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RESEARCH ARTICLE

Some ecological parameters of *Artemia parthenogenetica Gahai* and their use in resource exploitation

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Abstract The effects of temperature on population characteristics of *Artemia parthenogenetica Gahai* from the Gahai Salt Lake, Qinghai Province, China, were studied in the laboratory at a salinity of 60‰. The major conclusions are as follows: (1) It was found that the adaptive temperature for the development of brine shrimp ranged from 10°C to 39°C. The threshold temperature of development (TD) and the effective accumulative temperature (TA) for hatching were 9.94°C·d and (22.91±2.08)°C·d, respectively. The TD and TA for the larva were 10.33°C·d and (261.26±24.1)°C·d, respectively, and for the whole generation were 10.28°C and (458.68±57.60)°C·d, respectively. (2) It showed that the population's net reproduction rate (R_o), the intrinsic rate of natural increase (r_m), the mean generation time (T), the finite rate of increase (λ), and the days for population to double (t) of the brine shrimp were determined over temperatures ranging from 19°C to 34°C by analyzing the life table and numerical model. In the temperature range of 14.3°C to 37.3°C for $R_o > 1$, the optimum temperature (°C) for R_o, r_m, λ, and t were 25.8°C, 29.8°C, 30.5°C, and 29.02°C, respectively. The maximum values of R_o, r_m and λ were 54.86 ind., 0.106138/d, and 1.1070/d, respectively. The minimum value of t was 4.73 d. The value of T was in a range of 96.77 to 16.10 d. (3) Based on the 1993–1994 and 1997 data of the water temperature in the Gahai Salt Lake, Qinghai Province, it was estimated that the number of generation of *A. parthenogenetica Gahai* and the number of the reproductive peak value were 2.67±0.34 and 4.69±0.43 in a year, respectively. The peak of nauplii of the first generation was on April 20 to 28. The last whole generation began on August 10. The first reproductive peak was on June 18 to 25. The last reproductive peak was on September 12 to 17. The nauplii that hatched after September 1 cannot complete the development from nauplii to adults because of insufficient habitat effective accumulative temperature. During the period from July 11 to September 20, there was a relatively high productivity of the population. In this case, doubling the population would take less than 30 d, and the intrinsic rate of natural increase was over 0.02/d. Therefore, the value of resource exploitation would be maximal during that period annually.

Keywords Gahai Salt Lake, *Artemia parthenogenetica Gahai*, temperature, life table, generation, exploitation potentiality

1 Introduction

As living stage after hatching, the *Artemia* production is conditioned mainly by the hydrological regime (Newmark, 1991). Both of temperature and salinity obviously influence the processes of growth and reproduction of *Artemia* (Dana et al., 1993; Jia et al., 1995a, 1995b). Temperature affects the survival rate, productivity, and growth rate of different *Artemia* strains markedly (Barata et al., 1996; Sorgeloos et al., 1986; Jia et al., 2002a, 2002b). In addition, the dynamics of the population of *Artemia* mainly depends on temperature characteristics under the condition of adaptive salinity (Lenz, 1987; Lenz et and Browne, 1991).

The Gahai Salt Lake is an important salt lake in China because of the existence of an abundant *Artemia* resource, on which some basic research has been conducted (Ren et al., 1996; Jia et al., 1999a, 1999b, 2002b). However, there has been no basic data on population productivity or relationships between population dynamics and temperature available for *Artemia parthenogenetica Gahai*. Therefore, we investigated the threshold temperature for the development and hatching of eggs, the effective cumulative temperature of a generation, and population growth at different temperatures for *A. parthenogenetica Gahai*.

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2 Materials and methods

2.1 Materials

The adults and larvae of *Artermia* used for tests were hatched from dormant eggs collected from the Gahai Salt Lake. The animals were reared in salt water with a salinity of 60‰ and fed with *Dunaliella* sp., *Phaeodactylum tricornutum*, and marine *Chlorella* sp.

