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Patterning Zooplankton Dynamics in the Regulated Nakdong River by Means of the Self-Organizing Map

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자가조직화 지도 방법을 이용한 조절된 낙동강 내 동물플랑크톤 역동성의 모형화. 김동균・주기재・정광석・장광현[1]・김현우[2,]* (부산대학교 생물학과, [1]에히메대학교 해양환경연구센터, [2]순천대학교 환경교육과)

본 연구는 지난 10여년간의 (1994～2003) 주간격의 자료를 이용한 자가조직화 지도 (SOM) 방법으로 낙동강 하류역 (물금: 낙동강 하구언으로부터 27 km 상류지점)에서 동물플랑크톤 군집 동태에 대한 계절별 유형화 분석을 하는데 목적이 있다. 담수생태계내의 먹이망에서 동물플랑크톤 군집의 역할은 매우 중요하나, 다른 군집 구성원들과의 비교 연구는 다소 미진하게 진행되었다. 비선형 모형 알고리즘인 SOM을 동물플랑크톤 군집 역동성과 강 환경 인자들과의 상관관계 파악을 위하여 적용하였다. 육수학적 환경인자 (수온, 용존산소, pH, 세키투명도, 탁도, 클로로필 *a* 농도, 유량 등) 들을 동물플랑크톤 군집 구조(윤충류, 지각류 및 요각류)의 계절적 변화 유형파악을 위하여 사용하였다. 학습된 SOM 모형은 육수학적 환경인자와 연관 지어 지도상에 동물플랑크톤을 배치되었다. 동물플랑크톤의 주요 세 군집들은 계절별 변화 유형에 있어서 높은 유사성을 가지고 있었다. 다양한 육수학적 환경인자 중, 수온은 동물플랑크톤 군집 역동성과 매우 높은 연관관계를 나타내었다 (특히, 지각류). SOM 모형은 여름기간 증가된 강 유량에 의해서 동물플랑크톤을 매우 저해하는 요인으로 표현되었다. 클로로필 *a* 농도는 우점한 초식성 동물플랑크톤 활성도에 의해 지도상에서 구획되었다. 본 연구는 비선형 방법을 이용한 육수학적 환경요인과 동물플랑크톤 역동성을 연관 지어 소개하였으며, 이러한 정보는 먹이망이라는 관점에서 볼 때, 강 생태계 관리에 유용한 정보로 활용될 것으로 사료된다.

Key words : Self-Organizing Map, rotifer, cladoceran, copepods, the Nakdong River, Regulated River

INTRODUCTION

An ecosystem contains many biotic and abiotic components with functional interactions (Odum, 1983). Ecologists have conducted experiments or field surveys in order to explain and understand the dynamics of ecosystems. The results from experiments with restricted conditions are more easily interpreted than general survey data set, because the latter one might embody highly complex characteristics of ecosystem data set, shown by Fielding (1999). The regulated river ecosystem, which has river and reservoir aspects in turns associated with seasons, is being considered as one of the complex environments (Jeong

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et al., 2003b; Joo and Jeong, 2005). Due to the increasing tendency of flow regulation in the world (Tharme, 2003), it is meaningful to give ecological attention to the regulated rivers, in terms of explanation, utilization and conservation of rivers.

In estimating and assessing water quality in the freshwater systems, beyond the regulated rivers, the structure and dynamics of phytoplankton assemblage were mainly considered. Many researches have presented patterning and analyzed the temporal dynamics and the spatial distribution of phytoplankton regarding water quality (e.g., Park and Lee, 2002; Millie *et al*., 2004). The trophic state of the river was considered to explain phytoplankton dominance, related to nutrient availability through long-term management (e.g., Edmondson and Lehman, 1981; Reynolds, 1984). Recently, water quality improvements have been reported in terms of food web dynamics. The grazing impacts of the zooplankton community on phytoplankton could produce enhancement of water quality, noticed as a clear water phase (Kim *et al*., 1999; Kim *et al*., 2003). This ecological phenomenon has been observed in lake ecosystems (e.g., Hwang *et al*., 2004; Tan *et al*., 2004) and rivers (e.g., Gosselain *et al*., 1998; Kim *et al*., 1999; Leonard and Paerl, 2005). The zooplankton grazing on phytoplankton (Thompson *et al*., 1982) and bacteria (Urabe and Watanabe, 1991) have received increasing attention in freshwater ecosystems.

