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Habitat carrying capacity index: a formalized assessment of habitat importance to maintain diversity of the littoral fish assemblage

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To assess the significance of the habitat for maintaining biodiversity, for example habitats of coastal fish assemblages the following carrying capacity index for habitats was developed (A):

$$A = 1 - \frac{1}{1+\frac{1}{Q}\sqrt{(N+S)\left|\sum_{i=1}^{S}\frac{n_i}{N}ln\frac{n_i}{N}\right|}}$$

where N is the total number of specimens, S – the number of species, n_i – the number of specimens of each species, Q – coefficient, which makes possible to obtain A index values more convenient for perception. In our case, the most convenient is Q=100, so the equation is as following:

$$A = 1 - \frac{1}{1+\frac{1}{100}\sqrt{(N+S)\left|\sum_{i=1}^{S}\frac{n_i}{N}ln\frac{n_i}{N}\right|}}$$

The minimum value of the index as 0 is reached when S=1 for any value of N, regardless of the evenness of the system. A larger index value corresponds to larger species number and total number of specimens considering equable distribution of the elements in community. If S and N tend to infinity, the index tends to 1. Evaluation of the effectiveness of the index applying to an analysis of the carrying capacity concerning fishes of the littoral habitats according to visual counts showed the suitability of the index for these purposes. There is every reason to believe that the proposed index is suitable for assessing the carrying capacity of the habitats for other groups of aquatic organisms also, however, a comparison of the habitats using this index is possible only if the way of presenting the results of quantitative estimates of abundance is identical.
Key words: carrying capacity index; habitat; fish assemblage; visual records of fishes; species abundance; number of fishes

Introduction

Synecological research includes the study of both various properties of biota within the ecosystem (biogeocoenosis according to V.N. Sukachev (1964), and abiotic features of habitats (biotopes). Value of a habitat is recognized as ability to maintain the existence of associated biota and assessment of such a value is particularly important. Thus, according to traditional notions, the number of species that dwell in a habitat (species richness, composition according to V.D. Fedorov (Fedorov, Gilmanov, 1980) is extremely important indicator of habitat value. At the same time, numbers (number of individuals per unit of space) also determine carrying capacity of the biotope, because the greater number of individuals even without regard to certain species and their number mean that the greater resources involved into the energy flow "here and now".

Since the middle of the last century, the use of various kinds of indices for the mathematical generalization of empirical information on the abundance of biota and its diversity has become popular among ecologists. The analysis of numerous literature sources (Simpson, 1949; Margalef, 1958; Shannon, Weaver, 1963; Shitikov, Rosenberg, 2005; De Kerckhove et al., 2008; Kadye, 2008; Dong et al., 2015) devoted to this problem, concerning both composition and structure of communities (recognized, according to V.D. Fedorov (Fedorov, Gilmanov, 1980), as the ratio of abundance of community elements), showed that there is no reason to hope for the universality of both existing diversity indices, and newly created. This includes, among other things, indices that combine a significant number of indicators, such as Multi-metric indices of biotic integrity (IBI) (Trebitz A.S. et al., 2004; Sarkar et al., 2017).

The ratio of total number of organisms and number of species in the community can be estimated by different researchers in

different ways; it motivates researchers to analyze various aspects of this problem (Hurlbert, 1971). We are also interested in it, and this was the reason for writing this article.
The habitat (biotopic) principle of nature protection adopted by the European Union is based on the conservation of habitats, which is regarded as a guarantee of the sustainable existence of species typical for the site. Different habitats play different roles in maintaining biodiversity due to the certain environmental conditions, even if habitats are near one another (Winemiller, 2000, Bain, Wine, 2010). In this regard, it is relevant to assess the value of habitats especially their capacity to attract organisms such as fishes.
We have defined the following tasks:
1. To develop an index of carrying capacity of the biological system, which would depend on the species richness and total number of individuals at the study area; it is also important that this index takes values from 0 to 1.
2. To check the effectiveness of the application of the index obtained for analyzing the carrying capacity of biotopes of the coastal water area of the Black Sea (at the protected water area of the Karadag Nature Reserve) concerning fishes of the coastal fish assemblage.
3. To develop recommendations on the application of the index obtained, considering the limitations of mathematical and biological nature.

