Article

Hierarchicalization of chaotic food webs using Interpretive Structural Modeling

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Abstract
Ecologists always meet complex food webs without clear hierarchical structure. At certain degree it will retard further analysis of food webs. In present study we transferred chaotic food webs into hierarchicalized food webs using Interpretive Structural Modeling (ISM). As an example, the hierarchical structure of seven food webs was clearly identified and defined using ISM. ISM was thus proven to be effective.

Keywords Interpretive Structural Modeling; food web; hierarchicalization.

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1 Introduction

Food webs are complex networks to describe the relationship between species. Food webs are mainly divided into two types, herbivorous food webs and saprophagous food webs. The earliest definition of the food web was made by Darwin in 1859, which was described as an entirety bounded together through a complex and well-connected network (Huang and Zhao, 1992). Food web studies had stagnated since MacArther published his famous study on the food web. Since mid-20th century, the studies on food webs have being quickly increased (Briand, 1983). Up till now, a large number of food web studies were conducted using various quantitative methods, such as network analysis (Cohen, 1978, 1988; Cohen et al., 1990; Matsuda and Namba, 1991; Martinez et al., 1992; Dunne et al., 2002; Montoya et al., 2006; Arii et al.,2007; Bascompte and Jordano, 2007; Vazquez et al., 2007; Hegland et al., 2009; Dormann, 2011; Zhang, 2011, 2012).

One of current focuses on food web research is trophic level-based food webs (Cohen, 1988). In a typical food web, various trophic levels form a pyramid structure (Lawton, 1989). Species, their abundance and stability in the same trophic level determine the function and structure of food webs (Paine, 1966; Polis and Winemiller, 1996). In such a food web, the loss of any species may reduce stability of the ecosystem. To study the hierarchical structure and trophic levels of the food web will facilitate the analysis of species diversity, ecosystem stability and functional characteristics.

After many years of observation studies, researchers have established various food web databases also. Among which Interaction Web Database is a detailed and open access database that includes seven types of food webs, Anemone-fish, Host-parasite, Plant-ant, Plant-herbivore, Plant-pollinator, Plant-seed disperser, and Predator-prey food webs.

Food web research starts from the analysis on hierarchical structure of food webs. Interpretive Structural Modeling (ISM) is an approach for analyzing complex socio-economic systems. It can be used to transfer a system with chaotic structure to a system with distinct hierarchical structure (Warfield et al., 1972). ISM is mostly used to analyze direct and indirect between-element relationships, and to find crucial factors, etc. Ecologists always meet food webs with a large number of species and complex interactions. Thus ISM will provide an effective tool for hierarchicalization of such food webs.

Based on the seven food webs in Interaction Web Database, the present study tried to transfer the chaotic food webs into the structural models with distinct hierarchical structure using ISM, in order to provide the basis for in-depth food web research.

2 Material and Methods

2.1 Data sources

Data were collated from Interaction Web Database (http://www.nceas.ucsb.edu/interactionweb/). Seven typical food webs, namely Anemone-fish, Host-parasite, Plant-ant, Plant-herbivore, Plant-pollinator, Plant-seed disperser, Predator-prey food webs in the database were used. Food webs selected are described as follows:

(1) Anemone-fish food web: recorded from the coral reef of Manado region, Sulawesi, Indonesia. It contains 8 species of anemones, 7 species of fish.

(2) Host-parasite food web: recorded from the freshwater reservoir, Ontario, Canada. It includes 6 species of hosts, 25 species of parasites.

(3) Plant-ant food web: recorded from the rainforest, Peru. It contains 8 species of plants, 18 species of ants.

(4) Plant-herbivore food web: recorded from Finland. It contains 5 species of plants, 64 species of herbivores.

(5) Plant-pollinator food web: recorded from rocks and open herbaceous communities, Azores Islands. It consists of 10 species of plants, 12 species of pollinators.

(6) Plant-seed disperser food web: recorded from the tropical rain forest, Central Panama. It contains 13 species of plants, 11 species of seed dispersers.

