxygen (mg L^{-1}), conductivity (μm), pH were measured in situ with a multi-function meter (CX401®, Elemetron). Turbidity was measured with 2100P turbidimeter (StablCal®, Hach Company). Discharge was calculated by integrating medium depth (m), total width (m) and current velocity (m s^{-1}). Precipitation data in Seoul were obtained from the Korea Meteorological Administration.

Because the sampling sites located in the Bukhansan National Park, the sampling sites were relatively clean and not heavily disturbed by the chemical or domestic wastes. Therefore, the main disturbance factors in this area were natural disturbance events such as floods. There was a heavy rain at sampling area before the first sampling in July 2006, and it affected severely on the stream habitat. Water flow and discharge at the sampling sites were strongly influenced by precipitation. Based on the stream flow condition, therefore, the sampling sites were classified into three stream types: perennial stream type (water flowed consistently at sampling sites during study period. Sites 2 and 5), intermittent stream type (stream was not completely dried out, but partially dried out with pools. Sites 1 and 3), and drought stream type (sampling sites were in the downstream and completely dried out during the dry season. Sites 4 and 6).

Each species of benthic macroinvertebrates was categorized into one of five functional feeding groups (collector-gatherer (CG), collector-filterer (CF), predator (P), scraper (S), and shredder (SH)) according to its feeding type. At each sampling sites, additionally, community indices such as Shannon diversity index and species richness were calculated to evaluate the target community structures and ecosystems.

2. Exergy

Exergy for benthic macroinvertebrate communities can be estimated by means of the following equation:

$$Ex=\sum_{i=1}^{n}(w_i c_i)$$

where c_i is the concentration (in this case we used abundance data) of the ith state variable (i.e., species), w_i is the information stored in the ith state variable, and n is the number of variables. The weighting factors express the information that each species in benthic macroinvertebrates carries by the genes. For example, w_i for inorganic components is '0' due to no information, while w_i for organic matter (e.g. detritus) is '1'. The weighting factors are unfortunately only known roughly because our knowledge to the genes of species is very limited. Furthermore, it is not possible to calculate the exergy of an ecosystem due to its very high complexity. It should, therefore, be stressed that the calculations only give an exergy index for a model of an ecosystem. The use of the weighting factors is, however, robust, as it has been possible to apply this approach successfully in structurally dynamic modelings (see Jørgensen *et al.* 2000, 2002). In this study, data for benthic macroinvertebrate communities were used for calculating exergy. Based on Fonseca *et al.* (2000), we assigned 230 for Crustacean, 450 for Gastropoda, 50 for Annelida, and 70 for Insecta.

Each exergy of five FFGs was transformed by natural logarithm in order to reduce their variation range. To avoid a problem of logarithm zeros, the number one was added to the density of each species. Subsequently, the transformed data were proportionally scaled between 0 and 1 in the range of the minimum and maximum for each species. Through these procedures, each FFG gets the same weight (i.e., importance) in the data matrix.

3. Modeling process

Self-Organizing Map (SOM) was used to characterize spatial and temporal dynamics of ecological exergy at the study sites. SOM is an unsupervised learning algorithm of artificial neural networks and approximates the probability density function of the input data (Kohonen 2001). SOM consists of input and output layers connected with computational weights (connection intensities). The array of input neurons (computational units) operates as a flow-through layer for the input vectors, whereas the output layer consists of a two-dimensional network of neurons arranged in a hexagonal lattice.

In the learning process of SOM, initially the input data (exergy of five FFGs in this study) were subjected to the network. In this study, the number of output neurons was set to 28 ($=4 \times 7$) in 2D hexagonal lattice. A hexagonal lattice is preferred because it does not favor horizontal or vertical directions (Kohonen 2001). The number of nodes was determined as $5 \times \sqrt{\text{number of samples}}$ (Vesanto 2000). Subsequently, the map size was determined. Basically, the two largest eigen values of the training data were calculated and the ratio between side lengths of the map grid was set to the ratio between the two maximum eigen values. The actual side lengths were then set so that their product was close to the determined number of map units. Subsequently, the weights of the network were trained for a given dataset. Each node of the output layer computes the summed distance between weight vector and input vector. The output nodes are considered as virtual units to represent typical patterns of the input dataset assigned to their units after the learning process. Among all virtual units, the best matching unit (BMU), which has the minimum distance between weight and input vectors, becomes the winner. For the BMU and its neighborhood units, the new weight vectors are updated by the SOM learning rule. This results in training the network to classify the input vectors by the weight vectors they are closest to.

