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ESTIMATING THE CARRYING CAPACITY OF COASTAL AREAS POTENTIALLY SUITABLE FOR MUSSEL CULTURE IN THE UPPER ADRIATIC, CROATIA

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ABSTRACT

This paper deals with the application of a carrying capacity model, designed to evaluate the suitability of ten coastal inlets situated on islands in the upper Adriatic Sea for mussel production, and to estimate a potential production quantity. This approach allowed the estimation of a potential carrying capacity of the researched stations and suggestions for a possible launch of mussel production in these areas. The results of this study are considered to be useful for the management of coastal areas suitable for bivalve farming, especially in this particular case of island development. It has been established that the model was suitable for evaluation and that all selected stations have good conditions and carrying capacity for mussel production. Mussel farming could, therefore, improve the island economy.

Key words: carrying capacity, mussel farming, dimensioning of mussel farms, island development, Croatia

VALUTAZIONE DI AREE COSTALI POTENZIALMENTE IDONEE ALLA MITILICOLTURA NEL NORD ADRIATICO, CROAZIA

SINTESI

L'articolo tratta l'applicazione del modello di capacità portante destinato alla valutazione dell'idoneità alla mitilicoltura di dieci insenature costali situate su isole del Nord Adriatico e alla stima della quantità di produzione potenziale. L'approccio permette la valutazione della capacità portante potenziale delle stazioni studiate, nonché la formulazione di proposte per un possibile lancio della mitilicoltura in tali aree. I risultati del presente studio vengono considerati vantaggiosi per la gestione delle aree costali idonee alla coltura di bivalvi, in particolare nell'ambito dello sviluppo insulare. Il modello si è rivelato adatto alla valutazione e tutte le stazioni prescelte hanno dimostrato di avere condizioni e capacità portanti favorevoli alla mitilicoltura. La coltura di mitili pertanto potrebbe migliorare l'economia insulare.

Parole chiave: capacità portante, mitilicoltura, dimensionamento di mitilicolture, sviluppo insulare, Croazia

INTRODUCTION

The coast of Croatia and especially its islands have a number of areas potentially suitable for sea organism farming. Seashell farming has a long tradition on the eastern Adriatic coast, probably dating from the Roman period, but the first written documents originating from the 16th century describe Mali ston Bay. In the 20th century, seafood farming intensified on over 30 localities from Slovenian coast down to Boka Kotorska Bay (Basioli, 1981). Former seafood production (during the Austro-Hungarian Empire) was much higher than today. The Austrian Fishery and Mariculture Society used several locations on the coast and islands for oyster and blue mussel culture (Quinto Congresso generale della Società Austriaca di Pesca e piscicoltura marina, 1893). One of the main social and economical problems in Croatia today is maintaining the population on the islands and revitalising the economy. Aquaculture could be one of the main economy branches on the islands and on the coast in general.

Aquaculture is characterised by great dependence on the quality and productivity of the environment. Its development also bears a risk of negative environmental impact, such as pollution, landscape modification, or biodiversity change. Aquaculture development needs to follow the rules for use and conservation of natural resources in aquatic ecosystems (Bussani, 1983). Aquaculture as a renewable resource is a capital that must ensure a sustainable flow of benefits to users.

Coastal zones are always subjects of different conflicting needs, which include recreational and tourist requirements, navigational access and traditional commercial fishing rights. Optimisation of available space is consequently a challenge that also faces the developing aquaculture industry.

Few mussel species are farmed all around the world. The world production in 2000 exceeded 1.5 million. More than 20 countries have significant production, although only two of them dominate the market, *i.e.* China with 40% of the total world production and Spain with 20%.

On the eastern Adriatic coast, the majority of shell production is located in Mali ston Bay (90% of total production), with other larger farms situated in Lim Bay, Piran Bay, mouth of the river Krka, and Budava Bay (Hrs-Brenko, 1985). In 1984, 300 t of mussels, 40 t of oysters and 260 t of blue mussels were produced in Mali ston Bay (Benović, 1980, 1997). Considering the natural features of our coast, it could be said that the seafood production is still far from possible and satisfactory.

The most farmed mussels are those belonging to the genus *Mytilus* (*M. edulis* - blue mussel), while the genus *Perna* (former green mussel) is farmed in warmer waters, as around Thailand, China or New Zealand.