The Nakdong River is situated on the south-eastern area of South Korea (Fig. 1). The catchment area is the second largest and nearly 10 million people inhabits along the river. Many multi-purpose dams have been constructed for the stable supply of water resources, and an

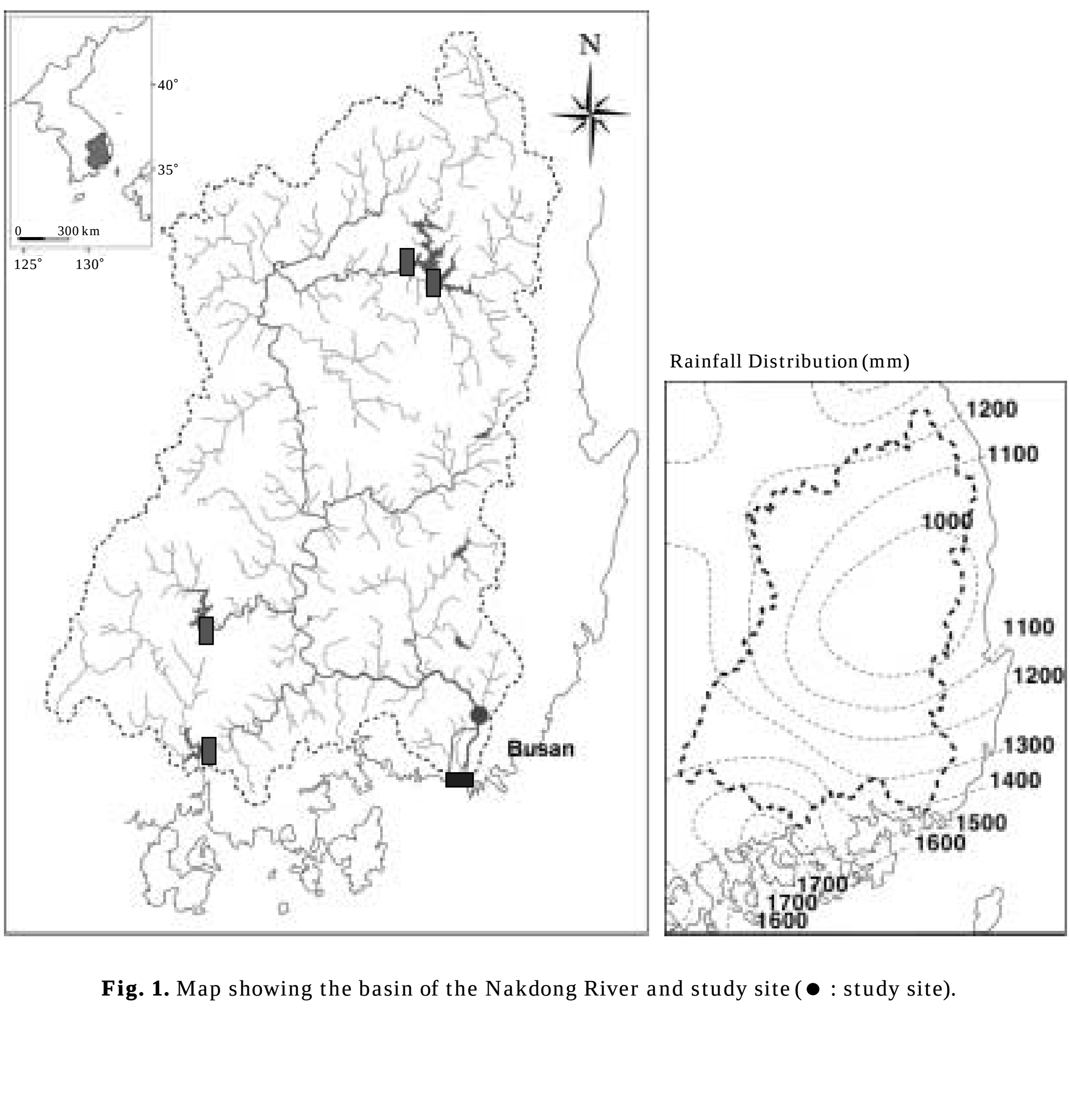

Fig. 1. Map showing the basin of the Nakdong River and study site (● : study site).