2.2 Methods

2.2.1 Threshold temperature of the development (*C*) and constant of effective accumulative temperature (*K*)

Based on $K=N(T-C)$ and acquisition of the roots by using the least square method, the threshold temperature of the development (*C*) and the constant of effective accumulative temperature (*K*) were calculated with the following equations:

$$Vj = 1/Nj,$$

$$Vi = (\sum Vj/n) = 1/(\sum Nj/n) = n/\sum Nj,$$

$$K = (mr\sum ViTi - \sum Vi\sum Ti)mr\sum Vi^2 - (\sum Vi)^2,$$

$$C = (\sum Vi^2\sum Ti - \sum Vi\sum ViTi)/mr\sum Vi^2 - (\sum Vi)^2,$$

$$R = (\sum TiVi - \sum Ti\sum Vi/mr)/ \mathrm{SQR}[(\sum Ti^2 - (\sum Ti)^2/mr)(\sum Vi^2 - (\sum Vi)^2/mr)]$$

$$i = 1,2,\cdots,m\times r\cdots$$

Degrees of freedom (*df*) = $m\times r-r-2$,
where Nj = development time (d) of the *j*th sample; Vi = mean development rate (d^{-1}); Ti = experimental temperature (°C), K = constant of effective accumulative temperature of a generation (C degree–days); r = times of repetition at m experimental temperatures; C = threshold temperature of development (°C); R = correlation coefficient; and n = number at each temperature.

2.2.2 Test of life table

A life table of *Artemia* was designed and calculated with the formulas by Wu et al. (1991). The experiments of the life table were conducted under 16°C–34°C with a gradient of 2°C. In total, 1000 nauplii were cultured in each chamber filled with 2 L salt water. The salinity in all experiments was fixed at 60‰. The experimental temperatures were controlled by the ICL-216 thermostat, with errors of ± 0.3°C. Natural light was adopted for illuminating. The survival rate, span of each developmental stage, and reproductive rate were recorded. In the ranges of 0°C–16°C and 34°C–38°C, the survival rate and reproduction characters were also observed. Average generation time (*T*), population reproduction (R_o), intrinsic rate of natural increase (r_m), infinite rate of increase (λ), and doubling population time (*t*) were calculated with the following equations (Wu et al., 1991):

$$T = (\sum l_x m_x X)/(\sum l_x m_x) \quad (1)$$

$$R_o = \sum l_x m_x \quad (2)$$

$$r_m = \log_e Ro/T \quad (3)$$

$$\lambda = \exp\ (r_m) \quad (4)$$

$$t = \log_e 2/r_m \quad (5)$$

where X = age (day); l_x = survival rate at X age; and m_x = output female offspring number per female adult at X age.

2.2.3 The definition for generations

The field water temperature of the Gahai Salt Lake was recorded weekly at 1 m under the surface from July to August in 1997. Based on water temperature data recorded in the Gahai Salt Lake from 1993 to 1994, the distributing time (*X*, day) as abscissa, and the water temperature (*Y*, °C) as ordinate, we achieved a regression equation $f(X)$. We counted the temperature above the threshold temperature of the development for larvae and calculated the range of effective time [0, *t*].

$$Y = f(X). \quad (6)$$

Then, by the use of the mean effective accumulative temperature of generation as objective function (*A*) and the initiative time of the first generation as lower limit, the upper limits were calculated with a definitive integral equation (Eq. (7)). Furthermore, using the upper limit as the lower limit of the next generation, we calculated the upper limit repeatedly until the time of the borderline of each generation was in the range of [0, *t*]:

$$\int_a^b f(X) = A, \quad (7)$$

where X = distributing time (d).

Set $a=0$, we get b; set $a=b$, we get a new b; if $b>t$, the calculation is finished; otherwise, we repeat the calculation.

3 Results

3.1 Temperature adaptability and requirement of the quantity of heat for development

We recorded the development rate on each development stage of *Artemia* at eight temperatures (Table 1).