Methods

Based on the analysis of literature information, approaches to compiling the habitat carrying capacity index were developed. Using the method of mathematical analysis, the dependence of value of the index and its dynamics on the values of variables (number of species, number of individuals of each species, total number of individuals) was checked.
The information on the abundance of fishes of the coastal fish assemblage was collected using the method of visual accounting (Maltsev, Ivanchikova, 2015) for transects as large as 25-50 m long and 10 m wide; then recalculation of the obtained data for 1 hectare of the water surface took place. Three habitats located within the water area protected by the Karadag Nature Reserve (Black Sea, Crimea) were examined in this way:
Habitat 1 (coordinates: 44º54.691 N, 35º12.757 E): small bay with depths up to 6 m, bordered from the east by a vertical rock wall, and from the west – by large fragments of rocks protruding to the surface of the sea. Bottom is composed of cobblestone and pebble deposits (the size of stones is 10-300 cm), formed by rocks of volcanic origin, overgrowing with macro-algae with dominance of *Cystoseira sp*.
Habitat 2 (coordinates: 44º54.690 N, 35º12.662 E): open shallow waters with depths up to 4 m. The Bottom is composed of large and medium-sized fragments of rocks, also overgrown with macro-algae.
Habitat 3 (coordinates: 44º54.705 N, 35º12.546 E): also, an open shallow water, gently sloping into the sea, with depths as much as 1-3 m. Bottom is mainly composed of medium-sized stones, also overgrown with macrophytes.

Results

Value (significance) of the biotope as an abiotic component of the ecosystem can be assessed by the state of its biotic part – the biocoenosis. That state can be estimated in different orders of magnitude, first empirical (quantity, biomass, as well as production and destruction measured directly in nature) and calculated (production and destruction values obtained by calculative methods, production/destruction ratio, etc.). Also generalized indicators are used: different coenotic indices connecting and generalizing empirical and calculated values.
Traditionally ecologists use indices of diversity such as the Shannon diversity index (Shannon, Weaver, 1964) for various kinds of estimation of biocoenoses:

$$H = -\sum_{i=1}^{S} \frac{n_i}{N} \log_2 \frac{n_i}{N}$$

On this basis the index which is equal 0, if only one species of aquatic organisms is present in the water body and assumes the maximum value if there are S species with the same number of individuals, the following carrying capacity index of the biological system (A) was obtained:

$$A = 1 - \frac{1}{1+\frac{1}{Q}\sqrt{(N+S)\left|\sum_{i=1}^{S}\frac{n_i}{N}ln\frac{n_i}{N}\right|}} \quad (1)$$

where N is the total number of individuals, S is the number of species, n_i is the number of individuals of each species, Q is the coefficient allowing to obtain the values of the index A more convenient for perception due to the "stretching" of its scale. In our case, with "our" values of n_i, N and S, Q = 100 is most convenient. Therefore, the presented expression takes the form:

$$A = 1 - \frac{1}{1+\frac{1}{100}\sqrt{(N+S)\left|\sum_{i=1}^{S}\frac{n_i}{N}ln\frac{n_i}{N}\right|}} \quad (2)$$

The minimum value as 0 the index takes when S = 1 for any number N, regardless of the alignment of the system. The greater value of the index corresponds to the larger values of species richness and the total number of individuals, considering the uniformity of the distribution of the community. For S and N tending to infinity the index values tend to 1.
If we consider the index as a function of one variable of S, then for each fixed value of N (Fig. 1) commonality of curves defined in the interval [0; N], located between the graphs of the minimum and maximum possible values of the index, depending on the distribution of n_i. The closer is the distribution of individuals by species to the uniform, the closer is the curve to the

"maximum". At a fixed value of N, for any distribution there exists a value of S for which the distribution by species becomes uniform, and the maximum of the index values can be reached. However, it should be noted that such a value of S may not be realizable in real natural conditions.

