SELF-ORGANIZING FEATURE MAP CLASSIFICATION AND ORDINATION OF ENDANGERED MEDICINAL PLANT (*GLYCYRRHIZA URALENSIS*) COMMUNITIES IN NORTH CHINA

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(Received 24th Feb 2022; accepted 20th May 2022)

Abstract. *Glycyrrhiza uralensis* is an endangered medicinal plant and is mainly distributed in semiarid and arid areas in Northern China. The conservation of this species and its communities is important and urgent. In the present work, we examined, by artificial neural network theory and methods, the ecological relationships of *G. uralensis* communities in Northern China, which is the basis for conservation. Data from 100 samples of 2 × 2 m were collected along a precipitation gradient from east to west in Northern China. Species composition data and environmental data were measured and recorded for each sample. Self-organizing feature map (SOFM) is an important and superior network in neural network theory, and SOFM clustering and SOFM ordination was used to analyze ecological relations of these community data. The results showed that there were twelve communities dominated by *G. uralensis* in Northern China. These communities represent almost all community types and distribution of *G. uralensis* in China. They had different characteristics in composition, structure and environment. Precipitation was the key environmental factor affecting *G. uralensis* populations and communities. Water condition was a limited factor for plant community distribution in semiarid and arid areas in Northern China. Topographical variables, such as elevation, slope and slope direction, were also important to the studied communities. Conservation for *G. uralensis* populations and communities must consider these relations. SOFM clustering and ordination were effective and useful techniques in the study of endangered medicinal plant community and should be applied more frequently.
Keywords: *neural network, quantitative analysis, medicinal plant conservation, G. uralensis communities, semi-arid and arid area*

Introduction

Medicinal plants are important natural resources and significant to people's health in many countries and regions, such as China, Pakistan, India, and so on (Nautiyal et al., 2009). Multivariate analysis is important in studies of ecological relations between medicinal plant community and environmental variables (Kathe, 2006). The objective of multivariate analysis is normally to generate hypotheses about the relationships between the composition of the plant community and the environmental factors which determine it (Zhang, 2011; Moniruzzaman et al., 2021). There are many multivariate analysis methods available in plant ecology, such as Two-way indicator species analysis (TWINSPAN) classification, Principal components analysis (PCA) and Detrended correspondence analysis (DCA) ordination etc. (ter Braak, 1986). With the development of mathematics and statistics, some new multivariate techniques were applied to ecology, such as Fuzzy Set Ordination (FSO) (Roberts, 2008) and Self-Organizing

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2004_36193629

Feature Map classification and Ordination (SOFM) (Giraudel and Lek, 2001; Song et al., 2020).

Self-organizing feature map is a type of artificial neural network (ANN) that is trained using unsupervised learning to produce a two-dimensional, discretized representation of the input space of the training samples, called a topology-preserving projection map, and it is therefore a method to do dimensionality reduction (Kohonen, 1982; Murugesan and Murugesan, 2021). Giraudel and Lek (2001) introduced SOFM into ecology, and successfully analyzed the distribution data of eight plant species in Southern Wisconsin by using this method. After that, SOFM clustering was compared with TWINSPAN and fuzzy C-means clustering in woodland study which confirmed its effectiveness (Zhang et al., 2010). SOFM ordination was applied and compared with PCA and DCA in the study of plant communities in the Taihang Mountains, which proved that they provided consistent results (Zhang et al., 2008). SOFM clustering and ordination have not been applied to studies of endangered medicinal plant communities and their conservation.

Glycyrrhiza uralensis is one of the most useful Chinese herbal medicines and widely used in medicine, food, tobacco, chemical industries in China (Zhou, 2006). Annual production of root medicine of this species is over 60000 tons in China. *Glycyrrhiza uralensis* is widely distributed from east to west in Northern China (*Fig. 1*). The wild resources of this medicinal species are reduced quickly since 1970s and it has been listed in the national endangered and protected plants and in IUCN red list as EN class. The conservation and restoration of this species and its community become urgent (Zhang et al., 2011). The objectives of this study are: 1) to apply SOFM clustering and ordination to the analysis of endangered medicinal plant (*G. uralensis*) community study and to test the effectiveness of these methods; 2) to analyze the relationships between *G. uralensis* communities and environmental variables and test the hypothesis that precipitation is the key factor to its populations and communities.