esturine barrage was built in order to suppress saline damage in the 1980s. Artificial alterations to the river caused structural and functional changes in the river limnology. First of all, the physical alteration of the river through dam construction increased the retention time of the water body and converted the river ecosystem into a river-reservoir hybrid ecosystem (Kim *et al.*, 1998). The Nakdong River is a good example of a regulated river, because the river flow is highly dependant on the dam controls.

In the Nakdong River, much research and many surveys have been conducted with respect to limnological components (Ha *et al.*, 1998; Lee, 1999; Park *et al.*, 2003) and several case studies have been done concerning zooplankton communities (Kim and Joo, 2000; Kim *et al.*, 2001). Hydrological parameters such as discharge can affect zooplankton dynamics and especially the intensive rainfall in S. Korea may have a critical effect on the proliferation of cladocerans and copepods during the summer period (Kim *et al.*, 2000).

Because of the complicated characteristics of ecological data from the regulated river systems, it is difficult to apply traditional predictive or patterning models to the systems, such as statistical or deterministic methods (Jeong *et al.*, 2003b). An alternative pathway to representative ecological models, known as machine learning, has been suggested and applied in past decades. The algorithms in the field basically deal with data in non-linear ways, which are thought to be suitable for the complicated ecosystem data set (e.g., Stankovski *et al.*, 1998; Wilson and Reckangel, 2001; van Den Grink *et al.*, 2002). Among the methods, the Self Organizing Map SOM algorithm is considered a good pattern recognizer or classifier for the ecological dynamics (Chon *et al.*, 1996, 2003; Brosse *et al.*, 2001; Park *et al.*, 2003).

In this study, long-term limnological parameters and zooplankton community dynamics were modeled with an SOM algorithm. The aim of this study is to investigate and assess the seasonal pattern of zooplankton community dynamics (i.e. rotifers, cladocerans and copepods) in the lower Nakdong River, associated with environmental variables. From the model, information regarding the seasonality of zooplankton community dynamics and relationships with environments were abstracted. This may be useful for managing the river ecosystem, with respect to the food web interactions.

MATERIALS AND METHODS

1. Limnological data collection and parameters

Limnological parameters were measured at Mulgum water intake station (27 km upstream from the estuarine barrage), and water samples were collected at the depth of ca. 50 cm from the surface weakly. Water samples were measured for water temperature, dissolved oxygen (DO), turbidity, Secchi disc transparency, pH, discharge, chlorophyll *a*. The abundances of zooplankton communities (e.g. rotifers, cladocerans and copepods) were counted from the samples as well. We used the dataset measured from 1994 to 2003 (n=350).

Water temperature and DO were measured by YSI model 58 meter. Turbidity (NTU) was observed by the use of model 11052 turbidity meter, and pH was measured by Orion model 250A meter. A 20 cm-diameter Secchi disc was used to measure transparency. Discharge data were provided from Nakdong River Flood Control Center (NRFCC). Chlorophyll *a* concentrations were determined by a spectrophotometer using an extraction method of Wetzel and Likens (2000). Zooplankton sampling was conducted by filtering 8 liters water using a 35-μm net, and by adding 10% formalin (4% final concentration). Copepods and cladocerans were counted by an inverted microscope at $\times 25 \sim 50$ magnification, and rotifers were counted by one at $\times 100 \sim 400$ magnification. Identification of zooplankton taxa was conducted at the level of genus or species using Koste (1978), Smirnov and Timms (1983) and Bayly (1992).

