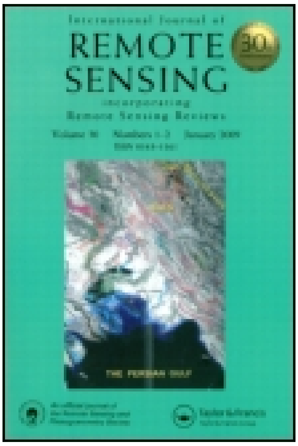

International Journal of Remote Sensing

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

Comparative analyses of the scaling diversity index and its applicability

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To cite this article: T.-X. Yue, S.-N. Ma, S.-X. Wu & J.-Y. Zhan (2007): Comparative analyses of the scaling diversity index and its applicability, International Journal of Remote Sensing, 28:7, 1611-1623

To link to this article: http://dx.doi.org/10.1080/01431160600887714

International Journal of Remote Sensing
Vol. 28, No. 7, 10 April 2007, 1611–1623

Comparative analyses of the scaling diversity index and its applicability

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(*Received 30 December 2005; in final form 24 February 2006*)

As well as the newly developed scaling diversity index, there are also eleven traditional diversity indices to be found in the literature. Analyses show that these eleven traditional indices are unable to formulate the richness component of diversity. In particular, the most widely used index, the Shannon-Weiner index, cannot express the evenness component. On the contrary, the scaling diversity index is able to formulate both the richness aspect and the evenness aspect of diversity. The scaling diversity index has been applied to developing scenarios of ecological diversity at different spatial resolutions and spatial scales. A case study in Fukang in the Xinjiang Uygur Autonomous Region in China shows that the scaling diversity index is sensitive to spatial resolution and is easy to understand. It is scientifically sound and could be operated at affordable cost.

1. Introduction

Species diversity has two components: richness, also called species density, based on the total number of species present, and evenness, based on the relative abundance of species and the degree of its dominance thereof (Odum 1983, Hamilton 2005). This concept has been used to formulate ecological diversity (Pielou 1975, Harper and Hawksworth 1996, Yue *et al.* 2001, 2002, 2003, 2004, 2005a,b).

Measuring ecological diversity has become a growth industry because of the great significance it has in studies related to ecosystems, ecosystem services, and their changes (Williams and Humphries 1996, Ibanez *et al.* 2005). Numerous indices of ecological diversity have been proposed. Unsatisfying diversity indices (table 1) have been criticized by many ecologists (Barrett 1968, Odum 1969, Pimm 1994, Harper and Hawksworth 1996, Beeby and Brennan 1997, Mladenoff *et al.* 1997, Yue *et al.* 1998, Ricotta 2002, Hoffmann and Greef 2003, Ricotta *et al.* 2004, Roy *et al.* 2004, Scholes and Biggs 2005). Odum (1969) stated that the Shannon-Weiner index (formula 1 in table 1) may obscure the behaviour of the two rather different aspects of diversity, richness and evenness. For example, in field experiments, an acute stress from insecticide reduced the number of species of insects relative to the number of

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160600887714

Table 1. Unsatisfying diversity indices.

Ordinal number	Formula	Explanation of parameters and variables	Reference
1	$H=-\sum_{i=1}^{m} p_i \,\mathrm{In}\, p_i$	p_i is the proportion of individuals found in the species i or the proportion of ecotope number in type i; m is the total number of species or ecotope types	Odum 1969
2	$HB=\frac{\mathrm{In}\, N!-\sum \mathrm{In}\, n_i!}{N}$	n_i is the number of individuals in the species i; N is the total number of individuals	Pielou 1966,
3	$d=\left(\sum_{i=1}^{m} p_i^2\right)^{-1}$	p_i is the proportion of individuals or biomass that contributes to the total in the sample; m is the total number of species in the community; d is Simpson's index	Harper and Hawksworth 1996
4	$HS=1-\sum p_i^2$	p_i is the proportion of individuals found in the species i	Simpson 1949
5	$N_a=\left(\sum_{i=1}^{m} (p_i)^a\right)^{\frac{1}{1-a}}$	N_a is the ath 'order' of diversity; p_i is the proportional abundance of the species i	Hill 1973
6	$D=\frac{\sum_{i=1}^{m} p_i \,\mathrm{In}\, p_i}{\mathrm{In}\, m}$	D is the measure of ecotope diversity; p_i is the proportion of the landscape in type i; m is the total number of ecotope types	Mladenoff *et al.* 1997
7	$d_{Mg}=\frac{m-1}{\mathrm{In}\, N}$	m is the number of species; N is the total number of individuals summed over all m species	Margalef 1957
8	$d_{Mn}=\frac{m}{N^{\frac{1}{2}}}$	m is the number of species; N is the total number of individuals summed over all m species	Whittaker 1977
9	$d=\frac{m}{\log N}$	m is the number of species and N is the number of individuals	McNaughton 1994
10	$d=\frac{N-\left(\sum n_i^2\right)^{\frac{1}{2}}}{N-N^{\frac{1}{2}}}$	n_i is the number of individuals in the species i; N is the total number of individuals	McIntosh 1967
11	$d=\frac{N_{\max}}{N}$	$N_{\max}$ is the number of individuals in the most abundant species; N is the total number of individuals	Berger and Parker 1970

individuals, but increased the evenness in the relative abundance of the surviving species (Barrett 1968). Thus, in this case, the 'richness' and 'evenness' components would tend to cancel each other. Harper and Hawksworth (1996) pointed out that the Shannon-Weiner index and the Simpson's index (formula 3 in table 1) are inadequate for some purposes because it is possible for high richness but less evenness to have a lower index than one that is less richness but high evenness. Beeby and Brennan (1997) described that various indices attempt to measure diversity, but no single measurement of diversity has yet been adopted as being the most effective under all circumstances.