The capacity at the Gulf scale depends on primary production, trophic relationships, and modification of bio-geochemical cycles and community structure in the vicinity of culture sites (Foster-Smith, 1975; Fréchette & Bourget, 1985; Fréchette *et al.*, 1991, 1992).

On a smaller scale, however, the possibility of local food depletion should be considered. In many coastal ecosystems, bivalve suspension feeders, such as mussels, oysters and clams, occur in high densities. Feeding is performed by pumping and filtering large volumes of water through gills. Due to the filtration activity by bivalves, depletion of organic matter, bacteria and phytoplankton in the overlying water has been observed in various ecosystems (Möhlenberg & Riisgård, 1979; Wright *et al.*, 1982; Mantoura & Llewellyn, 1983; Fréchette & Bourget, 1985). Indeed, dense arrays of long lines are likely to lead to a depletion of seston (Loo & Rosenberg, 1989), which could affect the optimal size of growing sites, a problem that has been considered by Incze *et al.* (1981). In addition, local depletion of seston raises the issue of determining the optimal distance between the sites, as they should be positioned in such a way to enable water replenishment by mixing and plankton growth before reaching next downstream site.

Early attempts to assess the impact of shellfish aquaculture focused on the issue of carrying capacity, or the ability of the system to support shellfish production were made (Incze *et al.*, 1981; Loo & Rosenberg, 1989). More recently, the emphasis has been on modelling the impact of shellfish (Rodhouse & Roden, 1987).

A carrying capacity model has been tested by applying it to ten island bays in the upper Adriatic. The model is based on particle and not on energy flow. The main objective was to test the model, and to apply it in specific conditions of the chosen bays.

A three-season field programme was undertaken to assess the spatial and periodical distribution of total and organic seston and transport mechanisms of water and seston in the vicinity of a site. These terms of the seston budget were used to determine the dominant processes involved, and thus to evaluate the possibility of launching mussel farming.

MATERIALS AND METHODS

Location

The study was carried out in the upper Adriatic Sea, on four Croatian islands. Ten potentially suitable stations for mussel farming were investigated (Fig. 1):

Cres Island: Pogana Bay (st. 1),

Krk Island: Puntarska draga (st. 2) and

Soline Bay (st. 3),

Rab Island: St. Eufemija Bay (st. 4), Kamporska draga (st. 5), Lopar Bay (st. 6) and Supetar Bay (st. 7),

Pag Island: Caska Bay (st. 8), Stara Novalja Bay (st. 9), and Stara Povljana Bay (st. 10).

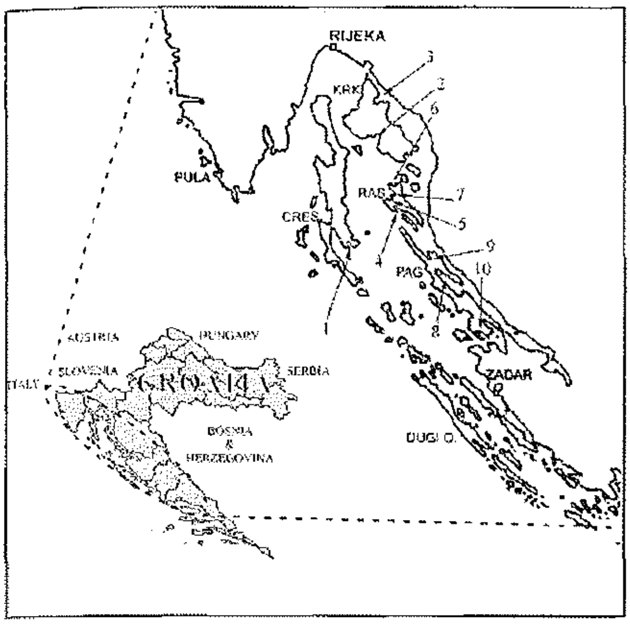

Fig. 1: Ten investigated stations along Croatian islands potentially suitable for mussel farming.
Sl. 1: Deset raziskanih vzorčišč vzdolž hrvaških otokov, potencialno primernih za školjkarstvo.

Sampling

Sampling took place in the winter (February) of 1998, and in the summer (July) and autumn (December) of 1999. Three replicates of water samples were taken at 0,5 and 10 m using a 5 l Niskin bottle. Currents were measured by a pseudo-eulerian method using Andria's cross (Mosetti, 1979). Compass recorded the direction.

Methods

Total particulate matter or seston (TPM) and particulate organic matter (POM) was determined as triplicates in the Zoology Department of the Faculty of Science.

