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Long-term dynamics of blue mussel (*Mytilus edulis* L.) culture settlements (the White Sea)

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Abstract

Spatial and temporal heterogeneity of growth and mortality of *Mytilus edulis* in cultured settlements from Kandalaksha Bay of the White Sea have been studied from an analysis of annual length/frequency distributions. It is shown that the values of annual length increment of mussels and their elimination are a function of their initial length and population density. A model suitable for predicting annual changes in mean length and density of mussels on artificial substrata has been constructed on the basis of multiple regression equations. The use of the model in predicting yield is discussed.

Keywords: Mytilus edulis; Aquaculture; Model; Density; Growth

1. Introduction

The temperature regime of the White Sea waters is not optimal for mussel *Mytilus edulis* L. growth. The potential for mussel mariculture is restricted by a prolonged period of ice cover (up to 7 months). Since 1985, however, industrial mussel aquaculture has expanded in the White Sea and its scale causes alarm with regard to its ecological impact (Chivilev and Minichev, 1993). In handling the problems of the White Sea mussel aquaculture industry, modelling changes in the population dynamics of artificial

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M. edulis settlements under the influence of internal and external factors may have considerable utility. It can be employed for prediction of both yield potential and the load from local aquaculture farms on natural bottom and pelagic ecosystems.

Since 1985, mussel culture farms have been controlled by ecological monitoring. The present work is devoted to determination and modelling of growth and mortality of commercial mussel settlements in the White Sea based on data obtained by the end of 1994.

2. Material and methods

The present investigations are based on annual observations and sampling within suspended mussel culture farms located in Kandalaksha Bay of the White Sea (Fig. 1).

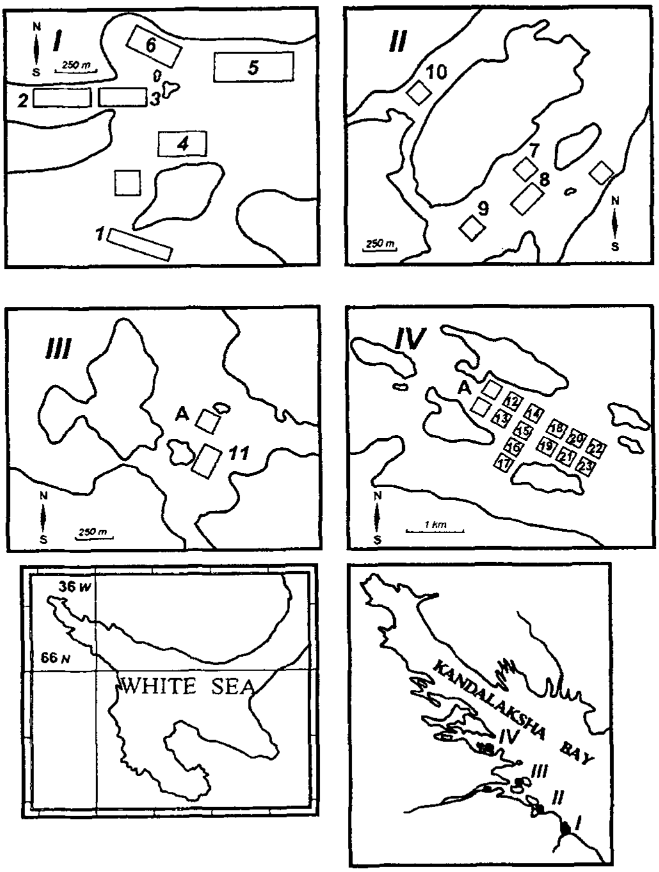

Fig. 1. Location of mussel aquaculture farms in Kandalaksha Bay (the White Sea). I – near Sonostrov Island; II – Nikol'skaya Inlet; III – Oborina Salma Straits; IV – Kuzokotskaya Inlet. Arabic numerals mark investigated local sites. A – sites which are characterised by fouling community with non-mussel dominants.