Pimm (1994) reviewed the research history of the relation between diversity and stability and concluded that many diversity indices ignore evenness of species and look only at the species list itself. Many measures focus on the richness aspect of diversity. For instance, most policy-makers are used to seeing species diversity simply as the changing number of species on a species list (Mace 2005). Many studies (Yoshida 2003, Haberl *et al.* 2004, Uys *et al.* 2004, Hanski 2005, Hodgson *et al.* 2005, Ibanez *et al.* 2005) equated richness to diversity. Richness is necessary, but it is not sufficient to support the components of ecological diversity that underlie the key functions and benefits of an ecosystem (Mace 2005).

Ecological diversity is the result of ecological processes acting at various spatial and temporal scales (Alados 2004). Studies on scaling issues are burgeoning because of the increasing need for ecological modelling and simulation. They are driven by progress in remote sensing technologies to obtain data on various resolutions and by the integration of geo-referenced data collected at various scales (Martin *et al.* 2005). However, all diversity indices in table 1 ignore the important parameter of scale.

A useful measure of ecological diversity should be theoretically sound, be sensitive to changes at policy-relevant spatial scales, allow for comparison with a baseline situation and policy target, be usable in the simulation of scenarios, and be amenable to aggregation and disaggregation on local, national, regional, and international levels (Scholes and Biggs 2005). The soundness of the scaling diversity index is theoretically proven, and the effects of spatial resolutions on diversity calculation are analysed in this paper.

2. Theoretical analysis of diversity indices

2.1 *Drawbacks of the unsatisfying diversity indices*

Every diversity index in table 1 has no relation with the investigation area, so these diversity indices are unable to formulate the richness aspect. Because in recent years the Shannon-Weiner index is most widely used to formulate diversity (Alados 2004, Mueller *et al.* 2004, Roy *et al.* 2005, Sandstroem *et al.* 2006), it is taken as an example for analysing the drawbacks of the unsatisfying models in details.

2.1.1 If the Shannon-Weiner index were to be used, individuals of every species or every ecotope type should be greater than 100. Suppose that n_i is the individual number of species i or ecotope type i, m is the total species number or total ecotope type, and N is the total individual number of all species or total number of all ecotopes. Then,

$$N = \sum_{i=1}^{m} n_i \tag{1}$$

and

$$R = \frac{N!}{\prod_{i=1}^{m} n_i!} \tag{2}$$

then

$$H = \frac{\ln R}{N} = \frac{1}{N}\left(\ln N! - \sum_{i=1}^{m} \ln n_i!\right). \tag{3}$$

According to Stirling's formula

$$n! = \left(\frac{n}{e}\right)^n (2\pi n)^{\frac{1}{2}} e^{w(n)} \tag{4}$$

$$\begin{aligned} H &= \frac{1}{N}\left(\ln\left(\left(\frac{N}{e}\right)^N (2\pi n)^{\frac{1}{2}} e^{w(N)}\right) - \sum_{i=1}^{m} \ln\left(\left(\frac{n_i}{e}\right)^{n_i} (2\pi n_i)^{\frac{1}{2}} e^{w(n_i)}\right)\right) \\ &= -\sum_{i=1}^{m} p_i \ln p_i + \varepsilon(n_1, n_2, \ldots, n_m) \end{aligned} \tag{5}$$

where $\varepsilon(n_1, n_2, \ldots, n_m) = \frac{1}{2N}\left(\ln(2\pi N) - \sum_{i=1}^{m} \ln(2\pi n_i)\right) + \frac{w(N) - \sum_{i=1}^{m} w(n_i)}{N}$; $e=2.7183$; $p_i = \frac{n_i}{N}$; $\pi=3.1415$; and $\frac{1}{12(n+0.5)} < w(n) < \frac{1}{12n}$.

When $n_i \geqslant 100$, we can get an approximate formulation (Haken 1983), i.e.

$$H \approx -\sum_{i=1}^{m} p_i \ln p_i. \tag{6}$$

Shannon and Weaver (1962) gave this formulation the name, entropy, in regard to the mathematical form that expresses uncertainty (Peters 1975). This Shannon-Weiner index has been widely used by ecologists to formulate biodiversity.

2.1.2 The Shannon-Weiner index does not include any information of the area under investigation. Species number is closely associated with area or spatial scale (MacArthur and Wilson 1967, Williamson 1981). 'You will find more species if you sample a larger area' (Rosenzweig 1995). The Global Biodiversity Assessment (Bisby 1995) states that 'the central single measure of ecological diversity is species richness' and 'species richness is related to area in a complicated way, so we must exercise caution in comparing the diversities of areas that differ greatly in size'. The relation between species number and area has been formulated as (Arrhennius 1921, Preston 1960, 1962, Gorman 1979, Browne 1981)

$$\frac{m}{C} = \left(\frac{1}{A}\right)^{-D_0} \tag{7}$$

where m is the number of species, A is area, C is a constant, and D_0 is the Hausdorff dimension.

A research report, compiled by the World Conservation Monitoring Center in collaboration with The Natural History Museum, the World Conservation Union, the United Nations Environment Program, the World Wide Fund for Nature, and the World Resources Institute, indicates that 'a ten-fold decrease in area leads to a loss of half the species present' (Groombridge 1992). In this case, it is easy to get a calculation result, $D_0=0.301$.