Samples for seston analysis in triplicates of 250 ml were filtrated on combusted and pre-weighted Whatman GF/F filters. The filters were transferred to a 60°C drying oven for 24 hours. On the following day, filters were weighted to obtain values of TPM and combusted at 450 to 500°C for 24 h and re-weighted to estimate particulate inorganic matter (PIM) and POM (Magazzù, 1984). We used standard statistic equations (standard deviation and t-test).

Filtration rate is defined as the rate of removal of particles from a suspension in which the animals feed, or a measure of the equivalent volume of water that must have been filtered to account for the rate of removal (Coughlan, 1969; Foster-Smith, 1975; Meyhöfer, 1985; Prins *et al.*, 1994; Riisgård, 2001). We used literature data for calculating the filtration rate. In Table 1, values of blue mussel filtration rates are presented. Finally, we used the average filtration rate for the blue mussel.

Food supply is a function of water movement and quantity of particles in the water, whereas food demand is a function of filtration rate and food concentration. Carrying capacity is calculated by dividing food supply with food demand.

Tab. 1: Data of mussel filtration rate from bibliography.
Tab. 1: Podatki iz bibliografije o hitrosti filtracije školjk.

Mussel filtration rate (l/h)	Bibliographic source
2.06	Foster-Smith (1975)
0.33-1.25 (0.79)	Foster-Smith (1975)
0.35-1.05 (0.7)	Foster-Smith (1975)
1.54	Foster-Smith (1975)
1.47	Foster-Smith (1975)
1.2-3.4 (2.3)	Schulte (1975)
0.5-2.0 (1.25)	Möhlenberg & Riisgård (1979)
1-2.5 (1.75)	Widdows *et al.* (1979)
2.50	Martinčić (1998)
1.60	**average value**

The modelling approach itself has shown certain weaknesses, including sensitivity to a restricted set of underlying assumptions and insensitivity to a potentially wide array of unspecified parameters. Despite these numerous limitations, approximations of carrying capacities for intensive cultivation remain of interest. The salient feature of both models is that it is based on particle flow, and not on energy flow. Clearly, the limitations of the modelling approach are not eliminated by these simplifications. This model is offered as an approach, and not as a unique solution.

The model is based on water movements and on the seston quantity in the area. A biological concept of the carrying capacity can be defined as the stock density at which production levels are maximized, without a negative environmental impact. The carrying capacity model studied here is based on balance between mussel nutritive needs and food supply within the system. The estimation of the carrying capacity of bivalves in open systems is rendered difficult due to several factors: 1) seasonal and size-related changes in the energy demands of the cultured organisms; 2) seasonal changes in the abundance and nature of potential food substrates found in natural waters; 3) general lack of knowledge concerning the degree to which bivalves utilize various particles in the seston, and 4) difficulties of quantifying mixing and flow through most culture areas.

The model of Carver & Mallet (1990) was developed in Canada (Nova Scotia). Authors used a somewhat simplistic but practical approach to determine estimates of carrying capacity for a mussel operation in a semi-closed coastal inlet on the Atlantic coast. Rather than relying on laboratory-derived values, authors obtained extensive field data on water exchange, food levels and *in situ* mussel filtration rates. The volume of the Basin was estimated as well as the volume of water flowing in and out of the system in each tidal cycle. Data of suspended particulate matter was used in order to calculate food levels (food supply and food demand). Finally, carrying capacity was obtained dividing food supply by food demand. Equations are presented in Table 4.

RESULTS AND DISCUSSION

Environmental study

Current velocities are shown in Table 2. As expected, the strongest currents were measured in winter as a consequence of meteorological conditions. We did not find significant differences between stations.

Measurements of the currents gave us results comparable with other authors (Princi *et al.*, 1980; Stravisi & Battista, 1992). Two current types are usually present in the Adriatic (Mosetti, 1966). On a large scale, there is a constant slow current below 10 m depth, parallel to the coast in the northern direction. On a small scale, currents are influenced by wind, tide and morphological circumstances. It is important for good water quality in mussel farms to have fast water exchange and currents able to replenish the water quite frequently.

The biggest bay is Caska on Pag Island, while the smallest is Pogana on Cres Island. As far as the bay volume is concerned, the largest goes to St. Povljana Bay on Pag, and the smallest to Punat Bay on Krk. In Table 4, all hydrologic data about bays is presented (water tidal oscillations, water surface and volume, water exchange).