After training, the Ward's linkage method based on the Euclidean distance (Ward 1963) was applied to the weights of the nodes in SOM for further clustering (Jain and Dubes 1988; Park *et al.* 2003). For training the SOM, we used the functions provided in the SOM toolbox (Alhoniemi *et al.* 2000) in Matlab (The Mathworks 2001). Kruskall Wallis test, non-paramnetric analysis of variance, was carried out to evaluate the differences of variables among clusters defined in the SOM, and then Dunn's multiple comparison test was conducted for variables in order to show the significant differences among clusters. The analyses were carried out by statistical software STATISTICA (StatSoft 2004).

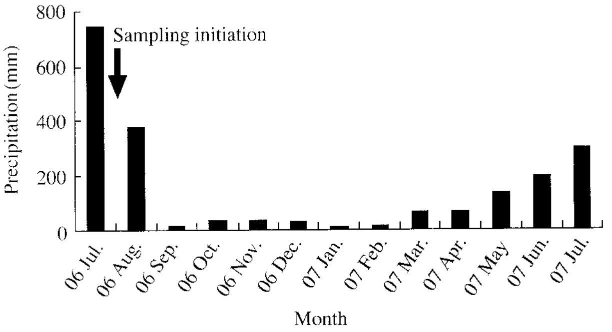

Fig. 2. Monthly precipitation in Seoul during study period. Arrow indicates the first sampling time.

Results

1. Exergy of benthic macroinvertebrate communities

There was a heavy rain at study area before the first sampling in July 2006. Fig. 2 shows the monthly changes of precipitation during the study period. A heavy rain was recorded with 745.1 mm for one month before the first sampling in July 2006. This heavy rain effect was reflected in the exergy values of the sampling sites. Fig. 3 shows the variations of exergy, species richness and Shannon diversity index at six different sampling sites. Right after a heavy rain, exergy value was relatively low in all study sites in the range of 3.4 ~ 19.4 kJ L^{-1}, and then gradually increased until winter showing the highest values with 578.9 kJ L^{-1} (Fig. 3a). However, different sites showed different exergy values at different months. Exergy values were relatively higher at study sites 2 (average 170.3 kJ L^{-1} per sample) and 5 (198 kJ L^{-1} per sample) which were the perennial stream type, representing also seasonal changes with high values in winter and low values in summer. Exergy was low at sites 1 (77.2 kJ L^{-1} per sample) and 3 (64.3 kJ L^{-1} per sample) which were the intermittent stream type as well as sites 4 (123.3 kJ L^{-1} per sample) and 6 (87.5 kJ L^{-1}) which were the drought stream type. Sites 1 and 3 were not completely dried, but partially dried, while sites 4 and 6 were completely dried during the dry season. Although there was enough water discharge after the dried period, exergy was very low. Species richness had also similar patterns with exergy (Fig.