Materials and methods

Self-organizing feature map (SOFM)

Artificial neural networks (ANN) are comparatively new mathematical theory and have already been successfully used in ecology (Giraudel and Lek, 2001). Based on the mechanism of the human brain, the Artificial Neural Network is a convenient alternative tool to traditional statistical methods. The Kohonen Self-Organizing Feature Map (SOFM) is one of the most well-known neural networks with unsupervised learning rules (Kohonen, 1982).

SOFM uses unsupervised learning and produces a topologically ordered output that displays the similarity between the samples presented to it (Foody, 1999). The network consists of two layers, input layer and output layer (Schalkoff, 1992; Suding et al., 2008). The input layer contains a unit (neuron) for each variable (species) in the plant community data set. The output layer is a two-dimensional array of units and each of these units is connected to the input layer unit by the associated weight. The learning is a competitive process in which the network adapts to respond in different locations for input that differs. Consequently, samples that are similar should be associated with units that are close together in the output layer while a dissimilar sample would be associated with a distant unit elsewhere in the output layer (Chon et al., 1996).

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SOFM clustering

Suppose the input data vector:

$$P_k = (P_1^k, P_2^k, ..., P_N^k),\ (k = 1, 2, \ldots, q) \quad \text{(Eq.1)}$$

The associated weight vector,

$$W_{ji} = (W_{j1}, W_{j2}, ..., W_{ji}, ..., W_{jN})\ \ i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, M \quad \text{(Eq.2)}$$

Then, the SOFM clustering procedure:

1. Initializing. Giving initial values of W_{ij} within [0, 1] randomly (i = 1, 2, …, N; j = 1, 2, …, M), initial values of learning rate $\eta(0)$ and neighborhood $Ng(0)$, and determining total learning times T.

2. Inputting a random sample unit drawn from the input dataset P_k into the network and calculating $\overline{P}_k$:

$$\overline{P}_k = \frac{P_k}{\|P_k\|} = \frac{(P_1^k, P_2^k, ..., P_N^k)}{\left[(P_1^k)^2 + (P_2^k)^2 + ... + (P_N^k)^2\right]^{1/2}} \quad \text{(Eq.3)}$$

3. Calculating $\overline{W}_j$:

$$\overline{W}_j = \frac{W_j}{\|W_j\|} = \frac{(W_{j1}, W_{j2}, ..., W_{jN})}{\left[(W_{j1})^2 + (W_{j2})^2 + ... + (W_{jN})^2\right]^{1/2}} \quad \text{(Eq.4)}$$

4) Calculating distance between $\overline{W}_j$ and $\overline{P}_k$ by Euclidean distance:

$$d_j = \left[\sum_{i=1}^{N} (\overline{P_i^k} - \overline{W_{ji}})^2\right]^{1/2}\ \ (j = 1, 2, \ldots, M) \quad \text{(Eq.5)}$$

5. Determining the minimum distance d_g, g is chosen as the winning neuron, called the Best Matching Unit (BMU).

$$d_g = \min\left[d_j\right]\ j = 1, 2, \ldots, M \quad \text{(Eq.6)}$$

6. Adjusting the weights W_{ji}:

$$\overline{W_{ji}(t+1)} = \overline{W_{ji}(t)} + \eta(t) \bullet \left[\overline{P_i^k} - \overline{W_{jt}(t)}\right]\ (j = 1, 2, \ldots, M) \quad \text{(Eq.7)}$$

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where $\eta(t)$ is the learning rate at t time, here we define it as follows:

$$\eta(t) = \eta(0)(1 - t/T) \;\; (0 < \eta(0) < 1) \qquad \text{(Eq.8)}$$

The neighborhood $N_g(t)$ is defined:

$$N_g(t) = \mathrm{INT}[N_g(0)(1 - t/T)] \qquad \text{(Eq.9)}$$

$N_g(0)$ is the initial value of $N_g(t)$.