(7) Predator-prey food web: recorded from the pine forest, Otago, New Zealand.

Assign each species in seven food webs an ID number. Obtain between-species relationships from the database, in which 0 denotes no trophic connection, 1 denotes a trophic connection, and other values denote frequencies.

2.2 Interpretive Structural Modeling

Interpretive Structural Modeling (ISM) enables the structuring of ‘elements’ *vs*. any transitive relationship. A transitive relationship is one in which the following property holds (Wikipedia): If element ‘A’ → element ‘B’ AND ‘B’ → element ‘C’ THEN ‘A’ MUST → ‘C’ (where ‘→’ stands for the transitive relationship under consideration).

ISM can be used to transfer a system with complex and ambiguous elements and relationships into several subsystems. A multi-level hierarchical and structural model is then constructed. Finally, the internal structure and hierarchy of the system can be determined according to the known relationships between the elements. It lays the basis for system optimization analysis.

ISM analysis of the food web follows these procedures:

(1) Identification of key species

Each species in seven food webs is recorded as a key species and assigned an ID number.

(2) Determine feeding relationship

In each of seven food webs, 0 denotes no trophic connection, 1 denotes a trophic connection, and other values denote frequencies. Feeding relationship is thus determined.

(3) Establish adjacency matrix

An element of adjacency matrix A shows feeding relationship between row species and column species (Zhang, 2012). Assume there are n species in the food web, a $n\times n$ adjacency matrix, $A=(a_{ij})_{n\times n}$, can be obtained. Species S_i is fed by species S_j, if $a_{ij}=1$; species S_i is not fed by species S_j, if $a_{ij}=0$.

(4) Establish reachability matrix

An non-zero element of reachability matrix M means that row species can reach column species. $M=(m_{ij})_{n\times n}=(A+I)^n$. $m_{ij}=1$, means row species S_i can directly or indirectly affect column species S_j.

(5) Establish structural model (antecedent set and attainable set)

$P(S_i)$ is called the attainable set, i.e., the set of species that species S_i can reach. $P(S_i)$ can be obtained through examining all column species that the element are 1's in the ***i***-th row of M. $Q(S_i)$ is called the antecedent set, i.e., the set of species that can reach species S_i. $Q(S_i)$ can be obtained through examining all row species that the element are 1's in the ***i***-th column of M.

Calculate the species set at level 1, $L_1=\{S_i \mid P(S_i)\cap Q(S_i)=P(S_i)\}$, and then delete the rows and columns of matrix M corresponding to the species in L_1. The matrix M' can be thus obtained. Operate M' to find the species of L_2 at level 2. Repeat this procedure, L_3, L_4, L_5…, can thus be calculated. By doing so, all species are assigned to corresponding levels.

(6) Establish interpretive structural model

L_1 contains species at level 1; L_2 contains species at level 2, etc. Finally, rows and columns of matrix M are re-arranged according to this sequence. M is thus transferred to a partitioned and triangularized matrix. Connect species between adjacent levels and species at the same level with directed edges. The hierarchical structure of the food web can then be clearly determined.

3 Results and Discussion

3.1 Anemone-fish food web

Table 1 shows the species IDs in the Anemone-fish food web.

Table 1 Species IDs in the Anemone-fish food web.

Genus	Species	ID	Genus	Species	ID
Amphiprion	*Clarkia*	1	*Entacmaea*	*Quadricolor*	9
Amphiprion	*Melanopus*	2	*Heteractis*	*Magnifica*	10
Amphiprion	*Ocellaris*	3	*Stichodactyla*	*Mertensii*	11
Amphiprion	*Perideraion*	4	*Heteractis*	*Aurora*	12
Amphiprion	*Polymnus*	5	*Stichodactyla*	*Haddoni*	13
Amphiprion	*Sandaracinos*	6	*Macrodactyla*	*Doreensis*	14
Premnas	*Biaculeatus*	7	*Heteractis*	*Malu*	15
Heteractis	*Crispa*	8			