Equation (7) shows that species number, taking $\frac{1}{A}$ as the scaling factor, has statistical self-similarity. The self-similarity is the property that at every scale of observation, new details are revealed; yet these details are reminiscent of details elsewhere in the structure of the object or in the same part of the object, but at a different scale (Iannaccone and Khokha 1996). The mathematician, Felix Hausdorff (1919), statistically defined such self-similarity as $D_0 = -\lim_{\varepsilon \to 0} \frac{\mathrm{In}\,N}{\mathrm{In}\,\varepsilon}$. When $\frac{\mathrm{In}\,N}{\mathrm{In}\,\varepsilon}$ is a constant, $N = (\varepsilon)^{-D_0}$ where ε is the scaling factor, D_0 the Hausdorff dimension, and N the fractal object. Obviously, area is so important that it has an essential effect on the number of species, but it is not included in the Shannon-Weiner index and other unsatisfying diversity indices (table 1).

2.1.3 The Shannon-Weiner index cannot express the 'evenness' component of diversity. For the Shannon-Weiner index, the essential function $f(x) = -x\,\mathrm{In}\,x$ is not strictly increasing because $\frac{df(x)}{dx} = -(\mathrm{In}\,x + 1)$. Thus, $\frac{df(x)}{dx}$ is, respectively, greater than zero, smaller than zero, and equals zero when x is smaller than 0.3679, greater than 0.3679, and equals 0.3679. In other words, $f(x) = -x\,\mathrm{In}\,x$ is increasing when x is smaller than 0.3679; it is decreasing when x is greater than 0.3679; and it reaches the maximum value when x equals 0.3679 (table 2). Therefore, when the individual proportion of the species i to total individuals of all species in the investigation region, p_i, is smaller than 0.3679, the contribution of p_i to the Shannon-Weiner index would increase with an increase of p_i; when p_i is greater than 0.3679, the contribution of p_i to the Shannon-Weiner index would decrease with an increase of p_i; and the contribution of p_i to the Shannon-Weiner index reaches maximum when p_i equals 0.3679. However, the Shannon-Weiner index has its maximum value, $\mathrm{In}\,m$, when $p_i = \frac{1}{m}$ (Alados *et al.* 2004). In other words, the Shannon-Weiner index is unable to express the evenness aspect of diversity.

2.2 *The scaling diversity index*

The scaling diversity index is expressed as (Yue *et al.* 2001, 2002, 2003, 2004)

$$D(\varepsilon, r, t) = -\frac{\ln\left(\sum_{i=1}^{m(\varepsilon, r, t)} (p_i(\varepsilon, r, t))^{\frac{1}{2}}\right)^2}{\ln \varepsilon} \tag{8}$$

where $p_i(\varepsilon, r, t)$ is a proportion of the area of the ith ecotope to the area of the whole investigation region or the individual number of the ith species to the total

Table 2. Relation between the function $f(x) = -x\,\mathrm{In}\,x$ and its independent variable x.

x	$f(x) = -x\,\mathrm{In}\,x$
0	0
0.00001	0.0001
0.0001	0.0009
0.001	0.0069
0.01	0.0461
0.1	0.2303
0.2	0.3219
0.3679	0.3679
0.4	0.3665
0.5	0.3466
0.6	0.3065
0.7	0.2497
0.8	0.1785
0.9	0.0948
1	0

individual number; $m(\varepsilon, r, t)$ is the total number of species or ecotopes under investigation; t represents time; $\varepsilon=(e+A)^{-1}$, A is the area of the investigation region measured by hectares; r is the spatial resolution of the dataset used; and e equals 2.71828.

In terms of Method of Lagrange Multipliers (Kolman and Trend 1971), the necessary condition, under which $D(\varepsilon, t)$ reaches the maximum value, is that

$$\frac{\partial D(\varepsilon, r, t)}{\partial p_j(\varepsilon, r, t)}+\lambda\cdot\frac{\partial k(p_1(\varepsilon, r, t), \ldots, p_m(\varepsilon, r, t))}{\partial p_j(\varepsilon, r, t)}=0 \tag{9}$$

where $j=1, 2, \ldots, m$; $k(p_1(\varepsilon, r, t), \ldots, p_m(\varepsilon, r, t))=1-\sum_{i=1}^{m(\varepsilon, r, t)} p_i(\varepsilon, r, t)$; and λ is an arbitrary constant.

The solution of the differential equation (9) is $p_j(\varepsilon, r, t)=\frac{1}{m(\varepsilon, r, t)}$. In other words, when every investigation species or ecotope has equal proportion, $D(\varepsilon, r, t)$ reaches its maximum value, $-\frac{\ln m(\varepsilon, r, t)}{\ln \varepsilon}$, under constraint condition, $\sum_{i=1}^{m(\varepsilon, r, t)} p_i(\varepsilon, r, t)=1$. For $p_j(\varepsilon, t)>0$ $(j=1, 2, \ldots, m)$, $\frac{\partial D(\varepsilon, r, t)}{\partial p_j(\varepsilon, r, t)}=\frac{1}{\left(p_j(\varepsilon, r, t)\right)^{\frac{1}{2}}\cdot\sum_{i=1}^{m}(p_i(\varepsilon, r, t))^{\frac{1}{2}}}>0$. $D(\varepsilon, r, t)$ is a strictly increasing function of $p_j(\varepsilon, r, t)$. Therefore, the scaling diversity index can express the 'evenness' aspect of diversity.