7. Increasing time t to $t + 1$. If $t < T$ then go to step 2), else stop the training.

The final topology map of small squares containing sample units can be used to classify samples into groups (Zhang et al., 2010). The number of small squares is usually determined according to the number of samples. We use 9 × 9 small squares for 100 samples (Chon et al., 1996).

SOFM ordination

Based on the topology map of small squares containing sample units above, a general ordination diagram can be obtained by rescaling the axes: considering the map of small squares of 9 × 9 is a diagram with coordinate scores of [0.0 – 9.0], and each sample has its two-dimensional scores. Rescaling is the transformation of these scores into coordinate values between 0.0 and 1.0 (Zhang et al., 2008).

G. uralensis community data

In order to clarify the wild resources of *Glycyrrhiza uralensis*, a general survey was carried out in 2015. According to its community distribution, five study regions, Chifeng and Hengjinqi (Inner Mongolia), Minqin (Ganshu), Aletai and Kashi (Xinjing) along a precipitation gradient from east to west in Northern China, were selected as sampling sites (Zhang et al., 2011) (*Fig. 1*). Twenty samples (quadrats) of 5 m × 5 m were set up randomly at each site. The species names, cover, mean height, and individual number was investigated in each sample. The cover was estimated by eyes, and the height was measured by use of a tape ruler. Totally 191 plant species were recorded in 100 samples. Elevation, slope and aspect for each sample were also measured and recorded. The elevation was measured by a GPS, slope and aspect measured by a compass meter.

The Importance Value (IV) of species was calculated and used as data in SOFM clustering and ordination analysis. The importance value was calculated by the following formulas (Zhang, 2011):

$$IV_{Shrubs} = \text{(Relative abundance +Relative cover + Relative height)/3} \qquad \text{(Eq.10)}$$

$$IV_{Herbs} = \text{(Relative cover + Relative height)/2} \qquad \text{(Eq.11)}$$

The relative abundance refers to the percentage of one species abundance over the sum of all species abundance in a sample, relative cover to the percentage of one species cover over the sum of all species cover in a sample, and relative height to the percentage of one species mean height over the sum of all species mean height in a sample. The species data matrix is consisted of importance values of 191 species in 100 samples.

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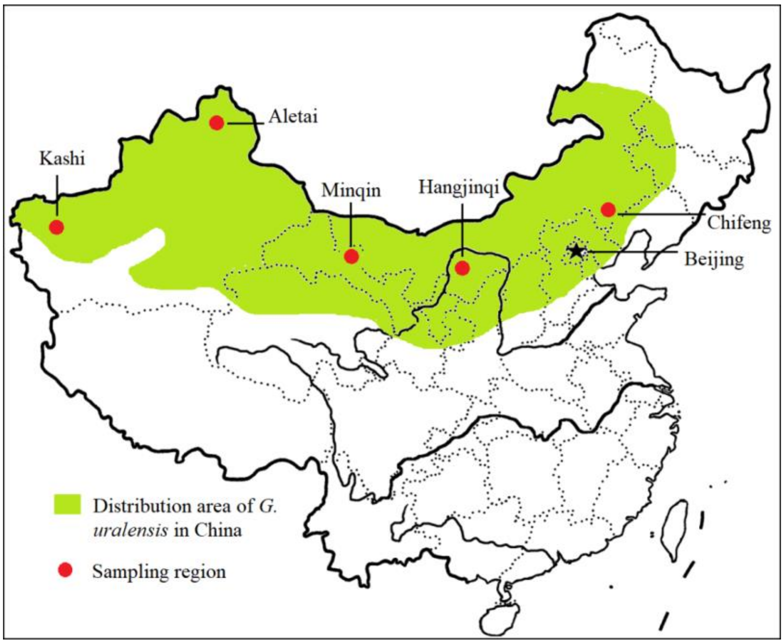

Figure 1. *The distribution area of Glycyrrhiza uralensis in China and the five sampling regions*

Results

In this study, SOFM was carried out with the learning rate of 0.1 for the ordinating phase and 0.02 for adjusting phase, 5000 steps for the ordinating phase and 50 000 steps for the tuning phase. A map of 9 × 9 small squares was chosen for 100 samples. When the learning process is finished, a topology map of 9 × 9 small squares is obtained and samples units can be mapped into the corresponding squares (*Fig. 2*).