Table 1 Influence of temperature on the mean development rate of *Artemia*

temperature/°C	hatching/d	larva/d	whole life time/d	mean generation time/d
12	12.04±7.82			
16	3.87±2.04	47.13±9.90	112.13±42.70	85.66
19	2.95±1.65	30.31±5.75	96.31±28.89	71.94
22	2.04±0.58	22.47±2.40	76.17±14.47	60.70
25	1.52±0.59	17.80±1.42	61.05±11.60	48.98
28	1.29±0.32	14.33±1.00	57.53±6.78	38.44
31	1.12±0.22	12.01±0.90	50.11±5.51	25.53
34	0.97±0.15	11.80±1.12	42.60±7.26	21.17
r	0.998	0.992	–	0.967
C/°C	9.94	10.33	–	10.28
K/°C·d	22.91±2.08	261.26±24.10	–	458.68±57.6

r: correlation coefficient; *C*: threshold temperature of development; *K*: constant of effective accumulative temperature.

Table 2 Life table of *Artemia* on age character

temperature/°C	16	19	22	25	28	31	34
eggs	1000	1000	1000	1000	1000	1000	1000
larvae	371.25	461.00	582.75	642.75	728.25	514.50	347.00
hypo-adults	108.5	185.75	352.75	340.00	413.00	232.50	67.00
adults	84.00	147.25	281.50	285.75	322.25	206.00	56.25
male	0	0	3	4	7	6	6.25
reproductive rate	65.21	79.08	86.65	160.09	157.70	129.70	38.5
population reproductive times	5.481	11.658	24.13	45.10	49.55	25.94	1.925
death rate before reaching adult	91.6	85.275	71.85	71.425	67.775	79.40	94.375

The close relationship between the mean development rates and temperature was shown by their correlation coefficients. Apparently, the development rates of hatching, nauplius, larvae, and adults were obviously shortened with elevated water temperature and so did the mean generation time.

By calculations, the threshold temperature for development (*C*) and the effective accumulative temperature (*K*) for hatching were 9.94°C and 22.91°C·d, respectively. For the larva, they were 10.33°C and 261.26°C·d, respectively; and for a whole generation, they were 10.28°C and 458.68°C·d, respectively.

3.2 Life table on age character

We constructed a life table of *Artemia* at seven temperatures. The numbers of eggs, larvae, and adults were counted, and the survival rate and reproductive rate were recorded (Table 2).

The death rate before reaching adult marked the adaptability of the population to the environment. The death rate was higher at either the high or low test temperature, while lower in the range of 22°C–28°C. Fitting the death rate with temperature, we obtained the temperature range for development from larvae to adults. The range was 10.10°C–39.56°C.

The reproductive times of the population reflected the population's potentiality of reproduction. Fitting the population's reproductive times with temperature, we found that the population had potentialities of increase in the range of 13.95°C–35.75°C. The maximal potentialities of increase were at 24.85°C. Putting the mean generation time and reproductive rate of each female *Artemia* together, we obtained the daily reproductive rate (Table 3).

Because of shorter generation time at high temperature, daily reproduction was higher, and both total reproductive rate and daily reproduction reached the highest values at the optimum temperature.

Table 3 Daily reproductive rate of the *Artemia*

	19°C	25°C	34°C
mean generation time/d	71.9	49.0	21.2
reproductive rate	79.1	160.1	38.5
daily reproductive rate	1.10	3.27	1.81

3.3 Some ecological parameters of *Artemia* and water temperature

Based on the observation of the process from the hatching of eggs to the death of the adults, the life table of *Artemia* at seven temperatures was established. The intrinsic rate of natural increase (r_m), the mean generation time (T), the reproduction rate (R_o), the finite rate of increase (λ), and the doubling time of population increase (t) of *Artemia* under different temperatures were calculated. The results obtained and the regression equations of the five parameters with temperature are listed in Table 4.

