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# Ecological exergy as an indicator of land-use impacts on functional guilds in river ecosystems

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ABSTRACT

The cumulative effect of land-use changes is one of the most important factors contributing to the continuous deterioration of river ecosystems. We used ecological exergy to evaluate the impacts of land-use changes on functional guilds of benthic macroinvertebrates. We classified 353 sampling sites into 3 groups based on land-use types: forested, agricultural, and urban rivers. For each sampling site, we calculated ecological exergy based on 5 trophic groups of macroinvertebrates. Differences in exergy, specific exergy, and structural metrics (i.e. species richness and Shannon index) suggested that land-use type was an important determinant of the composition of macroinvertebrate communities. Exergy values of the functional feeding groups and trophic groups were used as input data to train self-organizing maps – unsupervised artificial neural networks. The results showed that functional guilds responded differently to different land-use types: scrapers and carnivores dominated the forested rivers, whilst predators and omnivores, and gatherer-collectors and detritivores dominated agricultural and urban rivers, respectively. These results suggest that ecological exergy can be used as a functional bioassessment indicator to evaluate river condition. A generalized additive model and random forest also highlighted that a combination of both conventional structural indicators (e.g. species richness and Shannon index) and novel functional indicators (e.g. exergy and specific exergy) can be used to assess biotic integrity.



## 1. Introduction

Changing land-use patterns as a result of human disturbance often affect river ecosystems (Richards and Host, 1994). The conversion of land from pristine forest to open agricultural, pastural, or urban areas can have negative impacts on river ecosystems, primarily as a result of an increased amount of impervious surfaces and construction near riparian zones, which can alter patterns of sediment deposition and the flow regime (Oberlin et al., 1999). Land-use changes may also negatively affect aquatic organisms and result in a reduction in aquatic biodiversity (Gage et al., 2004). Recent studies evaluating the relationship between physicochemical habitats and macroinvertebrate biota have shown that the structure of macroinvertebrate communities is progressively modified along a land-use degradation gradient (Hall et al., 2001).

Recent investigations into the relationship between community structure and environmental degradation have highlighted the need for the sustainable management of ecosystems (Gage et al., 2004; Silow and Mokry, 2010), which requires appropriate diagnostic tools to identify various conditions. Bioassessment based on structural measurements, including the structural biodiversity indicators $\alpha$, $\beta$, and $\gamma$, is one such diagnostic tool that has been widely used (Harding et al., 1998). However, although these conventional bioassessment indicators have been used successfully to identify the structural composition of a community, the importance of functional indicators is increasingly being recognized (Uehlinger, 2006; Death et al., 2009; Young and Collier, 2009). In particular, it has been shown that functional indicators are able to discriminate between low levels of impairment, which is often difficult using structural indicators, and may also detect initial movements away from a degraded state, allowing tangible improvements in ecosystem health to be demonstrated during the early stages of restoration (Palmer et al., 2005).

Several functional indicators have been proposed to describe the direction of ecosystem development, including maximum power (Odum, 1960), exergy (Jørgensen, 1982), ascendency (Ulanowicz,

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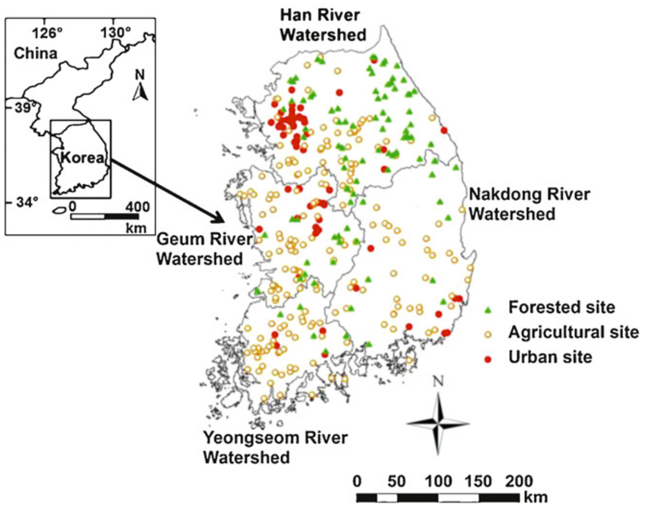


**Fig. 1.** Geographic locations of the sampling sites in 4 main watersheds in the Republic of Korea.

1986), entropy (Schneider, 1988), and emergy (Fath and Patten, 1999). Recently, thermodynamic studies have also investigated the measurement of indirect effects based on material or energy flows (Chen and Chen, 2012). Among, the concept of exergy provides a unified indicator of different forms of material and energy flows by evaluating the distance between the studied system and thermodynamic equilibrium (Dai et al., 2012). Although exergy ignores the inter-relationships between components, Jørgensen (2000) suggested that exergy has a good theoretical basis in thermodynamics. Exergy has often been used to assess ecological health (Libralato et al., 2006; Pedersen et al., 2007; Silow and Mokry, 2010; Chen et al., 2011), and is particularly popular in benthic studies (Silow and Mokry, 2010) because of its ability to evaluate the impacts of human disturbance on benthic communities (Libralato et al., 2006).