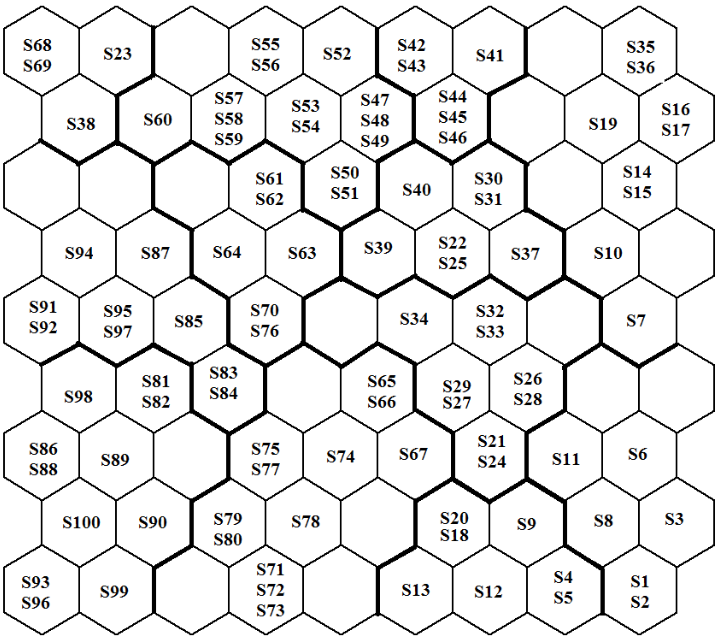

Figure 2. *The topology map of 100 samples of Glycyrrhiza uralensis communities in 9 × 9 small squares from self-organizing feature map (SOFM) clustering. S with number refers to sample and its ordinal number*

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According to the similarity of neurons (units), small squares were clustered into 12 groups (*Fig. 3*). Samples in each neuron group constituted a community, and therefore 100 samples were classified into 12 *Glycyrrhiza uralensis* communities (*Table 1*). These communities represent the general vegetation types of *Glycyrrhiza uralensis* in Northern China (Zhang et al., 2011). The main characteristics of community composition, structure and environment were listed in *Table 2*.

Table 1*. Twelve Glycyrrhiza uralensis communities and their composition of samples recognized by SOFM clustering along a precipitation gradient in Northern China*

Community number	Sample composition
I	1, 2, 3, 6, 8, 11
II	4, 5, 9, 12, 13, 18, 20
III	7, 10, 14, 15, 16, 17, 19, 35, 36
IV	21, 24, 26, 27, 28, 29, 32, 33, 34
V	22, 25, 30, 31, 37, 39, 40
VI	41, 42, 43, 44, 45, 46, 54
VII	47, 48, 49, 50, 51, 52, 53, 55, 56, 57, 58, 59, 60
VIII	23, 38, 68, 69
IX	61, 62, 63, 64, 70, 76
X	65, 66, 67, 71, 72, 73, 74, 75, 77, 78, 79, 80
XI	83, 84, 85, 87, 91, 92, 94, 95, 97
XII	81, 82, 86, 88, 89, 90, 93, 96, 98, 100

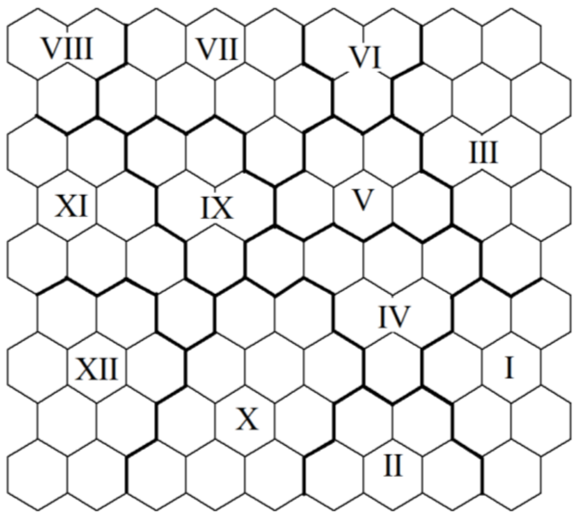

Figure 3. *The groups of neurons on the SOFM topology map from self-organizing feature map (SOFM) clustering. I-XII refer to the twelve groups and Glycyrrhiza uralensis communities in Northern China*

Variations of abundance (importance value) of dominant species among these communities were clearly shown by *Figure 4*. Each dominant species has its own distribution area and center.