2. Pattern analysis with Self Organizing Map

Self Organizing Map algorithm was from Kohonen (1982), which was capable of reducing data dimensionality (Lin and Lee 1996). Kohonen network is a competitive network system where the neurons in Euclidean map space compete each other. A two-dimensional Kohonen network was adapted to indicate a seasonal pattern of each ecological parameter.

In this study, a Kohonen network was prepared with M^2 artificial neurons (processing elements)

(Fig. 2). Input for the network was data of limnological variables i, x_i identified during the study period. All the input data was expressed in a vector, and input layer consisted of those species. Every node, j, of the output layer was connected to each node, i, in the input layer. Hexagonal array of neurons was selected. The weight vector, $\mathbf{w}^{(t)}$, represented the connection between input and output layers. As training preceded, each weight value, $w_{ij}^{(t)}$, was adaptively changed at each iteration t. In initial stage, $\mathbf{w}^{(t)}$ was randomly and uniformly distributed in the network architecture. As input signal entered the network, each neuron computed the summed distance between the weight and input through the equation below:

$$\|\mathbf{x}-\hat{\mathbf{w}}_{i*}\| = \min_i\{\|\mathbf{x}-\hat{\mathbf{w}}_{j*}\|\} \qquad \text{Eq. 2.}$$

The neuron of a maximum response in the given input data was selected as a winning neuron whose weight vector has the minimum distance to the input vector. The winning neuron and its neighborhoods learned by changing the weights in the way of reducing the distance between the weight and input vector. Following equation was adapted to this purpose:

$$w_{ij}^{(t+1)} = w_{ij}^{(t)} + \alpha^{(t)}\| x_j^{(t)} - w_{ij}^{(t)}\| Z_j \qquad \text{Eq. 3.}$$

where Z_j had value 1 for winner and its neighborhoods whereas 0 for the remaining neurons. α was the learning rate which dynamically changed during the training steps. The radius value $r^{(t)}$ was initially defined between 1 and m, where m is the integer of $(M$-1)/2. Radius gradually reduced to zero as convergence was achieved. Further and detailed references can be found in Hecht-Nielsen (1990), Lin and Lee (1996), and the methodology of applying SOM to ecosystem is explained in Chon *et al.* (1996).

Training of SOM was achieved using a time-series dataset of the study site. All data points were labeled into four seasons; spring (Mar.～May), summer (Jun.～Aug.), autumn (Sep.～Nov.) and winter (Dec.～Feb.). After training, data were