Table 1
Parameters of mussel culture farms

Site No.	Year of establishment	Total length of substrata (m)	Percentage cover by mussels (%)	Number of lines	Yield (tons)	Yield per line (tons)
1	1985	96000	30	–	52	–
2	1986	32120	90	22 (22)	98	4.7
3	1987	29200	90	10 (10)	83	8.3
4	1987	43800	90	15 (15)	105	7.0
5	1987	64240	90	22 (22)	200	9.1
6	1987	29200	90	10 (10)	48	4.8
7	1988	26280	70	9 (9)	69	7.6
8	1988	52560	65	18 (13)	170	13.1
9	1989	40880	75	14 (14)	79	5.6
10	1989	40880	95	14 (14)	146	10.4
11	1988	52560	95	18 (14)	169	12.1
12–23	1990	315360	95	108 (< 50)	–	–

Note: Site Nos. correspond to those in Fig. 1. Number of lines is given at the beginning of cultivation and (in brackets) by the end of the thirrd year of exposure as well as yield values.

Modelling was performed only on data obtained from commercial farms (since 1985). Rafts and other constructions for mussel cultivation within each farm are grouped together into 2–14 separate local units (sites). From 1985 to 1990, 28 such units with a total area of about 60 hectares have been established. Each site occupied 1.5–3 hectares of water surface. The present work was carried out on 23 units (Fig. 1., Table 1). Each aquaculture unit contained rafts which were made from polyethylene pipes, with hanging substrata comprising nylon net bands or ropes 3 m long. Substrata were suspended 20–40 cm apart and grouped in lines (about 1000 substrata per line). Samples were taken annually at the end of the growing season (late August–September) in each unit at 3–9 stations at two depths: 0.5 and 2.5 m. Sample size was 7–10 cm of substratum. Age and length (with an accuracy of 1 mm) of sampled molluscs were determined. Based on this data mean length and density were obtained for each unit. Yearly length increments (ΔL, mm) were estimated as the difference between mean lengths of mussels of the same generation in consecutive autumn samples. Decreases in density were calculated using the annual mortality coefficient $Z = (\ln N_1 - \ln N_2)$, where N_1 and N_2 are the initial and final mean mussel densities (individuals per linear meter of substratum) observed over a 1 year interval.

Biomass was estimated using the equation

$$W = 0.0001 \times L^{2.96}$$

(Sukhotin and Kulakowski, 1992),where W is the live weight in g and L is the shell length in mm.

3. Results

3.1. Conditions of formation and parameters of mussel settlements in local sites

Based on the preliminary studies local regions of investigated farms were assumed to be similar in conditions for spat settlement and mussel growth. Only site 1 (established

Table 2
Dynamics of mussel culture settlements parameters (from: Maximovich et al., 1993 updated)

Site No.	H,m	L/N	Parameters of generation by the end of growth season										
			1	2		3		4		5		6	
			A	A	B	A	B	A	B	A	B	A	B
1	0.5	L	–	–	–	22	–	37	36	42	49	–	–
		N	–	–	–	630	–	560	380	430	390	–	–
	2.5	L	–	–	–	22	–	33	35	37	44	–	–
		N	–	–	–	420	–	370	260	520	260	–	–
2	0.5	L	–	12	–	25	27	40	38	47	51	–	–
		N	–	4000	–	2570	1580	800	1350	510	570	–	–
	2.5	L	–	8	–	15	23	36	29	42	46	–	–
		N	–	4000	–	3040	1510	590	1350	450	410	–	–
3	0.5	L	1.5	15	16	27	30	43	40	–	53	–	–
		N	15000	3810	1960	1070	1580	530	650	–	490	–	–
	2.5	L	1.5	12	15	18	26	37	31	–	47	–	–
		N	15000	2190	1960	1670	1020	620	870	–	440	–	–
4	0.5	L	–	20	–	29	34	43	42	–	53	–	–
		N	–	1430	–	890	780	510	560	–	390	–	–
	2.5	L	–	17	–	25	31	39	37	–	50	–	–
		N	–	1130	–	660	610	360	420	–	270	–	–
5	0.5	L	–	19	–	32	33	43	44	55	54	–	–
		N	–	1670	–	780	880	550	510	400	420	–	–
	2.5	L	–	11	–	30	26	43	41	54	52	–	–
		N	–	1570	–	620	760	460	400	410	350	–	–
6	0.5	L	–	–	–	29	–	39	42	57	50	–	–
		N	–	–	–	480	–	400	310	270	290	–	–
	2.5	L	–	–	–	26	–	36	38	50	47	–	–
		N	–	–	–	460	–	390	290	430	280	–	–
7	0.5	L	1.5	26	16	40	39	–	51	–	–	–	–
		N	16000	1340	1910	550	790	–	400	–	–	–	–
	2.5	L	2.0	15	13	32	29	–	43	–	–	–	–
		N	26000	1980	1270	640	970	–	430	–	–	–	–