By rescaling, a general SOFM ordination diagram was obtained (*Fig. 5*). The first SOFM axis was a precipitation gradient, i.e. the precipitation was increased from left to right. The second SOFM axis represented a comprehensive gradient of elevation, slope and aspect.

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Table 2. *The characteristics of the twelve Glycyrrhiza uralensis communities recognized by SOFM clustering along a precipitation gradient in Northern China*

Community number and name	Community cover (%)	*G. uralensis* cover (%)	*G. uralensis* density (n/ha^{-1})	Elevation (m)	Slope (°)	Aspect	Common species
I. Comm. *Glycyrrhiza uralensis* + *Stipa bungeana*	75	25	3600	380 - 605	10-20	S, WS, ES	*Ziziphus jujuba* var. *spinosa*, *Lespedeza darurica*, *Pedicularis resupinata*, *Potentilla anserine*, *Saussurea epilobioides*, *Artemisia sacrorum*, *Artemisia mongolica*, and *Cynanchum hancockianum*
II. Comm. *Glycyrrhiza uralensis* + *Aneurolepidium chinense*	80	28	3950	350 - 650	10-20	S, WS	*Haloxylon Ammodendron*, *Caragana pygmaea*, *Lespedeza darurica*, *Berberis sibirica*, *Stipa glareosa*, *Artemisia mongolica*, *Cynanchum hancockianum*, *Carex duriuscul*, and *Carex stenophylloides*
III. Comm. *Glycyrrhiza uralensis* + *Potentilla anserine*	80	26	4120	350 - 580	10- 25	S, WS, ES	*Lespedeza darurica*, *Artemisia mongolica*, *Stipa bungeana*, *Vicia amoena*, *Carex duriuscul*, and *Saussurea amara*
IV. Comm. *Glycyrrhiza uralensis* + *Artemisia ordosica*	85	27	3680	300 - 650	15- 30	S, WS, ES, W, E	*Caryopteris mongolica*, *Lespedeza darurica*, *Artemisia mongolica*, *Stipa bungeana*, *Trigonella ruthenica*, *Trigonella ruthenica*, *Astragalus melilotoides*, and *Ephedra przewalskii*
V. Comm. *Glycyrrhiza uralensis* + *Carex duriuscul* + *Aneurolepidium chinense*	75	25	4500	300 - 600	20-30	S, WS, ES, W	*Lespedeza darurica*, *Haloxylon Ammodendron*, *Berberis sibirica*, *Cynanchum hancockianum*, *Stipa glareosa*, *Caragana pygmaea*, *Artemisia scoparia*, *Carex stenophylloides*, and *Astragalus melilotoides*
VI. Comm. *Glycyrrhiza uralensis* + *Polygonum bistorta*	70	35	5700	300 - 500	20- 30	S, WS, ES, W	*Oxytropis myriophylla*, *Polygonum divaricatum*, *Adenophora gmeliniia*, *Potencilla acaulis*, *Suaeda prostrate*, *Astragalus melilotoides*, *Allium condensatum*, *Artemisia ordosica*, and *Oxytropis grandiflora*
VII. Comm. *Glycyrrhiza uralensis* + *Ephedra przewalskii* + *Cancrinia discoidea*	70	40	59500	300 - 500	20-30	S, WS, ES, W, E	*Caragana korshinskii*, *Elaeagnus*, *mooceroftii*, *Suaeda prostrate*, *Artemisias phaerocephala*, *Saussurea laciniata*, *Saposhnikovia divariicata*, *Oxytropis glabra*, and *Artemisia ordosica*
VIII. Comm. *Glycyrrhiza uralensis* + *Astragalinae triloa* + *Stipa sareptana*	75	40	6000	400 - 700	10-30	S, WS, ES	*Artemisia scoparia*, *Kochia prostrate*, *Potencilla acaulis*, *Artemisia frigida*, *Ceratoides lates* and *Atraphaxis frutescus*
IX. Comm. *Glycyrrhiza uralensis* + *Carex pediformis* + *Stipa sareptana*	60	33	5500	350 - 650	15-35	S, WS	*Cleistogenes squarrosa*, *Caragana pygmaea*, *Hordeum brevisublatum*, *Ephedra sinica*, *Achnatherum sibiricum*, *Artemisia frigida*, *Viola tianschanica*, *Carex duriuscula*, and *Alopecurus pratensis*
X. Comm. *Glycyrrhiza uralensis* + *Artemisia frigida*	65	37	4900	280 - 500	15-25	S, WS, ES	*Salicornia Bigelivii*, *Carex duriuscula*, *Stipa sareptana*, *Artemisias phaerocephala*, *Alopecurus pratensis*, *Saposhnikovia divariicata*, and *Carex pediformis*
XI. Comm. *Glycyrrhiza uralensis* + *Aneurolepidium chinense* + *Stipa sareptana*	70	29	4100	400 - 750	15-35	S, WS, ES	*Caragana pygmaea*, *Astragalinae triloa*, *Stipa parpurea*, *Festuca logae*, *Artemisia kaschgarica*, *Polygonum viiiparum*, *Ephedra equisetina*, *Glycyrrhiza inflate*, and *Alyssum desertorum*
XII. Comm. *Glycyrrhiza uralensis* + *Festuca logae* + *Stipa sareptana*	80	30	4000	400 - 800	20-35	S, WS, ES	*Artemisia parvula*, *Scorzonera divaricata*, *Roegneria kamoji*, *Potentilla bifurca*, *Carex duriuscula*, and *Ranunculus japonicas*