Construct the adjacency matrix, $A=(a_{ij})_{n\times n}$, based on Table 1, in which species S_i is fed by species S_j, if a_{ij}=1; species S_i is not fed by species S_j, if a_{ij}=0. The adjacency matrix A is

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
9	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0
10	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
11	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
14	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Conducting ISM procedures above, the results are as follows:

Level 1 Species 8
Level 1 Species 9
Level 1 Species 10
Level 1 Species 11
Level 1 Species 12
Level 1 Species 13
Level 1 Species 14
Level 1 Species 15
Level 2 Species 1
Level 2 Species 2
Level 2 Species 3
Level 2 Species 4
Level 2 Species 5
Level 2 Species 6
Level 2 Species 7

Therefore, there are two functional levels (groups) in the Anemone-fish food web, which is coincident with the composition of the food web, i.e., anemones and fish. Level 1 includes the species No. 8-15, and Level 2 includes species No. 1-7. The interpretive structural model of the Anemone-fish food web is indicated in Fig. 1.

From Fig. 1, we conclude that the Anemone-fish food web is relatively stable. The loss of a species at a level can be replaced by other species at the same level. However, functional diversity of the food web is not ideal (only two functional groups).

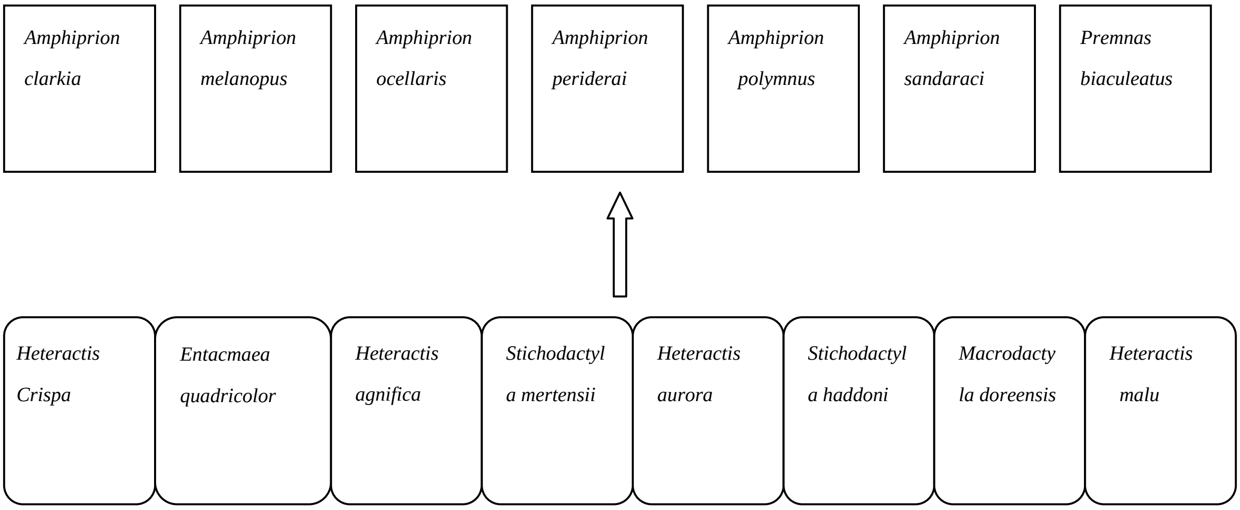

Fig. 1 Interpretive structural model of the Anemone-fish food web.

3.2 Host-parasite food web

Table 2 shows the species IDs in the Host-parasite food web.

Table 2 Species IDs in the Host-parasite food web.