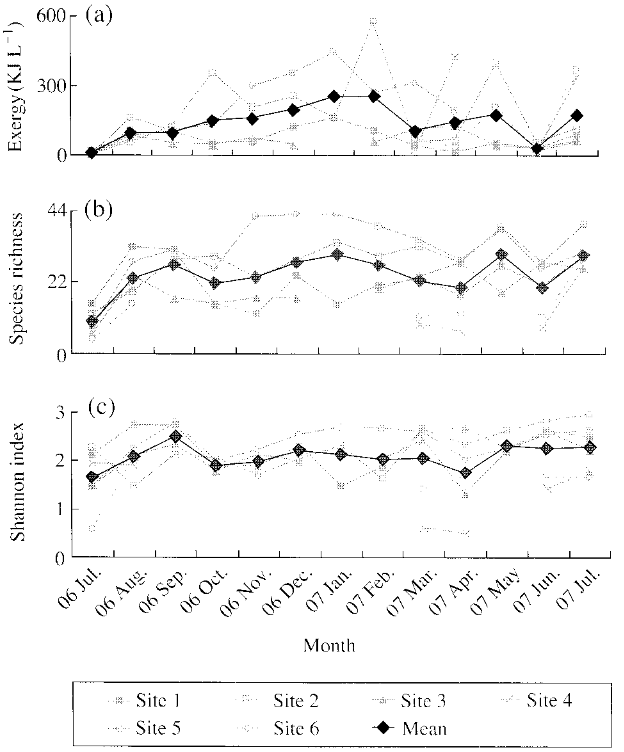

Fig. 3. Monthly changes of (a) exergy, (b) species richness and (c) Shannon diversity index at six different sites during the survey period.

3b). In addition, species richness was relatively low in the intermittent stream type and the drought stream type comparing with the perennial stream type. Shannon diversity index showed different values at different study sites, showing low values at drought stream type. However, the differences were not clear among perennial and intermittent stream type (Fig. 3c).

2. Patterning communities with SOM

Samples were classified through the learning process of the SOM based on the similarities of their exergy values of FFGs, displaying the differences of the sampling time and the sampling sites (Fig. 4). For example, samples from sites 4 and 6 were mostly in the upper right area of the SOM map, samples from sites 2 and 5 were in the lower area of the map and samples from sites 1 and 3 were in the upper left area in the ordination map. In addition, samples from July 2006 were in the upper area, whereas samples from winter were in the lower area of the SOM map. The units of the SOM map were classified into four (I-IV) clusters based on a cluster analysis with the Ward linkage method showing the spatial characteristics of the exergy value. Cluster

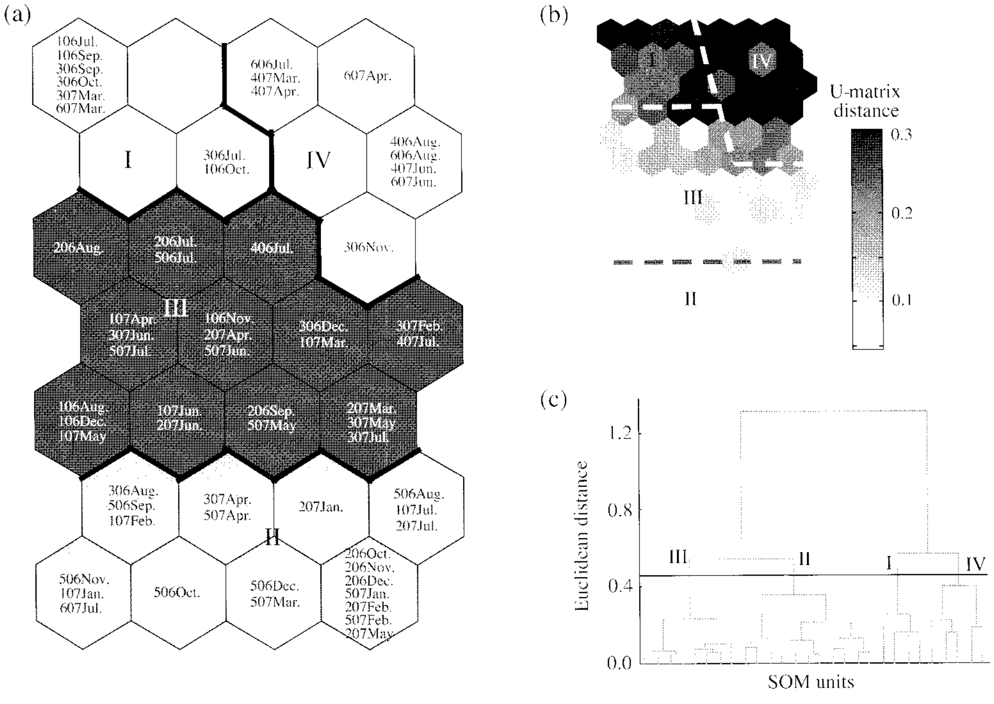

Fig. 4. (a) Classification of samples at six different sites at different months on the SOM map trained with exergy of five functional feeding groups. (b) U-matrix and (c) Dendrogram for clustering the SOM units with Ward linkage algorithm with Euclidean distance measure. Acronyms in the SOM units stand for the samples: the first number means site name, 06 and 07 indicate respectively 2006 and 2007 years, and the following letters represent sampling months.