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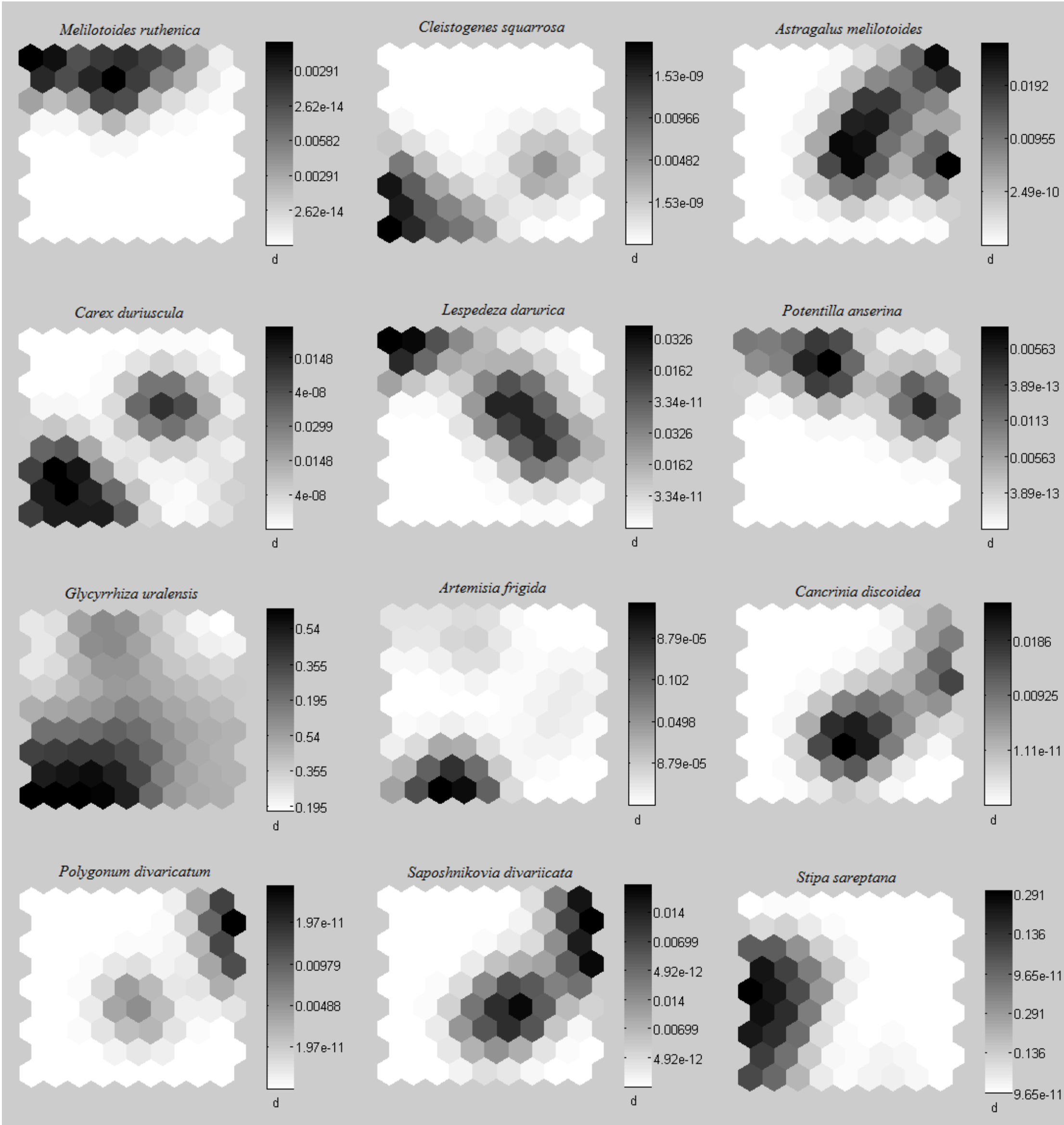