3. A case study in Fukang in the Xinjiang Uygur Autonomous Region

3.1 *Fukang in the Xinjiang Uygur Autonomous Region in China*

Fukang, in the Xinjiang Uygur Autonomous Region, is located in the northern foot of the eastern part of the Tianshan Mountains, and occupies an area of 8767 km^2. The ranges of the geographical coordinates of Fukang are 43°45′–45°30′ N and 87°465′–88°44′ E (figure 1). Fukang is 140 km in length from south to north and 75 km wide from west to east. The terrain of Fukang, slanting from southeast to northwest, can be divided into three geomorphologic units that are mountainous, plain, and desert. Bogda peak in the mountainous area has an elevation of 5445 m, which is the highest peak in the eastern part of the Tianshan Mountains; the south edge of the desert has an elevation lower than 460 m. The difference in elevation is about 5000 m. The area proportions of the mountainous, plain, and desert areas to the total area of Fukang are, respectively, 50.74%, 29.00%, and 20.26%. The Fukang region from Bogda peak to the north edge of the desert, about 80 km, has a clear vertical spectrum of natural zones that are alpine nival zone, alpine and sub-alpine meadow zone, forest zone, hilly grassland zone, piedmont semi-desertification zone, desertification zone in alluvial and diluvial plain, and fixed and semi-fixed sand dunes in desert zone.

3.2 *Data acquisition*

The Landsat TM image of Fukang was taken in the fall of 2002, and the spatial resolution is 30 m × 30 m. We applied unsupervised classification and generated clusters using ISODATA clustering analysis. Investigation data on the spot were used to identify training classes and to label and merge clusters for identification. Signatures of identified clusters were subsequently used in a maximum likelihood classification to generate a land cover map. The land cover types include woodland,

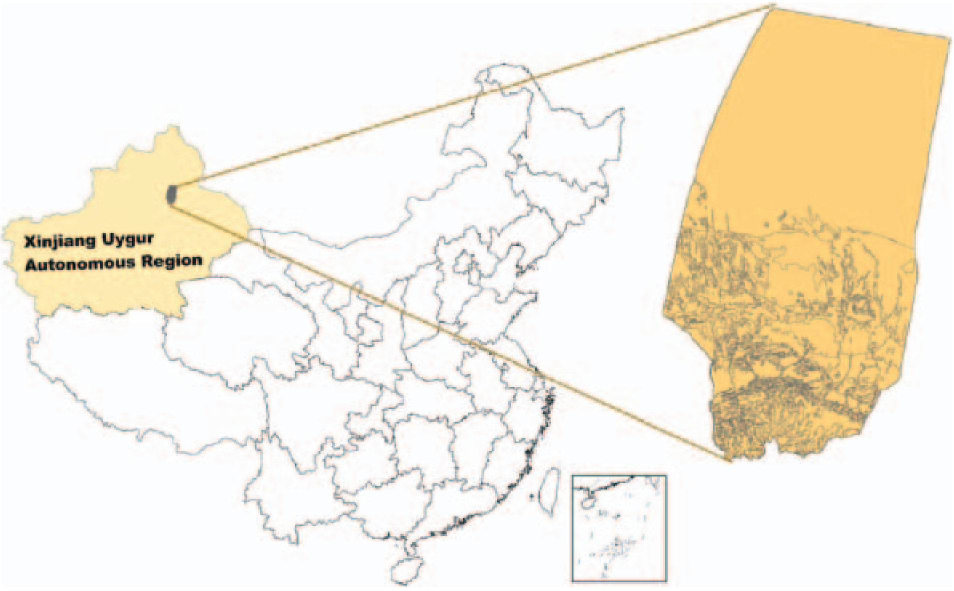

Figure 1. Location of Fukang.

sparse woodland, shrub land, other woodland, dense grassland, moderately dense grassland, sparse grassland, paddy field, dry farmland, lake, reservoir and water pond, urban area, rural residential area, other built-up area, nival area, beach land, sand land, saline–alkaline area, marshland, and bare rock and gravel area (figure 2). The land cover dataset on a spatial resolution of 30 m × 30 m is transformed into a series of land cover datasets on spatial resolutions of $(k \times 30)m \times (k \times 30)m$ (k=1, 2, 3, …, 16) by an up-scaling process. The land cover type in each pixel of the new land cover dataset is derived from the dominant land cover type of the transformed pixels. When every new dataset is created, the boundary of every newly created ecotope, the topological relationship, and the attributes of the new data are rectified. Finally, the newly created dataset is exported to a vector polygon file of Coverage of Arc/Info (figure 2).

Classification accuracy of the land cover was assessed by means of PCI Geomatica Focus. Three hundred and ninety-six samples were stratified and randomly selected from the land cover maps. Each sampled land cover type of the classified image was identified on the basis of a topographical map of Fukang on a scale of 1 : 50,000 and a land cover map on a scale of 1 : 100,000. Classification accuracies for our final products were evaluated in error matrices and are summarized in table 3. The overall accuracy achieved was 95.75%. The producer's and user's accuracies and the conditional kappa coefficient for each individual land cover type were also reported.