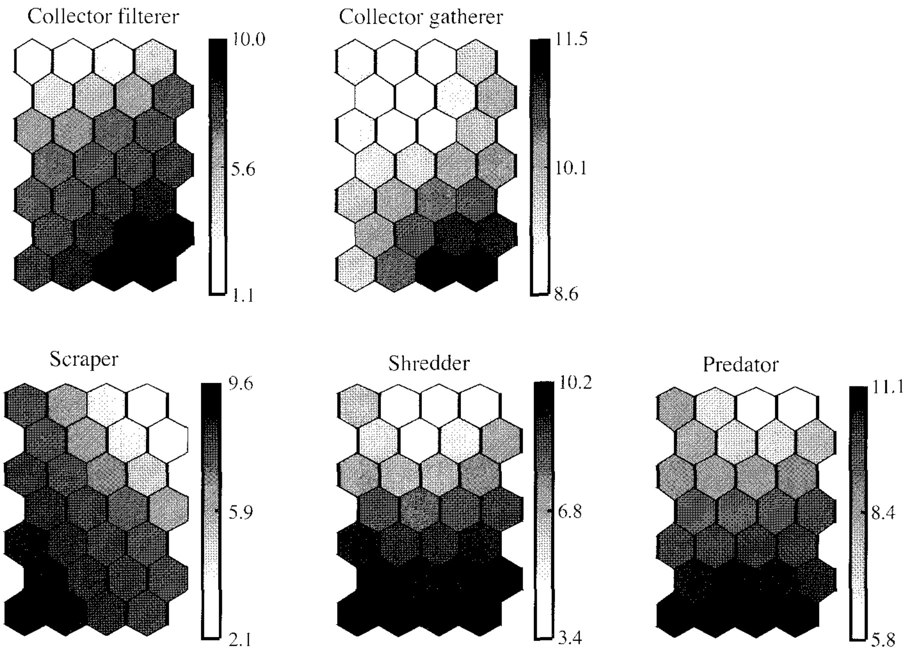

Fig. 5. Visualization of the estimated exergy of functional feeding groups through the learning process of the SOM. Dark scale represents high value of each variable, while light one is low value.

IV represented samples from sites 4 and 6, where the drought stream type, during the survey period, whereas cluster II represented samples from sites 2 and 5 where the perennial stream type. In addition, cluster I mainly included samples from sites 1 and 3 where the intermittent stream type.

Fig. 5 displays the distribution of estimated exergy of each FFG on the SOM map. The values were calculated as weights of the SOM through the learning process of the network. Dark represents high values of exergy, whereas light is low values. Overall, five FFGs showed different distribution patterns on the SOM map. Cluster II including the data from the perennial stream type had the relatively higher ratio of FFGs, whereas cluster I including the data from the intermittent stream type had the relatively lower ratio of FFGs, especially collector-filterer. In addition, cluster IV including the data from the drought stream type had the relatively lower ratio of SC, SH and P.

Exergy and community indices such as Shannon diversity index, evenness and species richness varied with different clusters (Fig. 6). Exergy was significantly higher in cluster II comparing with other clusters (Kruskall Wallis test, $p<0.05$). Shannon diversity index was significantly low in cluster IV (Kruskall Wallis test, $p<0.05$), while the index was not significantly different in other clusters. Species richness was also low in cluster IV, while it was high in cluster II and intermediate range in clusters I and III (Kruskall Wallis test, $p<0.05$). However, evenness was the highest in cluster I, whereas the lowest in cluster IV and intermediate in clusters II and III (Kruskall Wallis test, $p<0.05$).