Figure 4. *The variation of abundance of the dominant species on the topology map from Self-organizing feature map (SOFM) clustering of Glycyrrhiza uralensis communities in North China*

Discussion

SOFM clustering classified 100 samples into 12 communities dominated by *Glycyrrhiza uralensis* in Northern China. These communities varied in composition, structure, distribution and environmental conditions. They distribute from temperate moisture grassland in eastern area, through dry steppe and desert grassland in middle area, and to temperate desert regions in western area and represent the general vegetation communities of *G. uralensis* from east to west in Northern China. To conserve wild medicinal plant resources of *G. uralensis*, the conservation of these communities is important because these communities provide suitable survival environment for the studied populations (Pan and Zhang, 2002). These vegetation types are also significant for protecting and improving the ecological environment in semi-

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arid and arid regions in northern and western China (Wu, 1980; Zhang et al., 2010). The SOFM classification results were reasonable according to the Chinese vegetation classification system. These results were consistent with that of TWINSPAN classification and fuzzy C-means clustering (Zhang et al., 2010; Song and Zhang, 2017), which suggests that SOFM clustering was useful and significant in analysis of endangered medicinal plant communities.

The variation of dominant species on the SOFM topology map showed their importance roles in clustering and in community structure and composition. These species living in *Glycyrrhiza uralensis* communities and have close relationships with it. To conserve these species will be helpful to the conservation of *Glycyrrhiza uralensis* populations and communities (Pan and Zhang, 2002; Zhang et al., 2011; SuriGuga et al., 2011; Moniruzzaman et al., 2021).