8	0.5	*L*	1.8	24	19	41	37	54	52	60	63	–	–
		N	1600	1110	700	610	640	700	450	300	600	–	–
	2.5	*L*	2.5	20	18	35	33	50	46	62	58	–	–
		N	2800	980	1110	570	560	410	400	250	340	–	–
9	0.5	*L*	2	14	17	30	29	40	43	*51	51	*56	60
		N	12000	1200	2070	800	620	600	510	*410	440	*290	350
	2.5	*L*	1.5	5	6.5	23	21	32	36	*47	43	*52	56
		N	40000	800	440	800	400	650	480	*400	430	*250	320
10	0.5	*L*	–	–	–	30	–	36	43	*41	48	*53	55
		N	–	–	–	1280	–	1060	790	*490	710	*420	380
	2.5	*L*	–	–	–	20	–	32	33	*39	43	*48	49
		N	–	–	–	1980	–	1130	1030	*620	720	*480	450
11	0.5	*L*	1.5	20	16	39	34	45	50	57	55	–	–
		N	16000	1440	1910	550	780	580	400	500	450	–	–
	2.5	*L*	1.5	16	15	32	29	45	43	55	54	–	–
		N	16000	2160	1910	1050	1050	530	750	410	410	–	–
12–23	0.5	*L*	–	17	–	21	31	*31	35	–	–	–	–
		N	–	3500	–	3000	1530	*920	1450	–	–	–	–
	2.5	*L*	–	15	–	22	28	*27	34	–	–	–	–
		N	–	4900	–	2800	1850	*710	1390	–	–	–	–

Note: Site Nos. correspond to those from Fig. 1. *L* – mean mussel length, mm; *N* – mussel density, ind. per m of substratum. A – observed and B – predicted values. * indicates data obtained in 1993–1994 and not taken into account in modelling.

in 1985) was characterised by a higher density of substrata disposition. On the other hand, population dynamics differed between the investigated settlements. The farms have been established asynchronously over a 5 year period (from 1985 to 1989), causing variability in spat characteristics both in time and in density of settlement (Table 2). In winter periods the continuity in order and density of substrata was often broken. Hence, the growth conditions of mussels within the farms changed from year to year. Some farms lost entire lines of substrata (Table 1). At some farms in Oborina Salma and Kuzokotskaya (Fig. 1), due to early exposure substrata were completely and steadily occupied by other fouling species of Hydroidea, Ascidia and Algae. In other sites the dominance of these organisms was occasional. This effect was estimated as the percentage of substrata covered by mussels, which in all sites averaged between 30 and 95% (Table 1). In evaluating this parameter substrata with both complete and partial absence of mussels were taken into account. In the latter case, mussels as a rule massed on the upper parts of substrata. When a substratum was completely covered with mussels, the largest individuals occupied the upper part and relatively small molluscs the lower part of substratum.

Development of cultured mussel settlements at the White Sea has two main tendencies. First, if spat settlement is abundant, strong dominance of mussels of the first (main) generation is observed. Recolonization is not possible before 3 years of cultivation (Sukhotin and Kulakowski, 1992; Kulakowski et al., 1993) (Fig. 2). Second, if spat settlement in the first year is poor a significant additional settlement may occur in the following season. Size-frequency parameters of such populations vary greatly, modal mussel size is relatively low and density is high. This situation was most clearly observed in sites 1 and 2 (Fig. 3). These effects cause significant variation in size-frequency characteristics in mussel settlements of the same age as well as within whole farms. This complicates the use of easily measured parameters such as mean mollusc length and density for prediction purposes. Conditions that determine the dynamics of these parameters should be taken into account in each situation.