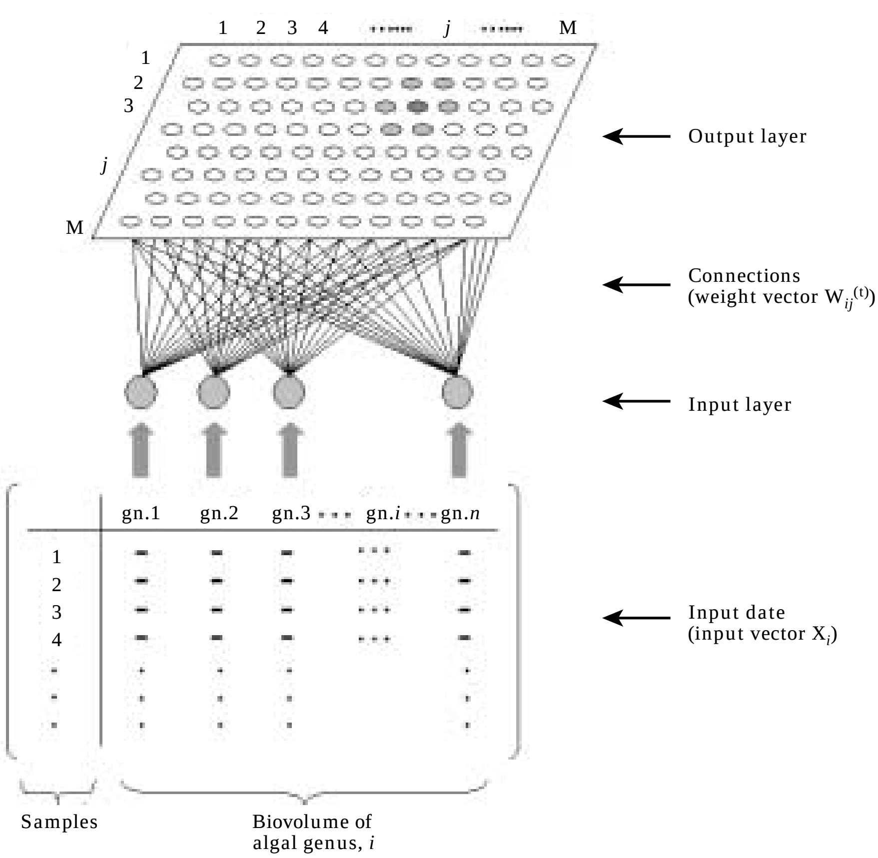

Fig. 2. The process of Self Organizing Map based on the artificial neural network.

clustered according to the calculated U-matrix, and season labels were distributed on the SOM plane. Each parameter had a respective SOM plane represented by color coding. The range of color coding was determined by average density or value of each parameter. For developing SOM model, Matlab 5.3 and SOM Toolbox for Matlab were used.

RESULTS

1. The characteristics of limnological parameters

The general characteristics of ecological variables input in the SOM algorithm are shown in Table 1. The mean water temperature was 16.8°C and large variations could be observed. The maximum temperature was over 30°C, which was recorded in mid summer. Water of the river was not frozen in winter. The saturation of dissolved oxygen exhibited nearly 100%. Strong over-saturation was frequently observed, and high oxygen consumption was detected as well. From the data set, these fluctuations were due to the seasonal changes of the river environment.

The values of pH at the study site averagely persisted slightly alkaline status. Mostly large variations were detected in summer. Light penetration could be inferred to almost 1 meter from Secchi disc transparency. In the spring seasons, high transparency was maintained, while penetration was low during flooding periods. Conductivity was 370 μs cm^{-1}, and abrupt decreases could be observed during rainy seasons. In winter, relatively high conductivity around 450 μs cm^{-1} was maintained. The average of turbidity was about 16, but similar to Secchi transparency, this parameter exhibited high variations in accordance with seasons (i.e., high turbidity in rainy periods). The variation of discharge at the study site was relatively large, and high floods could be observed in the monsoon and typhoon seasons as well.

The average value of chlorophyll *a* was nearly 40 μg L^{-1}, which means that the Nakdong River is highly eutrophic. Increases in the parameters occurred mainly when summer blue-green alage or winter diatom proliferations proceeded. Three groups of zooplankton communities exhibited large standard deviations (s.d.). In other words, their patterns of growth and death progressed quickly. In particular, cladocerans showed the highest relative variation (Coefficient of Variatioin=(s.d./mean)×100%; 424%, rotifers; 353%, copepods; 282%).

Table 1. The characteristics of ecological parameters in the lower Nakdong River (Mulgum) during 1994-2003.

	Unit	Max	Min	Mean	S.D.
Water temperature	°C	34.0	1.1	16.8	8.6
DO	%	183.0	28	107.5	28.7
pH		10.1	6.5	8.2	0.8
Secchi transparency	cm	262.0	5.0	79.6	34.0
Conductivity	μs cm^{-1}	670.0	84.0	326.2	127.6
Turbidity	NTU	648.0	1.6	16.6	54.4
Chlorophyll *a*	μg L^{-1}	251.1	0.0	36.1	35.4
Rotifers	Ind. L^{-1}	60796.8	0.0	1352.7	4782.9
Cladocerans	Ind. L^{-1}	3458.1	0.0	52.7	223.6
Copepods	Ind. L^{-1}	426.0	0.0	16.0	45.1
Discharge	CMS	6769.2	8.2	573.5	693.7