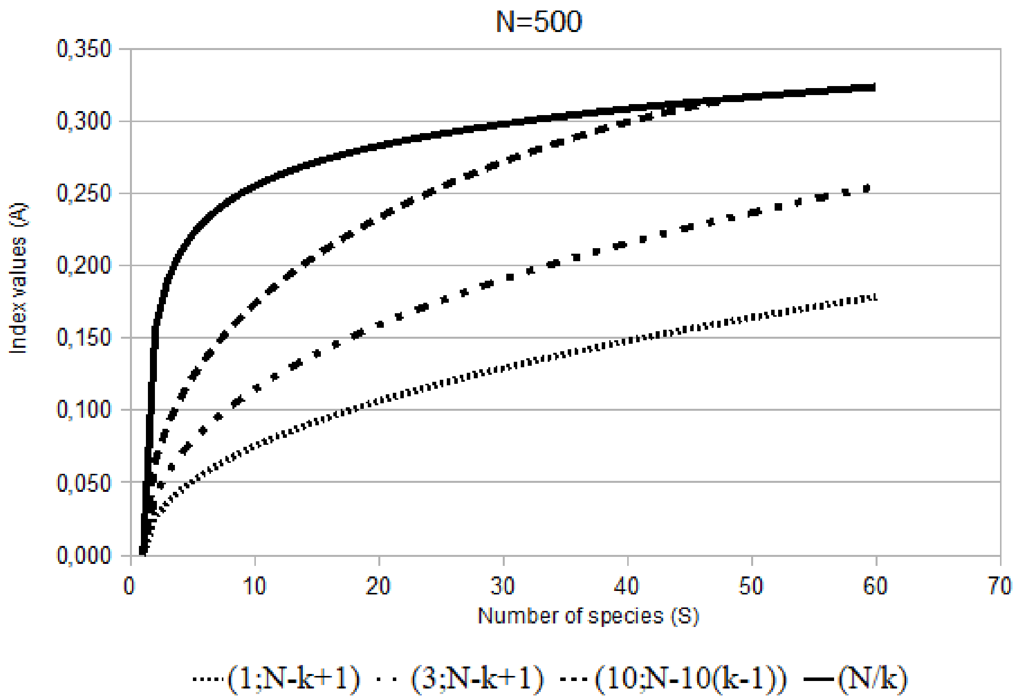

Fig. 1. Curves of index values at N = 500 and different evenness

In the case of a distribution of the species (1; 1; ... 1; N-S + 1) (that is, all species except one (S-1) are represented by one specimen, and the number of specimens of one remaining species is the remainder) we obtain the curve of the minimum possible values of the index, which for S=N intersects with the curve of the maximum possible values for a uniform distribution (n_i = N/S).
As can be seen from Fig. 2, the larger is the number of individuals (N), the greater is the index, which makes it possible to perform a comparative analysis of the results of site research concerning the carrying capacity of the biological system.