3.3 *Results*

Statistic analysis of ecotope diversity on different spatial resolutions shows that ecotope diversity of the Fukang landscape, which is calculated by the scaling diversity index, increases on average and converges to 0.210 with spatial resolution becoming finer (table 4). Ecotope diversity change can be formulated as the

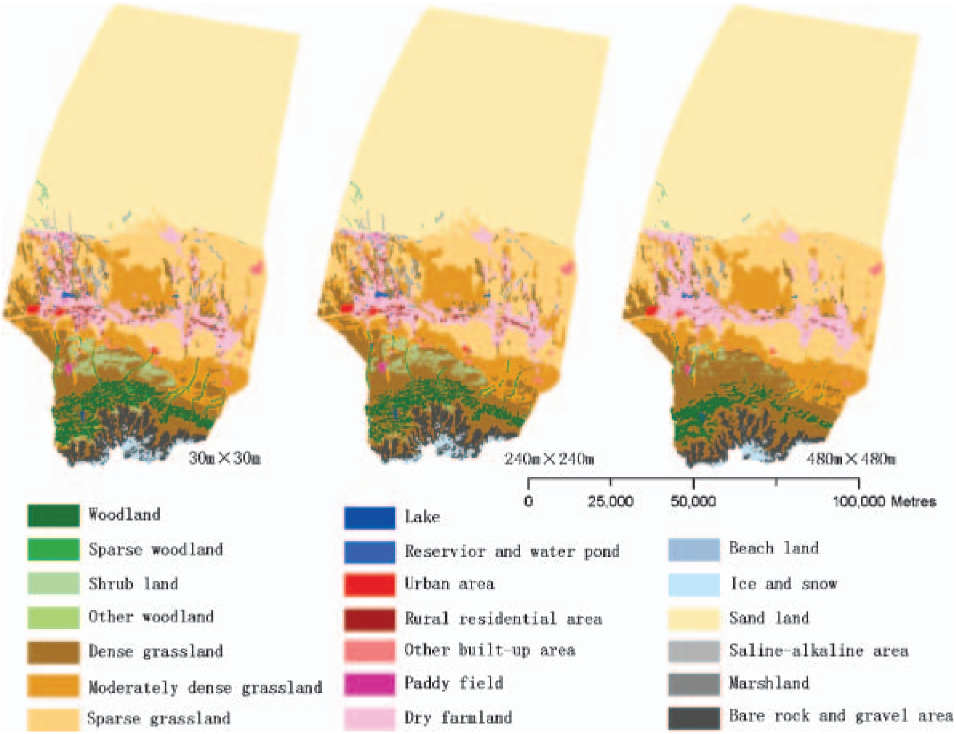

Figure 2. Land cover maps of Fukang on different resolutions: left map on resolution of 30 m × 30 m, middle map on resolution of 240 m × 240 m, and right map on resolution of 480 m × 480 m.

following regression equation (figure 3)

$$D = 0.21 + 0.0406r - 3.7275r^2 + 37.088r^3 - 162.47r^4 + 260.07r^5 \tag{10}$$

where D is ecotope diversity and r is spatial resolution of the dataset. Correlation coefficient of the regression equation is $R^2=0.9922$.

The change of ecotope density with spatial resolution can be formulated as (figure 4)

$$Ri = 0.1273e^{-3.2645r} \tag{11}$$

where Ri is ecotope density and r is spatial resolution of the dataset. The correlation coefficient of the regression equation is $R^2=0.9885$.

Relationship between ecotope diversity and ecotope density (figure 5) can be statistically expressed as

$$D = 0.2984Ri^{0.1673} \tag{12}$$

where D is ecotope diversity and Ri is ecotope density. The correlation coefficient of the regression equation is $R^2=0.9861$.

The results show that more ecotope types and ecotopes could be found in a given investigation region with spatial resolution becoming finer. Ecotope diversity has a closely positive relation with ecotope density. Regression equation (12) can be

Table 3. Classification accuracy and conditional kappa statistics for each land cover type.

Land cover type	Reference totals	Classified totals	Number correct	Producer's accuracy (%)	User's accuracy (%)	Kappa statistics
Woodland	15	14	13	86.67	92.86	0.93
Shrub land	9	8	8	88.89	88.89	0.89
Sparse woodland	8	6	6	75.00	100.00	1.00
Other woodland	1	1	1	100.00	100.00	1.00
Dense grassland	34	37	32	94.12	86.49	0.85
Moderately dense grassland	37	39	37	100.00	94.87	0.94
Sparse grassland	52	50	50	96.15	100.00	1.00
Lake	6	6	6	100.00	100.00	1.00
Reservoir and water pond	9	9	9	100.00	100.00	1.00
Nival land	7	7	7	100.00	100.00	1.00
Beach land	7	5	5	71.43	100.00	1.00
Urban area	6	6	6	100.00	100.00	1.00
Rural residential area	7	6	6	85.71	100.00	1.00
Other built-up area	5	6	5	100.00	83.33	0.83
Sand land	145	144	144	99.31	100.00	1.00
Saline–alkaline area	4	4	4	100.00	66.67	0.66
Marshland	2	2	2	100.00	100.00	1.00
Bare rock and gravel area	14	15	14	93.33	93.33	0.93
Paddy field	3	3	3	75.00	100.00	1.00
Dry farmland	25	28	25	92.59	89.29	0.89
Totals	396	396	383			
Overall accuracy (%)						95.75
Overall kappa statistics (%)						0.95

Table 4. Changes of relative indices with spatial resolution becoming finer.