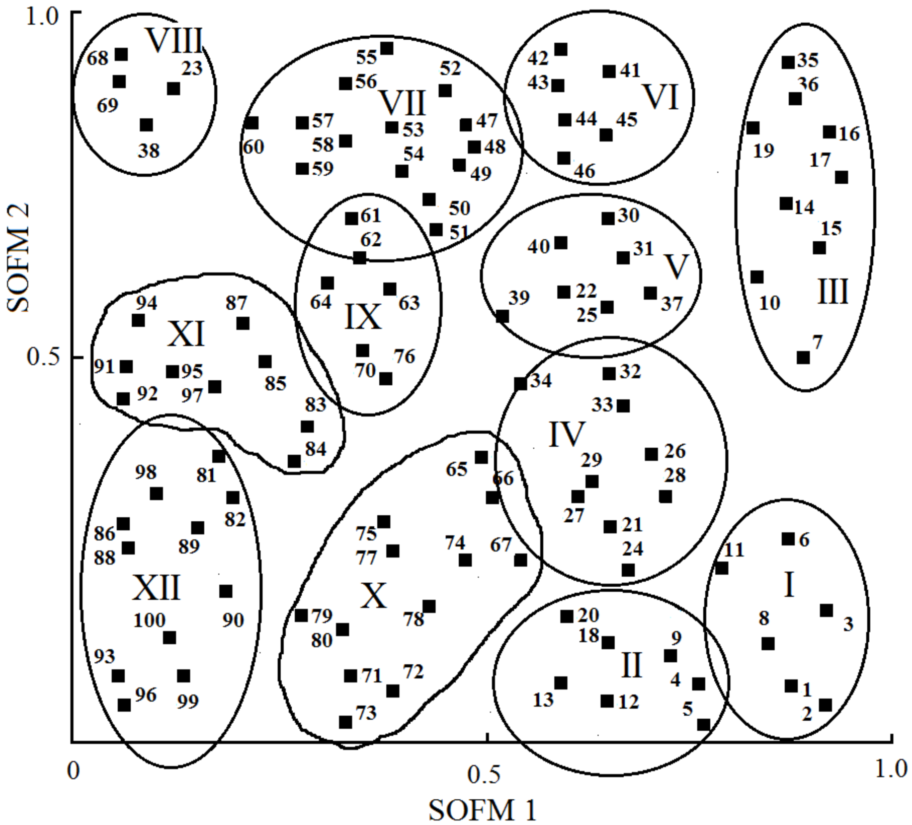

Figure 5. *The Self-organizing feature map (SOFM) ordination diagram of 100 samples of Glycyrrhiza uralensis communities in Northern China. Numbers refer to samples, and I-XII refer to the twelve Glycyrrhiza uralensis communities*

SOFM ordination displayed samples more clearly in topological space, which is identical to the result of SOFM clustering. Each community recognized by SOFM clustering had its own distribution area and center with clear boundary, which confirmed that SOFM clustering results were reasonable and reflected their differences of composition, structure and natural conditions. The first SOFM ordination axis was a precipitation gradient, which means that annual precipitation was the most important and key factor influencing *Glycyrrhiza uralensis* populations and communities. This is because water conditions are limitation variable in semi-arid and arid area for

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vegetation maintaining and development in Northern China (Zhang et al., 2011; Cullotta et al., 2015; Song et al., 2020). This result is consistent with other studies in this area (Zhang et al., 2010). The second SOFM ordination axis was a comprehensive gradient of elevation, slope and aspect, which suggested that topographical variables were also significant for *Glycyrrhiza uralensis* populations and communities. Similar as SOFM clustering, SOFM ordination was useful and significant in analysis of endangered medicinal plant communities.

To conserve *Glycyrrhiza uralensis* populations and communities, the management of wild *G. uralensis* and its communities must be legally and effectively, e.g. digging must be strictly controlled and grazing in these communities should be limited to keep its ecosystem composition, structure and function. Soil fertilization and irrigation, if possible, should be used for improving their habitat conditions. To meet the demands for medicinal market, more large-scale cultivation bases of *G. uralensis* should be set up and developed in different area in northern China. Studies on biology, ecology, economy, utilization etc. for *G. uralensis* species, populations and communities must be strengthened (Zhou, 2006; Larsen and Olsen, 2007; Zhang et al., 2011).

Theoretically, Self-Organizing Feature Map neural network has advantages in solving non-linear problems and in studying complicated systems (Schalkoff, 1992; Park, 2003; Zhang et al., 2008; Murugesan and Murugesan, 2021). Medicinal plant community system is a complexity ecosystem with various non-linear and fuzzy relationships of species, communities and environmental variables (Sproull et al., 2015). Therefore, SOFM techniques should be perfect methods and applied more frequently in endangered medicinal plant community studies, and it may be suggestible to combine SOFM clustering and SOFM ordination in a same study (SuriGuga et al., 2011).

Acknowledgments. This study was financially supported by the Young Teachers Found of Beijing University of Chinese Medicine (Grant No. 2018-JYB-JS), National Natural Science Foundation of China (Grant No. 31170494).

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DOI: http://dx.doi.org/10.15666/aeer/2004_36193629