Water exchange in all examined bays showed good results (from 5-30% of water exchange/day). For example, the Gulf of Trieste that is known for its high number of mussel farms (Martinčić, 1998) has an average water exchange of only 7%. The bay studied by Carver & Mallet (1990) had a water exchange of approx. 50%. This is particularly important for water replenishment that depends not only on tidal currents but also on permanent currents and also imports from the land.

Temperature, salinity and oxygen are parameters closely linked with each other and connected with external meteorological and hydrological conditions. Their variations are mostly of temporal character. During winter, the water column is homogeneous due to strong water mixing, while in spring it is possible to observe water stratification, which continues into and through the entire summer (Marchetti & Cotta Ramusino, 1992). Stratification is present both for temperature (presence of thermocline) and salinity (picnocline). In spring, superficial water in fact heats up, and due to the freshwater income from the land the salinity varies greatly between the sea's surface and floor.

Tab. 2: Current velocities at sampling stations.
Tab. 2: Hitrosti tokov na vzorčiščih.

Stations	Winter	Summer	Autumn
1	9.5	15.2	0.07
2	0.6	12.5	10.0
3	5.9	0.9	0.9
4	18.0	14.7	8.3
5	12.8	16.7	0.1
6	26.3	16.7	8.3
7	10.2	9.5	10.5
8	12.5	7.1	14.9
9	15.0	8.3	8.3
10	0.3	0.3	0.3

Analysis of TPM showed a maximum concentration of particulate matter in summer (Tab. 3). Considering the low depth of water at most stations, high TPM values are probably a consequence of bottom resuspension. The obtained data were not significantly different between stations.

The relatively high standard deviations can be explained with the fact that these values are calculated as an average of three depths (0, 5 and 10 m). These are depths at which mussels are farmed and although different they were not statistically significant. For further calculations, we thus decided to work with average data.

The lowest POM concentration was recorded in winter, the highest in autumn. Differences between winter and summer as well as between winter and autumn are statistically significant (t-test = 0.000828, t-test = 0.002804), while those between summer and autumn are not significant (t-test = 0.285358). All the examined stations had a good quantity of POM, ranging between 1.2 mg/l (Lopar and St. Novalja Bays) and 4.2 mg/l in St. Povljana Bay.

TPM is related to land contributions and also to phytoplankton production (Schulte, 1975; Valli, 1980; Fonda Umani & Ghirardelli, 1988; Williams & Claustre, 1991). Suspended matter is usually composed of inorganic detritus, especially close to the shore or in shallow waters. Even by taking this into consideration, we found some relatively high concentrations of organic matter, with values ranging from 14% (winter) to 77% (autumn) of POM. Bayne & Widdows (1978) recorded, for the coastal area of Spain, values from 3 to 100 mg/l of TPM, with only 5-30 % of organic components. Our results can be well compared to data measured in the Gulf of Trieste (Adriatic Sea). Authors measured from 0.7 to 4 mg/l of TPM, with 25 to 31% of organic matter (Fonda Umani & Ghirardelli, 1988).

Since the organic component is formed by live planktonic organisms and organic products of biodeposition, it is normal that we found the lowest concentration of organic matter in winter, when no planktonic

Tab. 3: Mean values (±s.d.) of total particulate matter (TPM) and particulate organic matter (POM) during three seasons at ten sampling stations. Relative contribution of POM as % of TPM is also shown.
Tab. 3: Srednje vrednosti (±s.d.) celotne suspendirane snovi (TPM) in partikulatne organske snovi (POM) v treh sezonah na desetih preučevanih vzorčiščih. Prikazan je tudi relativni prispevek POM kot % TPM.