3.2. Growth

Maximal distance between the investigated farms did not exceed 60 km (Fig. 1). The water temperature in these areas did not significantly differ from long-term average values observed in Kandalaksha Bay (Babkov, 1988; Babkov and Golikov, 1984). Therefore, strong differences in growth between and within sites were determined only by the spatial location and density of the molluscs (nutritional conditions) and their size/age parameters (Sukhotin and Maximovich, 1994).

The analysis of variation of yearly length increment was carried out according to the following factors: age, mean length and density of molluscs, their placement on substratum, location of the substratum within a site, and different sites. It showed population dominated by the first two generations can be considered as a single unimodal cohort characterised by mean mussel length and density (Fig. 3). The only exception to this settlement pattern within a local site is the formation of excessively dense aggregations containing smaller mussels on the lower end of substrata. In Table 2 the parameters of these cohorts are given separately for the upper and lower parts of the

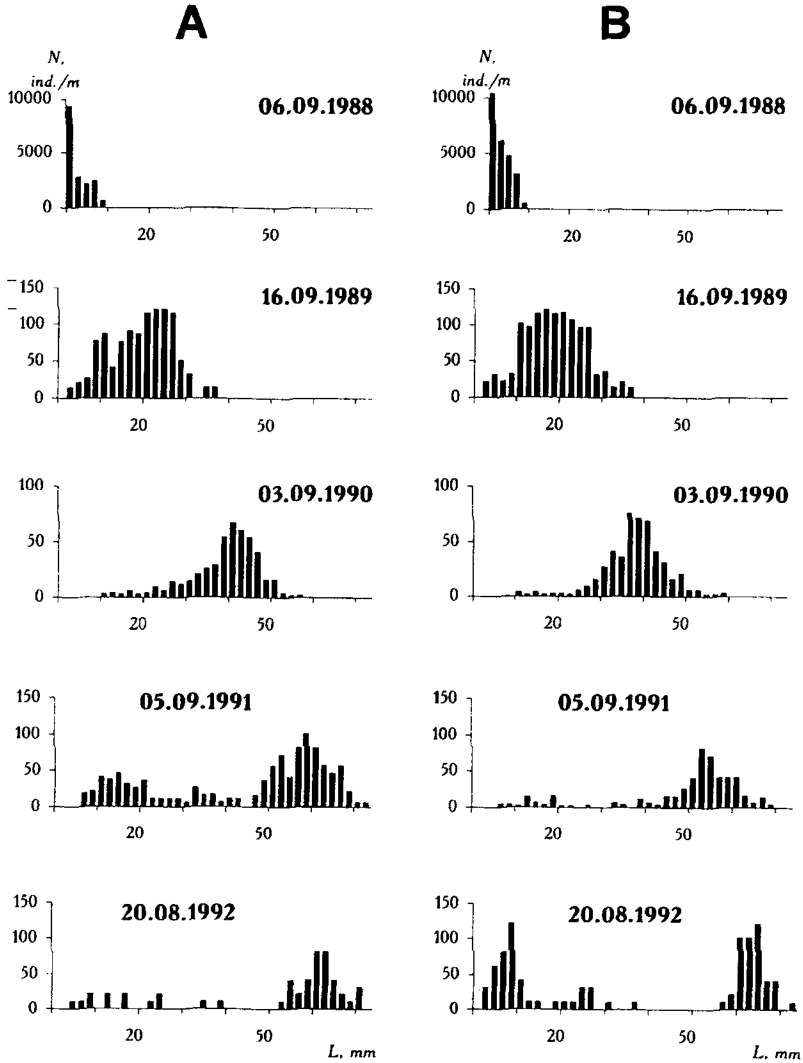

Fig. 2. Size–frequency dynamics in mussel settlement on local site No. 8 (year of establishment 1988). A – upper and B – lower parts of substrata. X-axis – shell length of mussels, mm; Y-axis – number, ind. m^{-1}.

substrata. Length increments of the cohorts were found to be significantly dependent (Table 3) on the initial size of the mussels, their density and position on the substrata (two depths — 0.5 and 2.5 m).