Spatial resolution (km^2)	Ecotope number	Ecotope density (ecotope number/km^2)	Ecotope type	Ecotope diversity
0.2304	547	0.12673	18	0.186
0.2025	583	0.12581	18	0.189
0.1764	622	0.12239	17	0.192
0.1521	654	0.12228	19	0.193
0.1296	737	0.12205	19	0.199
0.1089	749	0.11931	19	0.199
0.0900	829	0.11098	20	0.201
0.0729	856	0.10494	18	0.203
0.0576	920	0.09764	18	0.206
0.0441	973	0.09456	19	0.207
0.0324	1046	0.08543	20	0.208
0.0225	1070	0.08407	20	0.210
0.0144	1072	0.07460	20	0.210
0.0081	1111	0.07095	20	0.210
0.0036	1103	0.06650	20	0.210
0.0009	1073	0.06239	20	0.210

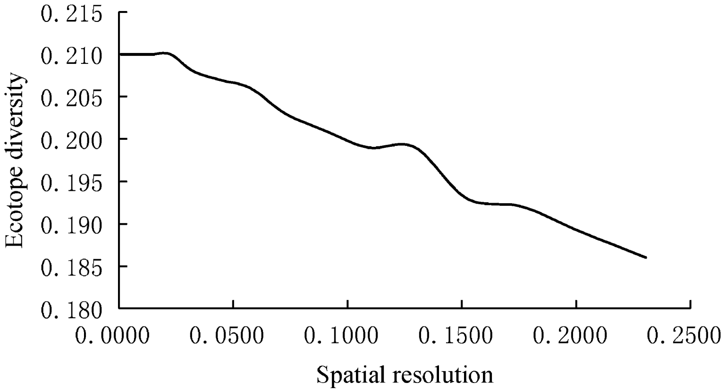

Figure 3. Ecotope diversity change with spatial resolution becoming finer.

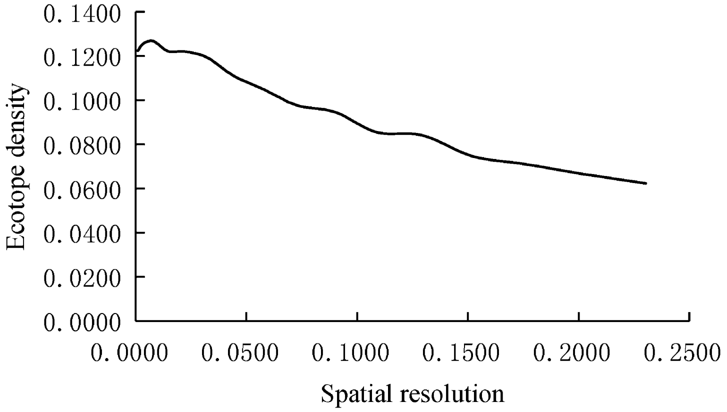

Figure 4. Relationship between ecotope density and spatial resolution.

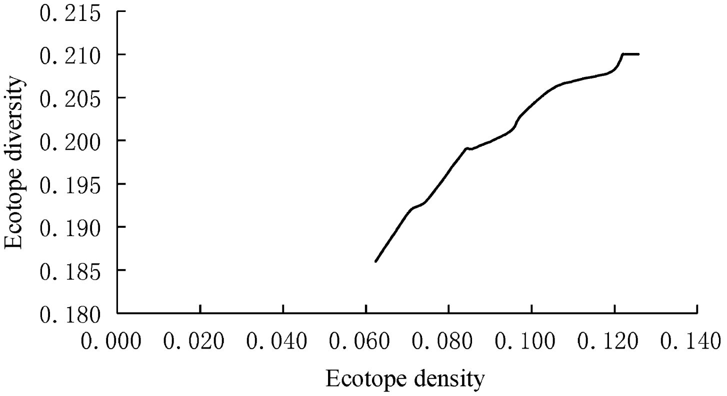

Figure 5. Relationship between ecotope diversity and ecotope density with spatial resolution becoming finer.

re-formulated as $\frac{D}{0.2984} = \left(\frac{1}{Ri}\right)^{-0.1673}$. Ecotope diversity, taking $\frac{1}{Ri}$ as the scaling factor, has statistical self-similarity and Hausdorff dimension is 0.1673. In other words, the scaling diversity index can express the richness aspect of diversity.

4. Conclusions

As well as the scaling diversity index that has been newly developed, a further eleven traditional diversity indices can be found in the literature. Our study demonstrates that these eleven traditional diversity indices are unable to express the richness aspect of diversity because they do not include any message on the area (or spatial scale) under investigation, while the area or spatial scale under investigation is so important that it, as the scaling factor, makes the species number have statistical self-similarity. It has been proved that the most widely used index, the Shannon-Weiner index, cannot express the evenness aspect.

However, in contrast, the scaling diversity index can formulate the evenness aspect of diversity in terms of our theoretical proof. The case study in Fukang in the Xinjiang Uygur Autonomous Region shows that the scaling diversity index can express both the richness component and the evenness component of diversity.

The case study indicates that the finer the spatial resolution is, the more ecotopes are found in the given region and the higher the ecotope diversity is on average. The scaling diversity index is sensitive to spatial resolutions.

The scaling diversity index has been applied to simulate trends and scenarios of ecological diversity at different spatial resolutions and spatial scales (Yue *et al.* 2001, 2002, 2003, 2004, 2005a,b). This index is usable in developing scenarios and is amenable to aggregation and disaggregation at local and national levels. It is simple and easy to understand.

In short, the scaling diversity index combines factors of spatial resolution, spatial scale and temporal scale with the richness component and evenness component of diversity together as a whole. It is scientifically sound and could be operated at affordable cost.