Temperature and conductivity were significantly different among clusters showing lower temperature in cluster II and lower conductivity in cluster III (Kruskall Wallis test, $p<0.05$) (Fig. 7). Although other environmental variables such as velocity, water depth, width, and DO were not significantly different among clusters, velocity and width were relatively low in cluster I and high in cluster IV, water depth was relatively low in cluster IV and high in clusters III, and DO was relatively higher in cluster II.

DISCUSSION AND CONCLUSION

In this study, exergy of FFGs was calculated with benthic macroinvertebrate communities based on taxa, and the study sites were patterned through an adaptive learning algorithm, SOM. In Korea, the precipitation usually concentrates on the summer periods. In this result, the monthly precipitation was very high in July and August (Fig. 2). It caused discharge, water depth and width to increase in the Musucheon stream in the summer periods so exergy value was

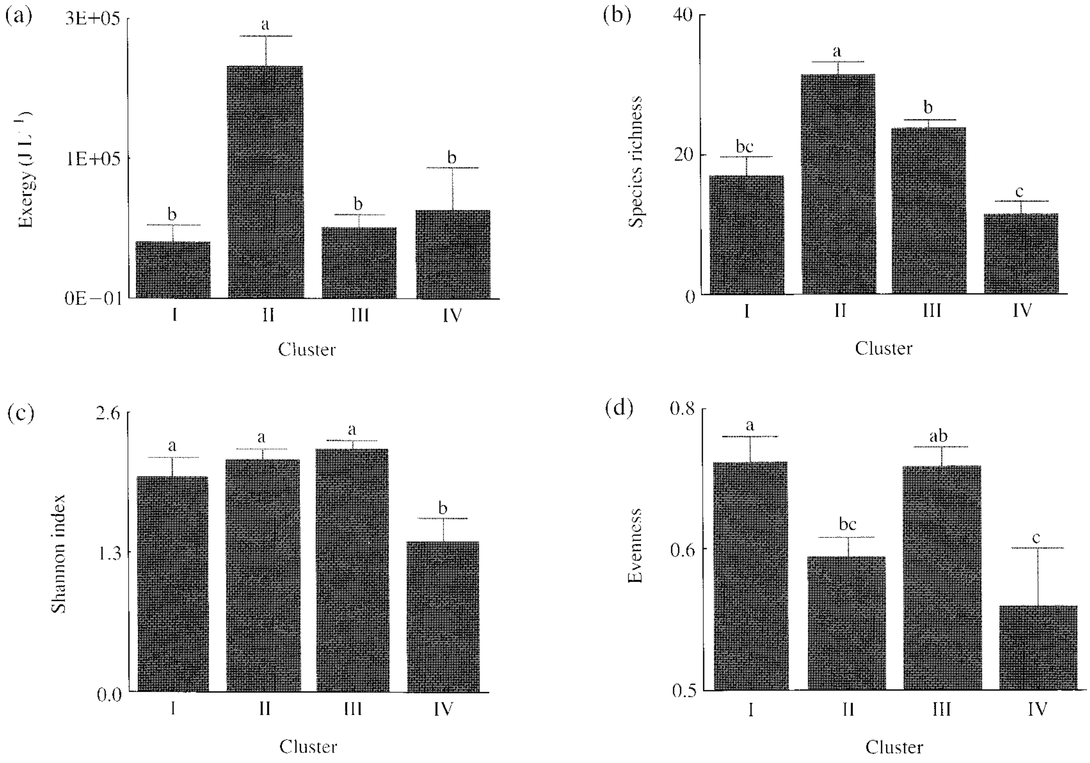

Fig. 6. Differences of biological variables at different clusters. (a) exergy, (b) species richness, (c) Shannon diversity index and (d) evenness. Error bars indicate mean and standard error of each variable. Different alphabets indicate significant differences among the clusters based on Dunn's multiple comparison test (p=0.05).

the lowest in all study sites at the first sampling time. The heavy rain disturbed strongly stream habitats for benthic macroinvertebrates as well as swept downstream benthic macroinvertebrates, resulting in the decrease of ecological exergy (Fig. 3). Additionally, in the autumn as the autumn shed leaves were degraded and much food was provided to benthic macroinvertebrates, the exergy value increased.