Allochthonous inputs, e.g. leaf litter from riparian vegetation, are the main source of energy in small rivers (Cummins et al., 1973; Wallace et al., 1997). Urbanization and agricultural activities close to rivers can result in nutrient enrichment, salinization, and toxin release (Shieh et al., 2002), which may alter the trophic pathways through which aquatic organisms obtain energy. A loss of biodiversity also affects numerous functions in river ecosystems (Covich et al., 1999). Thus, the energy in a river ecosystem can be changed throughout the land-use conversion process. The energy of a severely disturbed ecosystem is furthest from the thermodynamic equilibrium of a reference ecosystem (Jørgensen et al., 1995). Therefore, exergy can potentially be used to examine the consequences of land-use changes.

Macroinvertebrates in the upstream region play an important role in energy transportation, as they break down leaf litter, and release nutrients and energy for downstream consumers (Wallace and Webster, 1996; Covich et al., 1999). Nutrient additions may alter the energy base, and affect the community composition and spatial distribution of aquatic organisms (Pringle, 1990). In lotic waters, the distribution of macroinvertebrate functional guilds is expected to reflect the attributes of the ecosystem at a process level and, recently, functional guild measurements have been used in biomonitoring studies (Merritt and Cummins, 1996; Barbour et al., 1999). Since different feeding or trophic groups contain different amounts of exergy, the measurement of exergy can provide insight into the linkages between functional guilds and land-use changes.

In this study, we utilized self-organizing maps (SOMs) to classify macroinvertebrate metrics under different land-use conditions. SOMs produce virtual metrics in a low-dimensional network through an unsupervised learning process. They are used in the classification and ordination of ecological data, including the evaluation of environmental conditions (Park et al., 2003a; Céréghino and Park, 2009; Bae et al., 2012), the ordination of population and community data (Park et al., 2003b, 2007; Kwon et al., 2012), and the prediction of ecosystem state (Recknagel et al., 2006).

A combination of thermodynamics (i.e. exergy) and network analysis (i.e. SOM) to identify exergy patterns may provide important ecological information for understanding river ecosystems and may be of value for ecosystem management. Therefore, we investigated differences in benthic macroinvertebrate composition and energy conditions in 3 types of rivers exposed to different landuses. The specific objectives were: (1) to characterize exergy changes in river systems along a land-use gradient; (2) to use estimated exergy to evaluate the impacts of land-use changes on functional guilds; and (3) to evaluate the effectiveness of functional exergy and specific exergy in assessing river health.

## 2. Materials and methods

### 2.1. Ecological data

Data were obtained from the National Aquatic Ecological Monitoring Program operated by the Ministry of Environment and the National Institute of Environmental Research, Republic of Korea. Field data were collected twice from 720 sites across the Republic of Korea (Fig. 1) in April and September 2009, using standardized sampling protocols (NIER, 2008; Bae et al., 2011). Five major rivers (Han, Nakdong, Geum, Yeongsan, and Seomjin Rivers) and their main tributaries and small streams encompass the entire river system of this country.

Thirteen environmental variables were used to characterize the environmental condition of each sampling site. These variables were classified into the following 4 categories: hydrogeographical, landuse, substrate, and water quality. Altitude, river width, current velocity, substrate type, and some water quality variables, such as dissolved oxygen (DO) and electrical conductivity, were measured *in situ*. Biological oxygen demand (BOD) was determined using standard methods in the laboratory, following the collection of water samples from the field. At each sampling site, the proportion (%) of each land-use type (i.e. forested, agricultural, and urban) within a 200-m-wide and 1-km-long riparian zone was extracted using ArcGIS version 9.3 (ESRI, 2009). We classified substrate into 3 categories: micro-substrate (i.e. silt and sand), meso-substrate (i.e. gravel and pebble), and macro-substrate (i.e. cobble and boulder). At each sampling site, 3 samples were collected from the riffle zones of the rivers in a 200-m reach using a Surber net (area, 30 cm × 30 cm; mesh size, 1 mm). All collected macroinvertebrates were preserved in 10% formalin or 70% ethanol. In the laboratory, macroinvertebrates were sorted and identified to the lowest feasible taxonomic level, and the number of individuals was counted using a stereo microscope.

Five commonly used functional feeding groups (i.e. filter-collectors, gatherer-collectors, predators, scrapers, and shredders) and 5 commonly used trophic groups (i.e. carnivores, detritivores, detriti-herbivores, herbivores, and omnivores) (Merritt and Cummins, 1996; Barbour et al., 1999) were used to evaluate the responses of macroinvertebrates to land-use disturbances. For comparison, we also selected a tolerance value (Barbour et al., 1999) and evaluated the percentages of chironomids; oligochaetes; Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa; hydropsychids; 5 functional feeding groups; shredder-feeding Plecoptera; and 5 trophic groups; as well as the ratio of filter-collectors to gatherer-collectors (Table 1). We used structural (species richness and Shannon index) and functional (exergy and specific exergy) indicators to evaluate the impact of land-use changes on functional