Genus	Species	ID	Genus	Species	ID	Genus	Species	ID
Salmo	*salar*	1	*Phyllodistomum*	*lachancei*	12	*Capillaria*	*salvelini*	23
Salvelinus	*fontinalis*	2	*Triaenophorus*	*Crassus*	13	*Metabronema*	*salvelini*	24
Salvelinus	*namaycush*	3	*Triaenophorus*	*crassus (L)*	14	*Metechinorhynchus*	*lateralis*	25
Coregonus	*clupeaformis*	4	*Eubothrium*	*salvelini*	15	*Neoechinorhynchus*	*crassus*	26
Esox	*lucius*	5	*Diphyllobothrium*	*sp. (L)*	16	*Ergasilus*	*caeruleus*	27
Catostomus	*catostomus*	6	*Proteocephalus*	*pinguis*	17	*Salmincola*	*Salmincola*	28
Tetraonchus	*monenteron*	7	*Proteocephalus*	*tumidocollus*	18	*Salmincola*	*coregonorum*	29
Discocotyle	*sagittata*	8	*Proteocephalus*	*sp.1*	19	*Salmincola*	*edwardsii*	30
Crepidostomum	*farionis*	9	*Proteocephalus*	*sp.2*	20	*Salmincola*	*siscowet*	31
Crepidostomum	*cooperi*	10	*Raphidascaris*	*sp.*	21			
Phyllodistomum	*coregoni*	11	*Raphidascaris*	*canadensis*	22			

Similar to the above procedure, we obtained the adjacency matrix *A* as the following:

0	0	0	0	0	0	0	1	0	1	0	1	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	1	1	0	0	1	0	0	1	1	0	1	1	1	1	0	1	1	1	0	0	0	0	1	0
0	0	0	0	0	0	1	0	1	1	0	1	0	1	1	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	1	0	1	1	1	1	0	1	0	0	0	0	1	1	0	0
0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The results indicate that Level 1 has 6 species, species No. 1-6, and Level 2 has 25 species, species No. 7-31. The interpretive structural model of the Host-parasite food web is indicated in Fig. 2. The host is largely responsible for the reproduction and growth of its parasites (Holling, 1973). In the Host-parasite food web, the species in Level 1 are less than the species in Level 2. Relatively, the matter and energy flow are easily blocked, and the food web is easily disturbed (Winter, 1990).

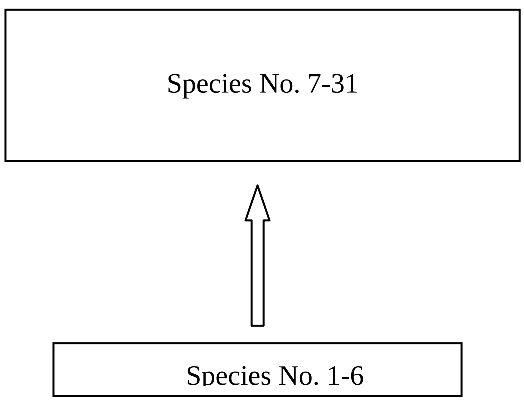

Fig. 2 Interpretive structural model of the Host-parasite food web.

3.3 Plant-ant, Plant-herbivore, Plant-pollinator, and Plant-seed disperser food webs

The ISM results for Plant-ant, Plant-herbivore, Plant-pollinator, and Plant-seed disperser food webs are concluded as follows.

Plant-ant food web: Level 1: 8 plant species; Level 2: 18 ant species.

Plant-herbivore food web: Level 1: 5 plant species; Level 2: 64 herbivore species.

Plant-pollinator food web: Level 1: 10 plant species; Level 2: 12 pollinator species.

Plant-seed disperser food web: Level 1: 13 plant species; Level 2: 11 seed disperser species.

For both Plant-ant and Plant-herbivore food webs, the number of species in Level 2 is much greater than that in Level 1. The feeding relationship between Level 1 and 2 is close. Level 2 is largely dependent upon Level 1 (Bai et al., 2004). In a sense, the two food webs are less stable. However in Plant-pollinator and Plant-seed disperser food webs, the number of species in Level 1 and 2 is similar to each other. In addition, the feeding relationship is not close. In a sense, the two food webs are relatively stable (Paine, 1992; McCann et al., 1998; Berlow, 1999).

3.4 Predator-prey food web

Table 3 shows the species IDs in the Predator-prey food web.