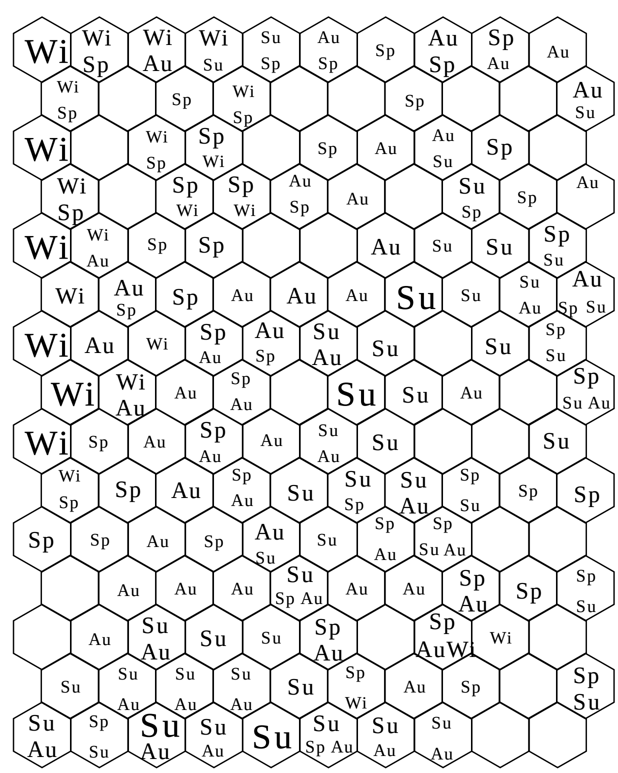

Fig. 3. The SOM plane expressed by season labels (AU: Autumn, Sp: Spring, Su: Summer, Wi: Winter).

2. Seasonal patterns of zooplankton from the SOM model

The developed model distributed seasonal labels into the SOM plane (Fig. 3). This figure explained where each season (spring, summer, autumn and winter) was arranged on the SOM plane. For example, we could distinguish where winter was on the plane. However, in the case of summer, it was difficult to distinguish. Thus, the SOM algorithm exhibited patterns on the plane in respect to each input variable. Compared with the input variable plane, the SOM plane labeled according to seasons was able to conjecture the attributes of parameters. Then ten input variables were also represented on the SOM plane (Fig. 4). The variation of water temperature followed normal seasonal patterns. DO was high during the winter period when water temperature was very low. pH was low in late summer and autumn but relatively high in winter. Secchi disc transparency intermittently displayed unexceptionally high values. However, it was very low during the autumn season and partially similar to the patterns of zooplankton communities. This will be considered further in the discussion section. Turbidity and discharge had large similarity each other and the values were very high, specifically in summer and autumn. Chlorophyll *a* was also clearly distributed during the winter period. In