3.3. Density dynamics

From Table 2 it becomes evident that initial mussel densities in different local sites may vary significantly with a subsequent falling away of the differences. In this context

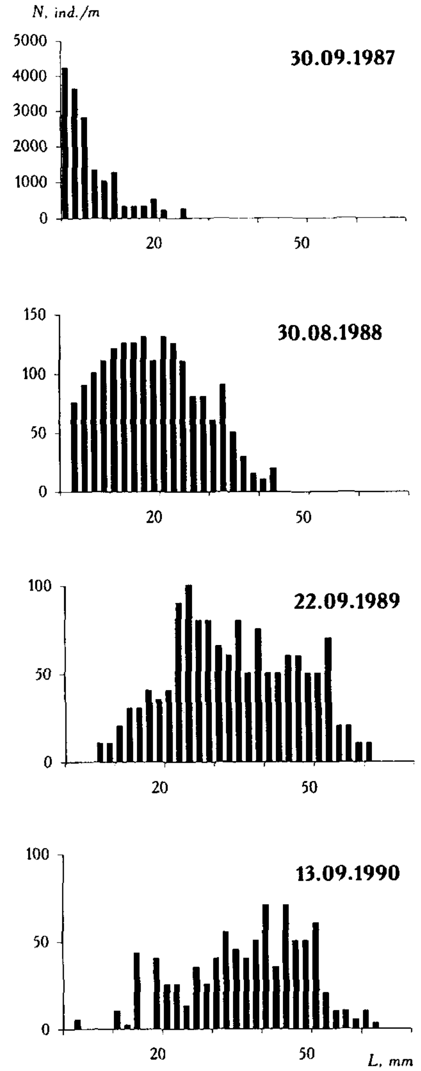

Fig. 3. Size–frequency dynamics in mussel settlement on local site No. 2 (year of establishment 1987). X-axis – shell length of mussels, mm; Y-axis – number, ind. m^{-1}.

it is convenient to use a reliable parameter — mortality coefficient (Z) as a characteristic of density decreasing, assuming Z to be constant within a year. From obtained data (Table 2) it appears that Z of the dominating group in average is proportional to initial density (N_i) and inversely proportional to initial length (L_i) of mussels. This function is clearly exponential, but pair correlation coefficient exceeds 0.7 so the relationship as a whole can be adequately fitted by a multiple linear regression equation with a high and significant determination coefficient (Table 3).

Table 3
Parameters of equations $\Delta L = a + bL_0 + cN_0 + dH$ (1) and $Z = a + bL_0 + cN_0$ (2) obtained using data from Table 2

Equation	Parameter	Value	S.E.	P	R^2	F-ratio	n
	a	18.17	4.00	0.000			
	b	−0.16	0.0064	0.000			
1	c	−0.00024	0.000012	0.008	0.21	4.2	60
	d	−0.42	0.076	0.227			
	a	0.694	0.215	0.001			
2	b	−0.0106	0.0011	0.075	0.90	117.0	29
	c	0.00009	0.00002	0.000			

Note: ΔL – mean year length increment of mussels (mm); Z – mortality coefficient per year; L_0 and N_0 – initial mean length (mm) and density (ind. m^{-1}) of mussels on substrata; H – sample position within substratum (depth) (m). S.E. – standard errors of parameters. P – significant level; R^2 – determination coefficient; n – number of observations.