Station	Winter			Summer			Autumn		
	TPM (mg/l)	POM (mg/l)	POM (% of TPM)	TPM	POM	POM (% of TPM)	TPM	POM	POM (% of TPM)
1	3.3 (1.0)	0.4 (0.3)	14.0 (11.5)	4.1 (1.7)	2.6 (0.8)	68.0 (20.7)	3.5 (0.9)	2.0 (0.3)	60.0 (11.0)
2	3.4 (1.4)	0.9 (0.1)	28.7 (8.1)	3.3 (1.0)	2.2 (0.5)	69.0 (7.5)	3.8 (1.7)	1.5 (0.9)	39.7 (15.6)
3	3.9 (0.8)	1.2 (0.1)	31.0 (2.8)	6.3 (3.3)	3.0 (1.2)	48.0 (22.3)	3.5 (1.1)	1.3 (5.7)	37.0 (15.5)
4	17.8 (20.5)	1.7 (1.1)	18.0 (10.5)	7.4 (2.0)	1.8 (0.9)	25.3 (12.5)	3.0 (1.8)	2.1 (0.7)	75.3 (15.9)
5	3.0 (1.6)	0.5 (0.3)	17.3 (4.2)	4.3 (2.9)	1.9 (0.6)	49.7 (13.7)	2.6 (1.0)	2.0 (0.7)	76.7 (4.2)
6	4.8 (4.0)	0.7 (0.0)	21.0 (13.1)	4.1 (2.3)	1.7 (0.7)	47.3 (15.3)	7.0 (5.8)	1.3 (0.5)	22.3 (8.1)
7	3.8 (1.4)	0.8 (0.4)	22.0 (6.9)	4.3 (1.9)	1.8 (0.3)	44.7 (11.7)	2.6 (0.6)	1.2 (0.2)	48.3 (19.5)
8	6.8 (4.8)	1.6 (0.8)	25.0 (5.6)	7.1 (4.0)	3.9 (1.1)	62.0 (17.1)	3.4 (1.1)	1.7 (0.6)	50.3 (4.5)
9	3.0 (0.7)	1.1 (0.3)	35.7 (7.8)	2.6 (0.3)	1.3 (0.4)	50.3 (19.8)	2.9 (0.4)	1.1 (0.4)	36.7 (7.5)
10	2.3 (0.6)	0.5 (0.1)	22.0 (7.8)	18.0 (6.5)	4.2 (1.3)	23.0 (9.8)	2.8 (1.3)	1.8 (6.0)	64.0 (25.3)

blooms are present, and the highest percentage in autumn due to the active planktonic bloom or scenescent phase of the bloom (Marchetti & Cotta Ramusino, 1992).

Carrying capacity model

There is an abundance of data in literature on the influence of water flow on the particles or food concentration (Dame *et al.*, 1980; Incze *et al.*, 1981; Cloern, 1982; Fréchette & Bourget, 1985; Loo & Rosenberg, 1989).

In estuaries, the seston movement is dominated by the river outflow, while in the coastal inlets it is primarily determined by tidal currents, which are often very weak. Food supply in the water depends not only on the water flow but also on the quantity and quality of particles present in it (Zentilin & Pellizzato, 1996).

Variations in food supply are in relation to tidal oscillations and thus to tidal volume, as well as to POM oscillations in the water. We observed that maximum POM levels at our stations were comparable to the values reported in other mussel studies (Bayne & Widdows, 1978; Widdows *et al.*, 1979; Wildish & Kristmanson, 1984; Carver & Mallet, 1990). Values lower than 1 mg/l are common along the Atlantic coast, while higher values are generally characteristic of estuaries and coastal inlets (Carver & Mallet, 1990). The lowest food supply was noted for the wintertime, as a result of the low primary production.

Among the stations, we calculated the highest quantity of food supply in Caska and St. Povljana Bays on Pag Island.

Rodhouse & Roden (1987) found that zooplankton compete with cultured mussels for food particles and estimated that herbivorous zooplankton consume 29% of the annual phytoplankton production in Killary Harbour, Ireland. On the other hand, recent evidence suggests that mussels can significantly reduce microzooplankton levels (Incze *et al.*, 1981), thereby effectively decreasing food competition. Given that increasing stock densities have a positive effect on primary production, our estimates of food supply should eventually include not only the POM delivered to the system, but also locally produced POM.

Food demand was calculated with estimates on filtration rate and food concentration. At our sites, there were always enough particles present in the water to satisfy the average filtration needs by mussels. Mussels consume live and inorganic particles in the water (plankton and detritus).

Since we did not find significant differences in carrying capacities measured in winter, summer and autumn, average data is presented (Tab. 4). In the end, we concentrated on potential differences between stations.

Relatively large water volumes and high POM concentrations gave high carrying capacities. St. Novalja and St. Povljana Bays had a carrying capacity higher than 2000 t. The lowest carrying capacity was calculated for Pogana (about 600 t).

In estimating the carrying capacity, we assumed that the mussels had access to 100% of the available food supply. This approach does not allow factors such as incomplete mixing of particles in the Gulf, loss of particles in the outflow, and contamination of "new" particle-rich water by "old" particle-depleted water from the previous tidal cycle. A positive effect of mussel stock densities on nutrient regeneration, which can enhance local primary production, should also be considered.