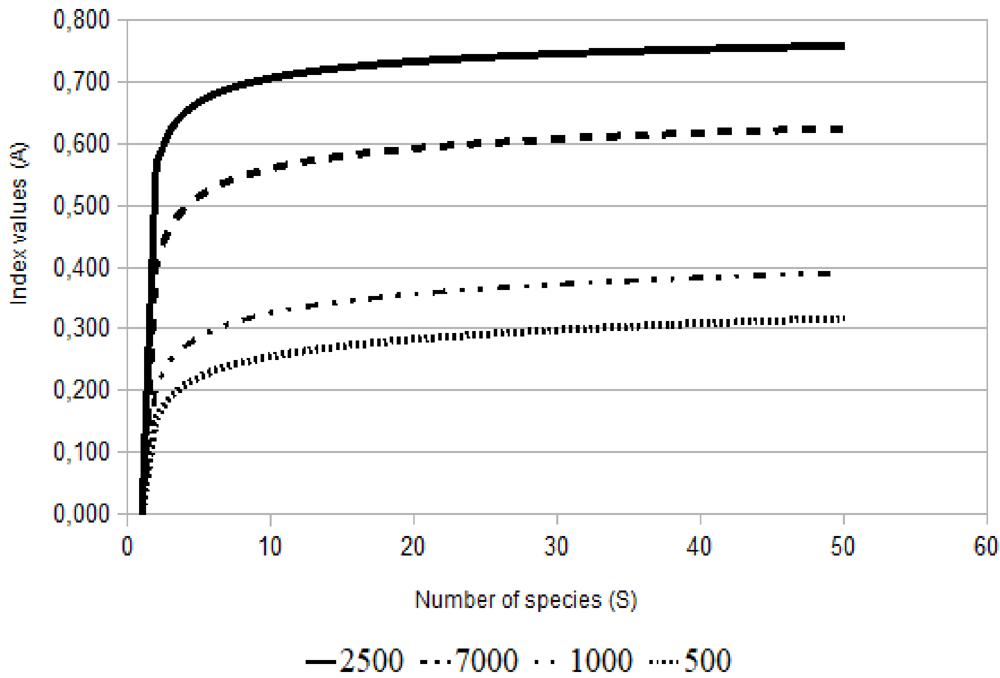

Fig. 2. Curves of the maximum index value towards different N (uniform individuals distribution)

The biological meaning of the proposed index is that its magnitude depends not only on the community evenness (its contribution is provided by the expression under the modulus), but also the number of species and the total fish abundance of the coastal fish assemblage (Fig. 2). After all, if a biotope ensures the presence of many individuals in it, even if number of species is very limited this still indicates a certain level of its supporting capacity for the biota inherent for a certain locality or even a region. Value of number of species as an important component of the carrying capacity of the habitat is determined by the expression N + S, while the role of S in the formula increases with decreasing of the value of N (total number).

Analysis of the carrying capacity of coastal habitats for fish according to visual records showed the suitability the proposed index for these purposes. Tables 1-3 summarize the data of visual accounts of fishes of the coastal fish assemblage and calculating of the indices of the carrying capacity for each of the observation stations.

Table 1. Carrying capacity index (fishs in habitat 1)

Species (S)	Results of visual registration of fishes in June-September2016, specimens per ha ($n_{i,}$)									$\sum_n$	$\bar{n}$
	22.06	28.06	04.07	27.07	03.08	11.08	26.08	06.09	16.09		
Mugil cephalus L.	80		40							120	13
Liza aurata (Risso)							200			200	22
Liza sp.					40					40	4
Atherina boyeri Risso			20		80			160	400	660	73
Syngnathus typhle L.			20		20	40			40	120	13
Scorpaena porcus L.				20						20	2
Diplodus annularis (L.)		40			80	20	6000	2000	8000	16140	1793
D. puntazzo (Cetti)		20								20	2
Spicara flexuosa Rafinesque					40	120				160	18
Sciaena umbra L.						40				40	4
Mullus barbatus L.	80	20		160	160	80	120	160		780	87
Crenilabrus cinereus (Bonnaterre)	40									40	4
C. roissali (Risso)		80	160	80		160	200		80	760	84
C. tinca (L.)	480	1360	920	3160	1480	2280	6480	2440	8440	27040	3004
C. ocellatus Forskal				20		40	120	40	2960	3180	353
Aidablennius sphynx (Valenciennes)			40	400	840	120	120	120	280	1920	213
Parablennius sanguinolentus (Pallas)	400	360	640	720	1280	1360	680	80	240	5760	640
P. zvonimiri (Kolombatovic)					20					20	2
Blenniidae (not identified)					40	40				80	9
Mesogobius batrachocephalus (Pallas)						40				40	4
Gobiidae 1 (not identified)	80									80	9
Gobiidae 2 (not identified)		120	40		40		40	120	80	440	49
Perciformes (not identified)						20	600			620	69
S	**6**	**7**	**8**	**7**	**12**	**13**	**10**	**8**	**9**	**23**	
N	**1160**	**2000**	**1880**	**4560**	**4120**	**4360**	**14560**	**5120**	**20520**		
$\bar{N}$											**6476**
A	**0.288**	**0.313**	**0.329**	**0.403**	**0.446**	**0.435**	**0.575**	**0.441**	**0.616**		
$\bar{A}$											**0.502**

n_i – number of specimens of each species, Σn – total number of specimens of a certain species during the season, $\bar{n}$ – average number of specimens of certain species per season, S – number of species, N – total number of fishes according to the results of certain registrations, $\bar{N}$ – average N during the seasons, A – values of the carrying capacity index for the biotope according to the results of certain registrations, $\bar{A}$ – average A during the season.