Changes of exergy also reflected the different stream habitat types. Exergy was higher in study sites 2 and 5 where perennial stream type (water flowed consistently at sampling sites during the study period), while exergy was lower at other sites where intermittent stream type (stream was not completely dried out, but partially dried out with pools. Site 1 and 3) or drought stream type (sampling area was completely dried out during the dry season. Sites 4 and 6) (Fig. 3). This might be caused as the intermittent streams have the frequent absence of flow, and insufficient water levels when it flows (Kinzie *et al.* 2006) resulting in the decrease of wetted width, resulting in decrease of available habitat (Cowx *et al.* 1984; Stanley *et al.* 1997; Brasher 2003), reduction of habitat diversity (Cazaubon and Giudicelli 1999), and alteration of habitat suitability (Cowx *et al.* 1984).

Sites 4 and 6, the drought stream type, flowed only after rainfall or melting of the frozen water at upstream. So the exergy values were highly various because of unstable environmental conditions. It is interesting to see the differences of exergy at site 4, showing high exergy in April and July 2007. This was caused by the increase of the Collembola sp. in April, and *Baetis fuscatus* and *Tanytarsus heusdensis* in July. After these periods, the study sites were completely dried out.

Species richness as an ecological indicator for ecosystem assessments and an integrative descriptor of the community reflects the changes of the natural environmental variables as well as anthropogenic disturbances (Rosenberg and Resh 1993). In this study, species richness was also lower in the intermittent stream type and the drought stream type comparing with the perennial stream type, however, it was difficult to show the community change pattern only using species richness. In addition, Shannon diversity index did not show clearly the differences of community structures