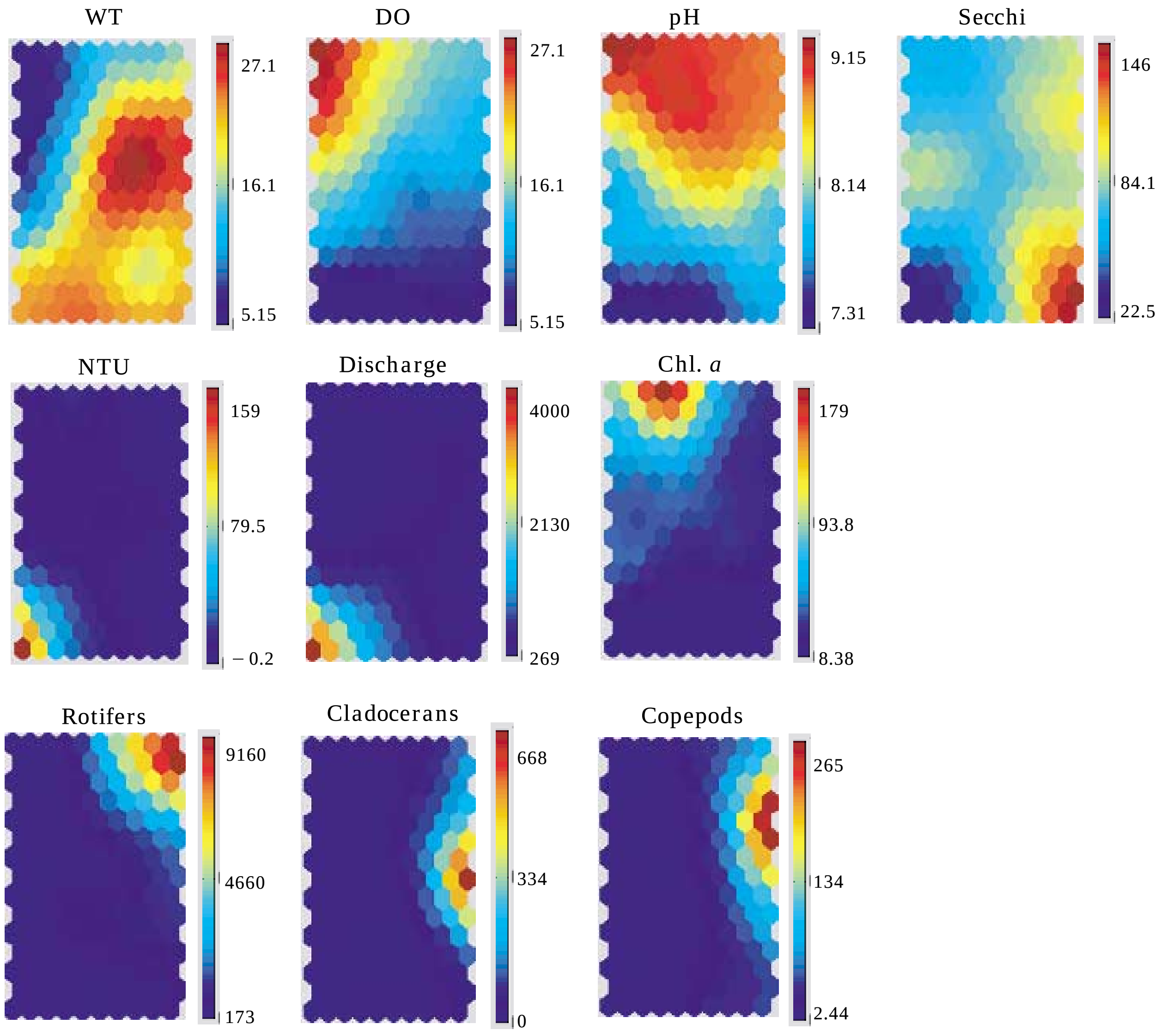

Fig. 4. The results of each input variable on the SOM matrix.

the patterns of zooplankton communities (i.e. rotifers, cladocerans and copepods), most of zooplankton communities were closely placed on the SOM planes. However, rotifers were mainly represented in spring and autumn, while both cladocerans and copepods were relatively dominant during the higher temperature period, including summer.

DISCUSSION

After obtaining the SOM results, the ten input variables were readily discernable on the hexagon matrices. The water temperature matrix could help the seasonal labels to classify and make distinctions. For instance, even in summer, we could easily distinguish rainy summer and non-rainy summer days by comparing the distributions of turbidity and discharge. The high value of DO in winter can be thought from two points of view. Firstly, low water temperature is able to enlarge the oxygen capacity of a water body. The second reason is the oxygen production of diatoms by photosynthesis during the winter period. In the lower Nakdong River, recurrent diatom blooms occur every winter. This was also conveyed by the SOM plane of chlorophyll *a*. Many case studies were conducted regarding winter diatom blooms in the Nakdong River (Ha *et al*., 1998, 2003; Jeong *et al*., 2003a). Especially *Stephanodiscus hantzschii* is well known as a predominant species during this period (Ha *et al*., 2003). The pH pattern may also be related to the diatom bloom. Shapiro (1990) explained pH concerning CO_2 complex with respect to blue-green algae. Low concentrations of carbon dioxide by the diatom bloom can contribute to an increase in pH values.