3.4. Model

The proposed modelling of *M. edulis* aquaculture farms development in the White Sea is summarised in the following assumptions:

1. During at least the first 5 years growth and mortality changes can be predicted using values of initial mean length and density of the predominant size/age group;
2. The unit of modelling is the local aquaculture site. Spatial dissimilarity of mussel settlement within the site is most usually evident as size-frequency differences in lower and upper parts of substrata;
3. Mean mussel length and density within the site are determined as characteristics of an average substratum;
4. Prediction of length increment values and mortality rates of mussels are performed in a stepwise (recurrent) fashion for each site separately, accounting for variation in initial settlement density in accordance with the multiple linear regression equations in Table 3. The mortality coefficient (Z) for each size/age group is assumed to be constant within a year from the time of observation. The required density (N) is calculated by the formula

$$\ln(N) = \ln(N_0) - Z,$$

where N_0 is mussel density at time of observation.

Theoretical values of L and N (Table 2), which were obtained using the model in interpolation regime, generally agree with observed values, particularly after the third year, except site 8. Mean deviation of modelled length increments from real values does not exceed 4 mm. Maximal errors of prediction (up to 50%) are characteristic for the second year. Mean deviation of modelled densities from observed ones in 2–5 years are 800 (40%), 360 (30%), 180 (30%) and 40 (20%) ind. per meter of substratum, respectively. Estimated density exceeded observed density by a factor of two at site 8 in the fifth year. We attribute this difference to error in sampling.

Table 4
Standing stock of aquaculture farms established in 1987–1989

Year of establishment	Growing seasons	Stock biomass per line (tons)	
		A	B
1987	2	1.9	1.9
	3	3.6	6.3
	4	8.0	7.2
	5	14.6	12.3
1988	2	2.8	1.5
	3	7.8	7.4
	4	16.1	12.3
	5	17.6	21.8
1989	2	0.4	1.3
	3	4.0	2.4
	4	9.3	10.2
	5	11.3	14.8
	6	12.6	15.4

Note: A – observed and B – predicted values. Biomass values are given as the average for all the farms established in corresponding years.

3.5. Yield

For every observation the stock of mussels in local sites can be estimated using data on substrata number, degree of their colonisation (Table 1) and characteristics of settlements (Table 2). It can be seen that by the end of the cultivation period (the end of the third year) investigated sites differed noticeably by values of yield — from 50 to 200 tons (Table 1). The highest yield per line was observed on farms established in 1988 in Nikolskaya Bay and Oborina Salma (sites 8 and 11). The main reason for this is markedly higher growth rates at these sites (Table 2).

Since investigated farms differed in size, comparison of predicted and observed yield values was estimated per line (Table 1). The most complete comparison of these values can be performed only for farms established in 1987–1989 (Table 4). Similarity of observed and calculated values of mussel stock was found to be satisfactory. Differences in observed and theoretical values in 9 out of 13 cases did not exceed 25%. Overall, for all investigated sites only site 8 in the fourth year and site 9 in the second year were characterised by two-fold excess of the observed value above the predicted one.

4. Discussion

Mollusc growth rate is a basic index of aquaculture efficacy. It is well-known that in temperate zones, mussels grow considerably faster that those living above the North Polar Circle. Our previous and present work shows that, compared with other reports of arctic mussel aquaculture, that in the White Sea is characterised by the lowest growth

Table 5
Age/length characteristics of *Mytilus edulis* cultured in arctic waters.

Sea	Latitude	Mean length (mm) at ages (years)				Source
		1	2	3	4	
Norwegian Sea	68.5°N	13	28	46	–	Wallace, 1983
Barents Sea	69.0°N	16.5	42.8	53.3	60.3	Fyodorov, 1987
White Sea	66.1°N	16.0	27.4	40.3	52.0	Present study

rate (Table 5). In the White Sea the limiting factor on mussel growth rate is not the maximal temperature (up to 20°) in summer, but the short growing season of only 3 months. Wallace (1980) found that near 70°N in Norwegian waters long-term (up to 6 months) delay in growth was characteristic only for mussels in shore settlements. Molluscs in cages suspended above the bottom did not stop growth in winter. The results of long-term monitoring of *M. edulis* aquaculture in coastal areas of the White Sea since 1986 unambiguously demonstrated that substrata density did not limit growth. In this respect spat formation conditions appeared to be much more significant. These conditions determine initial (by the second growth season) mean mussel size and density and thereby may subsequently define their growth rate. As a result of a prolonged period of spat settlement (late July–September), even during the first growth season differences in the length of young mussels reached the order of 0.5 to 10 mm (Kulakowski and Kunin, 1982). As a rule this variation in length increases with age. A similar effect was noted for *Macoma incongrua* (Maximovich and Lysenko, 1986).