Table 2. Carrying capacity index (fishes in habitat 2)

Species (S)	Results of visual registration of fishes in June-September2016, specimens per ha (n_i,)									∑n	n̄
	22.06	28.06	04.07	27.07	03.08	11.08	26.08	06.09	16.09		
Liza aurata (Risso)					1200					1200	133
Mugil cephalus L.		80			40					120	13
Mugilidae (not identified)					600					600	67
Atherina boyeri Risso	80			1000					10000	11080	1231
Diplodus annularis (L.)	40				1080	560		2800	6000	10480	1164
D. puntazzo (Cetti)							80			80	9
Sciaena umbra L.		40								40	4
Mullus barbatus L.					200	200	120	120	40	680	76
Crenilabrus cinereus (Bonnaterre)			360							360	40
C. roissali (Risso)					40	160	240			440	49
C. tinca (L.)	800	2520	1120	1200	2600	6440	6320	2600	4600	28200	3133
C. ocellatus Forskal		40	120			80		80	2160	2480	276
Aidablennius sphynx (Valenciennes)					40	120		40		200	22
Parablennius sanguinolentus (Pallas)	600	760	600	400	1280	2520	280	600	200	7240	804
Gobiidae (not identified)							80			80	9
S	**4**	**5**	**4**	**3**	**9**	**7**	**6**	**6**	**6**	**15**	
N	**1520**	**3440**	**2200**	**2600**	**7080**	**10080**	**7120**	**6240**	**23000**		
N̄											**7031**
A	**0.276**	**0.337**	**0.335**	**0.339**	**0.521**	**0.505**	**0.378**	**0.455**	**0.634**		
Ā											**0.517**

Symbols are the same as for Table 1

Fig. 3 shows increasing of the carrying capacity index during the season, as well as differences in the fish preference towards three closely located habitats.

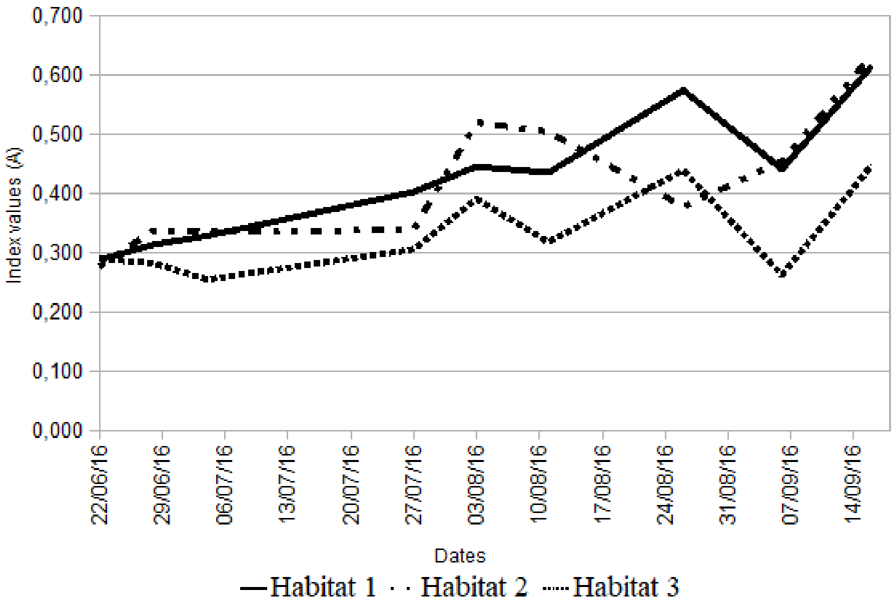

Fig. 3. Dynamics of the carrying capacity index during June-September 2016

Talble 3. Carrying capacity index (fishes in habitat 3)