Acknowledgements

This work is supported by Project (40371094) of the National Natural Science Foundation of China and the National Basic Research Priorities Program (2002CB412506) of the Ministry of Science and Technology of the People's Republic of China.

References

ALADOS, C.L., ELAICH, A., PAPANASTASIS, V.P., OZBEK, H., NAVARRO, T., FREITAS, H., VRAHNAKIS, M., LARROSI, D. and CABEZUDO, B., 2004, Change in plant spatial patterns and diversity along the successional gradient of Mediterranean grazing ecosystems. *Ecological Modelling*, **180**, pp. 523–535.

ARRHENNIUS, O., 1921, Species and area. *Journal of Ecology*, **9**, pp. 95–99.

BARRETT, G.W., 1968, The effects of an acute insecticide stress on a semi-enclosed grassland ecosystem. *Ecology*, **49**, pp. 1019–1035.

BEEBY, A. and BRENNAN, A.M., 1997, *First Ecology* (London: Chapman and Hall).

BERGER, W.H. and PARKER, F.L., 1970, Diversity of planktonic foraminifera in deep sea sediments. *Science*, **168**, pp. 1345–1347.

BISBY, F.A., 1995, Characterization of biodiversity. In *Global Biodiversity Assessment*, edited by V.H. Heywood and R.T. Watson (Eds), pp. 21–106 (Great Britain: Cambridge University Press).

BROWNE, R.A., 1981, Lakes as islands: biogeographic distribution, turnover rates, and species composition in the lakes of central New York. *Journal of Biogeography*, **8**, pp. 75–83.

GORMAN, M.L., 1979, *Island Ecology* (London: Chapman & Hall).

GROOMBRIDGE, B., 1992, *Global Biodiversity: Status of the Earth's Living Resources* (London: Chapman & Hall).

HABERL, H., SCHULZ, N.B., PLUTZAR, C., ERB, K.H., KRAUSMANN, F., LOIBL, W., MOSER, D., SAUBERER, N., WEISZ, H., ZECHMEISTER, H.G. and ZULKA, P., 2004, Human appropriation of net primary production and species diversity in agricultural landscapes. *Agriculture, Ecosystems and Environment*, **102**, pp. 213–218.

HAKEN, H., 1983, *Synergetics* (Berlin: Springer-Verlag).

HAMILTON, A.J., 2005, Species diversity or biodiversity? *Journal of Environmental Management*, **75**, pp. 89–92.

HANSKI, I., 2005, Landscape fragmentation, biodiversity loss and the societal response. *EMBO*, **6**, pp. 388–392.

HARPER, J.L. and HAWKSWORTH, D.L., 1996, Preface. In *Biodiversity: Measurement and Estimation*, D.L. Hawksworth (Ed.), pp. 5–12 (London: Chapman & Hall).

HAUSDORFF, F., 1919, Dimension und aeusseres Mass. *Mathematische Annalen*, **19**, pp. 157–159.

HILL, M.O., 1973, Diversity and evenness: a unifying notation and its consequences. *Ecology*, **54**, pp. 427–431.

HODGSON, J.G. *et al.* (30 authors), 2005, How much will it cost to save grassland diversity? *Biological Conservation*, **122**, pp. 263–273.

HOFFMANN, J. and GREEF, J.M., 2003, Mosaic indicators—theoretical approach for the development of indicators for species diversity in agricultural landscapes. *Agriculture, Ecosystems and Environment*, **98**, pp. 387–394.

IANNACCONE, P.M. and KHOKHA, M.K., 1996, Fractal geometry. In *Fractal Geometry in Biological Systems*, P.M. Iannaccone and M.K. Khokha (Eds), pp. 3–11 (New York: CRC Press).

IBANEZ, J.J., CANIEGO, J., SAN JOSE, F. and CARRERA, C., 2005, Pedodiversity–area relationships for islands. *Ecological Modelling*, **182**, pp. 257–269.

KOLMAN, B. and TREND, W.F., 1971, *Elementary Multivariable Calculus* (New York: Academic Press).

MACARTHUR, R.H. and WILSON, E.O., 1967, *The Theory of Island Biogeography* (Princeton: Princeton University Press).

MACE G.M., 2005, An index of intactness. *Nature*, **434**, pp. 32–33.

MARGALEF, R., 1957, La teoría de la información en ecologia. *Memorias de la Real academia de Ciencias by Artes de Barcelona*, **32**, pp. 373–449.

MARTIN, M.A., PACHEPSKY, Y.A. and PERFECT, E., 2005, Scaling, fractals and diversity in soils and ecohydrology. *Ecological Modelling*, **182**, pp. 217–220.

MCINTOSH, R.P., 1967, An index of diversity and the relation of certain concepts to diversity. *Ecology*, **48**, pp. 392–404.

MCNAUGHTON, S.J., 1994, Biodiversity and function of grazing ecosystems. In *Biodiversity and Ecosystem Function*, E.D. Schulze and H.A. Mooney (Eds), pp. 361–383 (Berlin: Springer-Verlag).

MLADENOFF, D.J., NIEMI, G.J. and WHITE, M.A., 1997, Effects of changing landscape pattern and USGS land cover data variability on ecoregion discrimination across a forest-agriculture. *Landscape Ecology*, **12**, pp. 379–396.

MUELLER, C., BERGER, G. and GLEMNITZ, M., 2004, Quantifying geomorphological heterogeneity to assess species diversity of set-aside arable land. *Agriculture, Ecosystems and Environment*, **104**, pp. 587–594.