In the majority of cases most mussels reach a commercial size of 4–5 cm by the end of 4–5 growth seasons (3–4 full years of cultivation). Furthermore, a predominance of younger and smaller animals and decrease in biomass of large ones would be expected to limit any increase of yield potential on the farm. This situation was noted in the fourth and fifth years of cultivation in the experimental–industrial mussel culture farm near Cape Kartesh(Sukhotin and Kulakowski, 1992). Among the investigated farms those established in 1988 (Nikolskaya Bay and Oborina Salma) stood out, commercial size being reached there by the end of the third year (Table 2).

At the final stage of cultivation the mean mussel density commonly varied between 400 and 500 ind. per meter, but this optimal density of adult mussels was reached over a wide range of variation of spat number — from 2 to 22 thousand ind. per meter. Maximal mollusc growth rate (Table 2, sites 7, 8 and 11) is more likely to occur at low and moderate intensity of larval settlement. There are strong grounds to believe that extraordinary spat density leads to decrease in efficiency of mussel aquaculture in the White Sea. In most investigated cases strong competition for food and space caused a drastic decrease of mussel density, even during the second year among molluscs 10–25 mm in length (Table 2). Stabilisation of mussel number at 400–500 ind. per meter of substratum in suspended culture was also observed in other farms in the White Sea (Sukhotin and Kulakowski, 1992; Kulakowski et al., 1993), as well as Skagerrak waters (Rosenberg and Loo, 1983). Rapid elimination of 10–25 mm mussels was noted on an aquaculture farm in Flensburger fjord (Meixner, 1971).

Long-standing series of observations on the structure of mussel populations represent the most adequate basis for modelling. Recourse to simulation models is usual (Incze et al., 1980; Radford et al., 1981; Ross and Nisbet, 1990; Brylinsky and Sephton, 1991). One of the most developed fields in population studies in mollusc aquaculture is estimation of the components of matter and energy flow through artificial biosystems (Rosenberg and Loo, 1983; Rodhouse et al., 1984; Deslous-Paoli et al., 1990; Sukhotin, 1992) for purposes of yield prediction and estimation of the influence of aquaculture farms on the environment. Simulation models of mollusc culture have the same aims, but the approach which is used often consists of creating integral schemes covering either the whole life cycle of the animals or an investigated period. These models are quite suitable, but unwieldy and too deterministic. Continuity of the estimations predicted by such models is often compromised by a reduction in accuracy. The approach suggested here is primarily oriented towards ease of operating with the model. Therefore it was taken into account that:

1. Functional parameters of mollusc settlements are directly connected with structural ones by known relationships (Alimov, 1981; Bayne and Newell, 1983). This leaves room for further development of model without additional sampling of data;
2. Prognostical properties of the model are determined mainly by the validity of input data rather than by the accuracy of functional equations.

The model may be successfully used for practical aquaculture purposes because it allows to make prognostic estimations in a stepwise regime and it is based on parameters which can be easily tested in field conditions.

The main aim of modelling was prediction of changes in parameters of cultured mussel populations. Similarity of observed and predicted values was demonstrated by interpolation (Table 2). Model fitness in extrapolation may be limited by the effect of collinearity (correlation coefficient between L_0 and N_0 reaches 0.7); however, even in this case multiple regression equations can be used for prediction (Aivazyan et al., 1985). In autumn 1993 and 1994 sampling was carried out on some sites investigated earlier, which allowed comparison of data (Table 2). Minimal difference between predicted and observed values of mussel mean length and density was found within site 10 of Nikolskaya farm. It is remarkable that site 10 is a ''typical'' one because by the third growth season mussel density stabilised at 500 ind. per meter of substratum. The proposed model has local significance and evidently cannot be directly used in other areas. Nevertheless, the approach including stepwise regime and using easily determined predictors may be valid for initial estimates of yield.

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