Species (S)	Results of visual registration of fishes in June-September2016, specimens per ha (n_i)									∑n	n̄
	22.06	28.06	04.07	27.07	03.08	11.08	26.08	06.09	16.09		
Liza aurata (Risso)					440					440	49
Mugilidae (not identified)					200					200	22
Atherina boyeri Risso									800	800	89
Diplodus annularis (L.)		40		80		40	2000			2160	240
D. puntazzo (Cetti)				600	40	20			80	740	82
Scorpaena porcus L., 1758							40		40	80	9
Mullus barbatus L.					200	40	40			280	31
Crenilabrus cinereus (Bonnaterre)	40		160							200	22
C. roissali (Risso)		40				20		80		140	16
C. tinca (L.)	680	1680	360	600	720	4140	2720	1440	1360	13700	1522
C. ocellatus Forskal								80	4160	4240	471
Parablennius sanguinolentus (Pallas)	720	480	720	320	1280	440	640	200	80	4880	542
Mesogobius batrachocephalus (Pallas)	40									40	4
Gobiidae 1 (not identified)							40			40	4
Gobiidae 2 (not identified)	80						40			120	13
S	**5**	**4**	**3**	**4**	**6**	**6**	**7**	**4**	**6**	**15**	
N	**1560**	**2240**	**1240**	**1600**	**2880**	**4700**	**5520**	**1800**	**6520**		
N̄											**3118**
A	**0.289**	**0.282**	**0.255**	**0.306**	**0.391**	**0.318**	**0.439**	**0.262**	**0.448**		
Ā											**0.415**

Symbols are the same as for Table 1

We have also calculated the average seasonal indices of the carrying capacity for the mentioned habitats (Fig. 4): the average values are obtained by adding the numbers by species, and then dividing by the number of observations).