Tab. 4: Carrying capacity equations and hydrological data for the ten sampling stations.
Tab. 4: Enačbe za izračun nosilnosti okolja in hidrološki podatki za deset vzorčišč.

	Parameter	Equation	Cres	Krk	Krk	Rab	Rab	Rab	Rab	Pag	Pag	Pag
			st. 1	st. 2	st. 3	st. 4	st. 5	st. 6	st. 7	st. 8	st. 9	st. 10
a	Average ebb tide (cm)		32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2
b	Average high tide (cm)		30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3
c	Daily oscilations (cm)	(a+b) x 2	125	125	125	125	125	125	125	125	125	125
d	Tidal volume per day (x 10^4 m^3)	c x i	201	377	430	320	463	271	560	1398	675	1030
e	Tidal volume per week (x 10^4 m^3)	d x 7	1407	2644	3016	2246	3244	1903	3920	9789	4731	7211
f	Bay volume in ebb tide (x 10^4 m^3)	j-d/2	1217	878	1106	2344	9732	2426	6274	11487	10683	15714
g	Bay volume in high tide (x 10^4 m^3)	j+d/2	1418	1255	1537	2665	10196	2697	6834	12886	11359	16745
h	Water exchange per day (%)	d/g	14	30	28	12	5	10	8	11	6	6
i	Total by surface (A_{tot}) m^2		1609300	3024209	3449123	2569200	3710500	2176800	4482500	11194100	5410100	8245700
j	Bay volume (V_{tot}) x 10^4 m^3		1318	1067	1322	2505	9964	2562	6554	12187	11021	16230
k	POM (mg/l)		1.7	2.6	2.4	1.9	1.5	1.2	1.3	2.4	1.2	4.2
l	Food supply (x 10^6 g POM/week)	e x k	23.4	68.4	72.4	42.0	47.6	23.4	49.4	233.2	55.1	202.1
m	Food demand (g POM/kg mussels/week)	k/1000 x 1.6 x 24h x 7 x 83	37.2	57.3	53.5	41.6	32.7	27.5	28.3	53.5	26.0	62.5
	Carrying capacity (tons of mussels)	l/m	629	1193	1353	1010	1456	851	1746	4359	2119	3234

All the sites have shown to be suitable for mussel production. Carrying capacities higher than 500 t can be considered as high. The lowest recorded carrying capacity was in Pogana Bay on the island of Cres (600 t). Generally, the best island for mussel production should be Pag, where all three bays showed very high carrying capacities (higher than 2000 t).

CONCLUSIONS

It can be concluded that all the examined sites on Croatian islands are suitable for mussel farming. The present study only confirmed this statement already known to national experts. Mariculture could be an additional motive and way of earning money for these island populations, as well as incentive for new people settling there.

Among 10 sites, the best are those on the island of Pag, but none turned out to be non-suitable for mussel farming. Similar study should be performed on other islands and new locations for this economic activity suggested.

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OCENJEVANJE NOSILNOSTI OKOLJA V SEVERNOJADRANSKIH OBALNIH OBMOČJIH, POTENCIALNO PRIMERNIH ZA VZGOJO ŠKOLJK

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POVZETEK

V desetih manjših zalivih ob severnojadranskih otokih je bil uporabljen model za ugotavljanje nosilnosti tamkajšnjega morskega okolja. Študija, katere namen je bil ugotoviti primernost teh voda za gojenje školjk, je slonela na terenskih podatkih o izmenjavi vode in količini hrane v njej, dobljenih med vzorčenjem pozimi, poleti in jeseni leta 1999.

Rezultati so pokazali, da so vse preučevane lokalitete primerne za školjkarstvo. Najnižja nosilnost okolja je bila ugotovljena v zalivu Pogana na Cresu, sicer pa je bila izmenjava vode zadostna v vseh preučevanih zalivih (od 5-30% na dan).

Dobljene rezultate bi lahko uporabili za upravljanje obalnih območij, primernih za vzgojo školjk, posebno v primerih načrtovanega otoškega razvoja. Školjkarstvo bi lahko seveda močno izboljšalo otoško gospodarstvo.

Ključne besede: nosilnost okolja, školjkarstvo, dimenzioniranje školjčišč, otoški razvoj, Hrvaška

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