ODUM, E.P., 1969, The strategy of ecosystem development. *Science*, **164**, pp. 262–270.

ODUM, E.P., 1983, *Basic Ecology* (Philadelphia: Saunders College Publishing).

PETERS, J., 1975, Entropy and information: conformities and controversies. In *Entropy and Information in Science and Philosophy*, L. Kubat and J. Zeman (Eds), pp. 61–81 (New York: Elsevier Scientific Publishing Company).

PIELOU, E.C., 1966, Species diversity and pattern diversity in the study of ecological succession. *Journal of Theoretical Biology*, **10**, pp. 370–383.

PIELOU, E.C., 1975, *Ecological Diversity* (New York: John Wiley and Sons).

PIMM, S.L., 1994, Biodiversity and the balance of nature. In *Biodiversity and Ecosystem Function*, E.D. Schulze and H.A. Mooney (Eds), pp. 347–359 (Berlin: Springer-Verlag).

PRESTON, F.W., 1960, Time and space and the variation of species. *Ecology*, **41**, pp. 785–790.

PRESTON, F.W., 1962, The canonical distribution of commonness and rarity. *Ecology*, **43**, pp. 185–215 and 410–432.

RICOTTA, C., 2002, Bridging the gap between ecological diversity indices and measures of biodiversity with Shannon's entropy: comment to Izsak and Papp. *Ecological Modelling*, **152**, pp. 1–3.

RICOTTA, C., CHIARUCCI, A. and AVENA, G., 2004, Quantifying the effects of nutrient addition on community diversity of serpentine vegetation using parametric entropy of type α. *Acta Oecologica*, **25**, pp. 61–65.

ROSENZWEIG, M.L., 1995, *Species Diversity in Space and Time* (Great Britain: Cambridge University Press).

ROY, A., TRIPATHI, S.K. and BASU, S.K., 2004, Formulating diversity vector for ecosystem comparison. *Ecological Modelling*, **179**, pp. 499–513.

ROY, P.S., PADALIA, H., CHAUHAN, N., PORWAL, M.C., GUPTA, S., BISWAS, S. and JAGDALE, R., 2005, Validation of geospatial model for biodiversity characterization at landscape level: a study in Andaman and Nicobar Islands, India. *Ecological Modelling*, **185**, pp. 349–369.

SANDSTROEM, U.G., ANGELSTAM, P. and MIKUSINSKI, G., 2006, Ecological diversity of birds in relation to the structure of urban green space. *Landscape and Urban Planning*, **77**, pp. 39–53.

SCHOLES, R.J. and BIGGS, R., 2005, A biodiversity intactness index. *Nature*, **434**, pp. 45–49.

SHANNON, C.E. and WEAVER, W., 1962, *The Mathematical Theory of Communication* (Urnaba: The University of Illinois Press).

SIMPSON, E.H., 1949, Measurement of diversity. *Nature*, **163**, pp. 688.

UYS, R.G., BOND, W.J. and EVERSON, T.M., 2004, The effect of different fire regimes on plant diversity in southern African grasslands. *Biological Conservation*, **118**, pp. 489–499.

WHITTAKER, R.H., 1977, Evolution of species diversity in land communities. In *Evolutionary Biology, 10*, M.K. Hecht, W.C. Steere and B. Wallace (Eds), pp. 1–67 (New York: Plenum).

WILLIAMSON, M., 1981, *Island Population* (Oxford: Oxford University Press).

WILLIAMS, P.H. and HUMPHRIES, C.J., 1996, Comparing character diversity among biota. In *Biodiversity:A Biology of Numbers and Difference*, K.J. Gaston (Ed.), pp. 54–76 (Cambridge: Blackwell Science).

YOSHIDA, K., 2003, Evolutionary dynamics of species diversity in an interaction web system. *Ecological Modelling*, **163**, pp. 131–143.

YUE, T.X., HABER, W., GROSSMANN, W.D. and KASPERIDUS, H.D., 1998, Towards the satisfying models for biological diversity. *Ekologia (Bratislava)*, **17**, pp. 129–141.

YUE, T.X., LIU, J.Y., JØRGENSEN, S.E., GAO, Z.Q., ZHANG, S.H. and DENG, X.Z., 2001, Changes of Holdridge life zone diversity in all of China over a half century. *Ecological Modelling*, **144**, pp. 153–162.

YUE, T.X., YE, Q.H., LIU, J.Y. and GONG, Z.H., 2002, Studies on models for landscape connectivity. *Journal of Geographical Sciences*, **12**, pp. 186–195.

YUE, T.X., LIU, J.Y., JøRGENSEN, S.E. and YE, Q.H., 2003, Landscape change detection of the newly created wetland in Yellow River Delta. *Ecological Modelling*, **164**, pp. 21–31.

YUE, T.X., XU, B. and LIU, J.Y., 2004, A patch connectivity index and its change on a newly born wetland at the Yellow River Delta. *International Journal of Remote Sensing*, **25**, pp. 4617–4628.

YUE, T.X., LIU, J.Y., CHEN, S.Q., LI, Z.Q., MA, S.N., TIAN, Y.Z. and GE, F., 2005a, Considerable effects of diversity indices and spatial scales on conclusions relating to ecological diversity. *Ecological Modelling*, **188**, pp. 418–431.

YUE, T.X., FAN, Z.M. and LIU, J.Y., 2005b, Changes of major terrestrial ecosystems in China Since 1960. *Global and Planetary Change*, **48**, pp. 287–302.