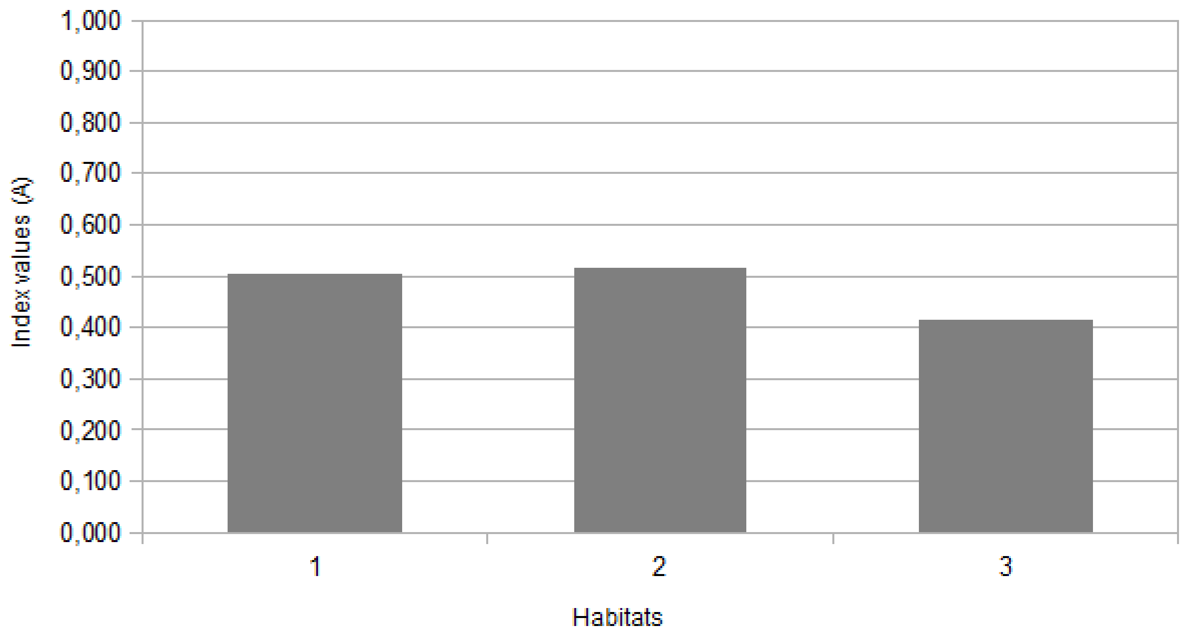

Fig. 4. Average seasonal indices of carrying capacity for habitats 1-3

According to the diagram (Fig. 4) during the season the most attractive is the habitat 2.
In our opinion, it is expediently to set a gradation of levels of the carrying capacity of habitat by index A (Table 4).

Table 4. Classes of carrying capacity of a biotope depending on the values of the index A

The interval for index A	Class of carrying capacity of a habitat	Carrying capacity level
[0-0.250]	IV	Low
[0.250-0.500]	III	Middle
[0.500-0.750]	II	High
[0.750-1.0]	I	Highest

Thus, the proposed index of carrying capacity makes it possible to characterize a habitat in terms of its carrying capacity concerning fishes of littoral fish assemblage. There is the reason to believe that the index is suitable for assessing the carrying capacity of habitats for other groups of aquatic organisms also.
However, it should be considered that comparison of habitats using this index is possible only if the way of presenting the results of quantitative abundance for calculating the index is the same every time (in our case this is the number of fish per 1 hectare of water area).
We recommend following way for choosing the coefficient Q, which avoids the compression of index values toward 1 for many specimens. Under each method of counting the number of specimens the order of values of the total number of specimens does not differ significantly, so it is possible to select the coefficient Q by using the smallest total number of specimens among all the data obtained or the possible smallest number of specimens. Let us assume that with the minimum N, the number of species S = 2, and the uniform distribution of specimens, the carrying capacity index takes the value 0.250 – in this case the habitat is of low level carrying capacity. Based on this, the table of Q values was calculated. If the smallest total number of specimens is greater than or equal to the number in row N, it is right to apply the corresponding value of Q (Table 5). If the number of specimens is less than 400, the value of the coefficient Q should be selected individually.

Table 5. Recommended values of Q as a function of the minimum N values

N	400	1600	6400	14500	26000	40000	58000	79000	103000	130000	161000	194000	230000
Q	50	100	200	300	400	500	600	700	800	900	1000	1100	1200

N	270000	315000	360000	410000	465000	520000	580000	640000	710000	775000	850000	925000	1000000
Q	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500

Conclusions

To assess the significance of a habitat for supporting biodiversity the following carrying capacity index of a biological system (A) have been developed using habitats of littoral fish assemblage as the example:

$$A = 1 - \frac{1}{1+\frac{1}{Q}\sqrt{(N+S)\left|\sum_{i=1}^{S}\frac{n_i}{N}ln\frac{n_i}{N}\right|}}$$

where N is the total number of specimens, S – the number of species, n_i – the number of specimens of each species, Q – coefficient, which makes possible to obtain A index values more convenient for perception. In our case, the most convenient is Q=100, so the equation is as following:

$$A = 1 - \frac{1}{1+\frac{1}{100}\sqrt{(N+S)\left|\sum_{i=1}^{S}\frac{n_i}{N}ln\frac{n_i}{N}\right|}}$$

The minimum value of the index as 0 is reached when S=1 for any value of N, regardless of the evenness of the system. A larger index value corresponds to larger species number and total number of specimens considering equable distribution of the elements in community. If S and N tend to infinity, the index tends to 1.
Evaluation of the effectiveness of the index applying to an analysis of the carrying capacity concerning fishes of the littoral habitats according to visual counts showed the suitability of the index for these purposes.
There is a reason to believe that the proposed index is suitable for assessing the carrying capacity of the habitats for other groups of aquatic organisms also, however, a comparison of the biotopes using this index is possible only if the way of presenting the results of quantitative estimates of abundance is identical.

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