Table 3 Species IDs in the Predator-prey food web.

Species	ID	Species	ID	Species	ID
Unidentified detritus	1	*Austrosimulium*	18	*Paracalliope purple*	35
Plant material	2	*Cricotopus I*	19	*Paralimnophila*	36
Terrestrial invertebrates	3	*Cricotopus II*	20	*Podonomous*	37
Blue green algae	4	*Cristaperla*	21	*Polypedellum*	38
Auodinella	5	*Deleatidium*	22	*Psilachorema*	39
Rhoicosphenia curvata	6	*Eriopterini*	23	*Psychodid*	40
Navicula avenacea	7	*Eukiefidrella*	24	*Pycnocentria*	41
Unknown green algae	8	*Hydora nitida a*	25	*Scirtid brd*	42
Calothrix	9	*Hydora nitida l*	26	*Spaniocerca*	43
Cocconeis placentula	10	*Hydrobiosella stenocerca*	27	*Stenoperla prasinia*	44
Achnanthes lanceolata	11	*Hydrobiosis silvicola*	28	*Stictocladius*	45
Gomphonema angustatum	12	*Isopoda*	29	*Zelandobius*	46
Navicula pusio	13	*Lumbriculiid pink*	30	*Zelandoperla*	47
Synedra ulna	14	*Naonella*	31	*Crayfish*	48
Aotepsyche	15	*Nothodixa*	32	*Galaxias*	49
Aspectrotanypus	16	*Oligo I*	33		
Austroperla cyrene	17	*Paracalliope other*	34		

The results show that Level 1 has 15 species, Level 2 has 28 species, and Level 3 has 6 species. The interpretive structural model of the Predator-prey food web is indicated in Fig. 3.

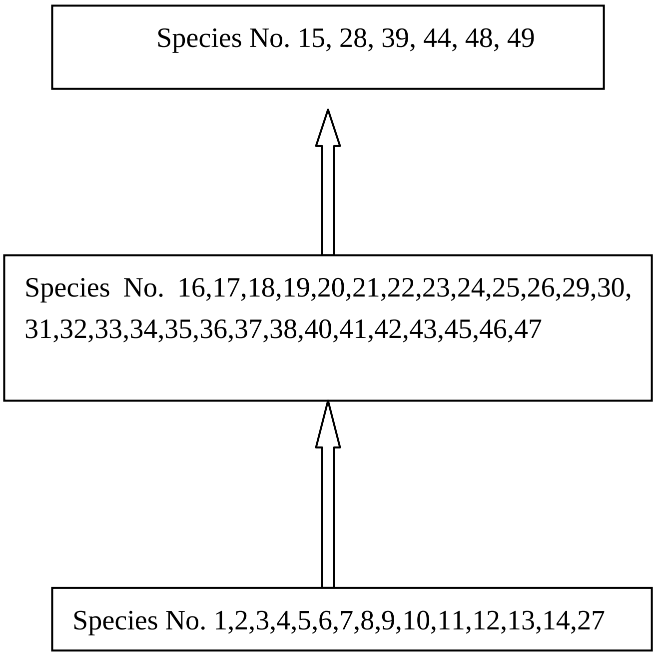

Fig. 3 Interpretive structural model of the Predator-prey food web.

It is obvious that the functional diversity of the Predator-prey food web is larger than other food webs. More diverse functional groups make the food web more stable (Korner, 1993; Grime, 1997). However, species distribution among these groups is less ideal.

4 Remarks

In the Interaction Web Database, Anemone-fish, host-parasite, Plant-ant, Plant-herbivore, Plant-pollinator, and Plant-seed disperser food webs have two trophic levels respectively; Predator-prey food web is more complex. The ISM results of present study were coincident with the definition in Interaction Web Database. ISM was thus proven to be effective. However, it should be noted that seven food webs used in present study are parts of complete ecosystems. All species in a food web are only a few from full species list of the corresponding ecosystems. Therefore the resulted food webs did not show a pyramid structure. ISM is encouraged for use in more practical food webs.

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