Secchi disc transparency was very low and it was matched with high turbidity on the SOM plane. However, high transparency was partly discrete with low turbidity. This is because meteorological conditions (e.g. irradiance time, light penetration, etc.) can largely affect to measure transparency. Interestingly, the transparency matrix could discriminate the influence of phytoplankton abundance, in contrast to the turbidity matrix. High concentrations of chlorophyll *a* decreased Secchi disc transparency during the winter period (De sève, 1993). On the turbidity matrix, it was difficult to discriminate the impact of chlorophyll *a*.

Zooplankton communities mostly dominated and were placed on similar positions of the SOM plane. However, rotifers exhibited high density in lower temperatures as compared with cladocerans and copepods. This matched the predominant period well. Generally, in the lower Nakdong River, zooplankton abundance has started to increase since March or April when water temperature goes up (Kim *et al*., 2000). At the beginning of the periods of zooplankton presence, rotifers were dominant and then cladocerans and copepods, which are bigger than rotifers were strongly dominant. During this period, the Nakdong River is seldom influenced by precipitation or high discharge. Swift grazing into phytoplankton occurs based on the macrozooplankton (i.e. cladocerans and copepods) activities (Kim *et al*., 2000). Thus, water transparency becomes very high, and this period is called the ‘Clear Water Phase’. This phenomenon was indirectly detected from the SOM plane of zooplankton community as compared with Secchi disc transparency. It was thought that cladocerans and copepods communities highly contributed to enhance water transparency, while rotifers’ effect was relatively low. Even though the cells containing the highest Secchi disc transparency values were relatively apart from the high zooplankton cells, these cells contained data from a serried of dates (i.e., April to May in 2000). The abundance of zooplankton communities in this period was higher than before and after this period (high transparency period, cladocerans, 109 ind. L^{-1}; copepods, 72 ind. L^{-1}; other periods, almost 0).

From the SOM results, many phenomena could be elucidated on the basis of limnological parameters. Normally modelling is required when researchers encounter difficulties in analyzing ecosystems directly, or need to predict the future dynamics of the ecosystems (Joo and Jeong, 2005). Researchers require feasible methods to explain and analyze their data set. From this point of view, the SOM model regarding zooplankton dynamics could be meaningful. First, this analysis was conducted on the basis of a non-linear algorithm as compared with traditional statistical approaches. Second, explaining and understanding the data sets is more easily acceptable through the visualization of the SOM. Moreover, a non-linear algorithm could be more effective and suitable for the elucidation of environmental parameters due to the complexity and non-linearity of ecosystems as well as the limitations in considering components.

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ABSTRACT

The aim of this study was to analyze the seasonal patterns of zooplankton community dynamics in the lower Nakdong River (Mulgum, RK; river kilometer; 27 km from the estuarine barrage), with a Self-Organizing Map (SOM) based on weekly sampled data collected over ten years (1994～2003). It is well known that zooplankton groups had important role in the food web of freshwater ecosystems, however, less attention has been paid to this group compared with other community constituents. A non-linear patterning algorithm of the SOM was applied to discover the relationship among river environments and zooplankton community dynamics. Limnological variables (water temperature, dissolved oxygen, pH, Secchi transparency, turbidity, chlorophyll *a*, discharge, etc.) were taken into account to implement patterning seasonal changes of zooplankton community structures (consisting of rotifers, cladocerans and copepods). The trained SOM model allocated zooplankton on the map plane with limnological parameters. Three zooplankton groups had high similarities to one another in their changing seasonal patterns. Among the limnological variables, water temperature was highly related to the zooplankton community dynamics (especially for cladocerans). The SOM model illustrated the suppression of zooplankton due to the increased river discharge, particularly in summer. Chlorophyll *a* concentrations were separated from zooplankton data set on the map plane, which would intimate the herbivorous activity of dominant grazers. This study introduces the zooplankton dynamics associated with limnological parameters using a non-linear method, and the information will be useful for managing the river ecosystem, with respect to the food web interactions.

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