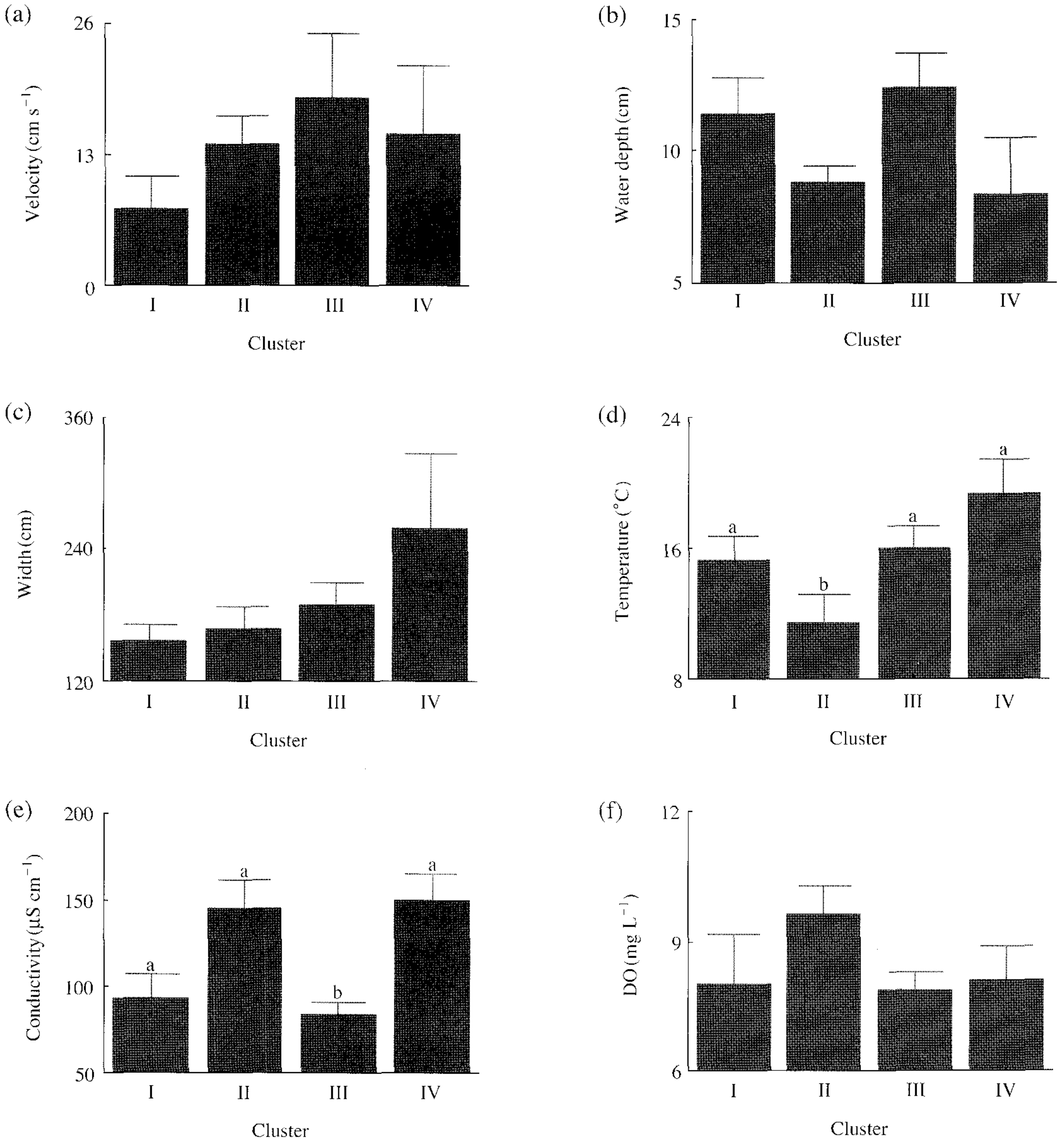

Fig. 7. Differences of environmental variables at different clusters. (a) current velocity, (b) depth, (c) width, (d) temperature, (e) conductivity, and (f) dissolved oxygen. Error bars indicate mean and standard error of each variable. Different alphabets indicate significant differences among the clusters based on Dunn's multiple comparison test (p=0.05). Velocity, water depth, width and DO were not significantly different among clusters in Kruskall Wallis test (p=0.05).

among the study sites. And the effects of the disturbance on community were not reflected in the index, although exergy showed spatial and temporal variations among samples. This represented exergy can differentiate more effectively the differences of communities of target ecosystems, although the biodiversity index can not distinguish the differences of communities (Park *et al.* 2006). Even though exergy can be used as great ecological indicators representing the community dynamics, it is not possible to calculate clearly the exergy of an ecosystem due to its very high complexity. Therefore, it should be stressed that the calculations only give an exergy index for a model of an ecosystem (Park *et al.* 2006).

SOM was used to extract ecological information from exergy of five FFGs at six different study sites in the Musucheon streams. SOM results showed the spatial and temporal dynamics of samples based on the similarities of their exergy values. Based on five input variables (CF, CG, P, S, and SH), the clusters were defined in a hierarchical manner depending on the exergy. SOM patterned the study sites based on the exergy of FFGs. Four clusters defined in the SOM clearly showed the differences of exergy at the different stream types (intermittent, perennial and drought). In addition, the different distribution patterns of five FFGs were shown in the SOM map. In cluster I including the samples from sites 1 and 3 characterizing with the intermittent stream type, exergy and species richness were significantly low. In cluster II including the samples from sites 2 and 5, the perennial stream type, exergy and species richness were higher comparing with other clusters. In addition, this cluster showed the higher ratio of FFGs comparing with other clusters. In cluster IV including the sample from the sites 4 and 6, Shannon diversity index was low comparing with other clusters. In cluster III including the samples collected during right after a heavy rain period, velocity was relatively high comparing with other clusters, however, conductivity was the lowest in the cluster. In this regards, SOM results also showed the variation of the exergy depending upon natural environmental changes in a small stream, indicating that SOM could be used for patterning the changes in exergy as well as for extracting information on relations between community and exergy data (Park *et al.* 2001).

In conclusion, exergy as a unique and efficient expression of energy status in ecosystems could be an alternative to represent the status of community development. In addition, the clustering of exergy values based on the different FFGs in the trained SOM was efficient in showing the changes of exergy through the spatial and temporal variations and natural disturbances such as floods and drought. Therefore, this could be effectively used for diagnosing various conditions of a community and setting up efficient management strategies for the target ecosystem.

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