3.4 Population productive potential and water temperature

3.4.1 Generations and water temperature

According to water temperature data of the Gahai Salt Lake during 1993–1994 and July to August in 1997 and the threshold temperature (10°C) for larva development, the total effective accumulative temperature in this salt lake was 1225.66°C·d as calculated by the integral method. The total accumulative temperature was divided by the mean accumulative temperature of a generation, (458.68±57.6)°C·d, which was used as an object function value (A). The theoretical number of generations we obtained was 2.67±0.34 per year.

In order to determine the time borderlines for each generation, we further adjusted the time distribution with water temperature and obtained equation (8). When water temperature was above 10°C, we obtained equation (9):

$$Y = 0.3066X - 0.001179X^2 \qquad (F_{(2,6)} = 99.94) \tag{8}$$

$$Y = -10 + 0.3066X - 0.001179X^2 \qquad (F_{(2,6)} = 99.94) \tag{9}$$

where Y = temperature (°C); X = generation time (d).

When $Y > 0$ in equation 8, the range of time was from 0 to 260 (or from March 17 to November 30). The second and third generation began on July 10 and August 26, respectively. The last whole generation began on August 10.

The definition of the borderline of each generation time calculated from the definitive integral equation is shown in Fig. 1.

Table 4 Main ecological parameters of *Artemia* at different temperatures

temperature/°C	r/(ind./♀·d)	T/d	R_o/(Nt/No)	λ/d^{-1}	t/d
16	0.01774	85.66	4.572	1.0179	39.073
19	0.02999	71.938	8.652	1.0304	23.112
22	0.05091	60.702	21.995	1.0522	13.616
25	0.08578	48.980	66.811	1.0896	8.081
28	0.10842	38.444	64.602	1.1202	6.393
31	0.12749	27.530	33.441	1.13597	5.437
34	0.07643	21.171	5.043	1.0794	9.069
regression	$R_o = \exp(-16.15491 + 1.56271X - 0.03028X^2)$			$F_{(2.4)} = 13.99$	
equations	$r_m = \exp(-11.13956 + 0.59790X - 0.01005X^2)$			$F_{(2.4)} = 57.49$	
	$\lambda = \exp(-0.32958 + 0.02827X - 0.00046X^2)$			$F_{(2.4)} = 9.20$	
	$t = 170.0153 - 11.3905X + 0.1962X^2$			$F_{(2,4)} = 298.58$	
	$T = 37.4685X\ \mathrm{EXP}(-0.1197X)$			$F_{(1,5)} = 2447.7$	

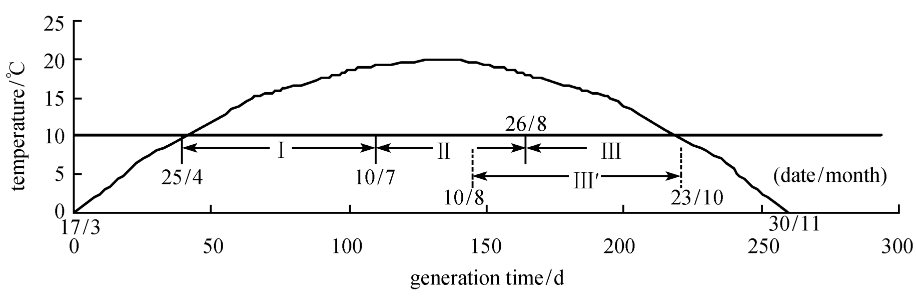

Fig. 1 The generations of *Artemia* and environmental temperature in the Gahai Salt Lake. I–III: first to third generations; III': the last whole generation.

3.4.2 Time of reproductive peak

Using the effective accumulative temperature for larvae as the object function value (A), we divided the total accumulative temperature. Then, we found the theoretical number of the reproductive peak was 4.69±0.43 per year. As Fig. 2 shows, the peak of nauplii in the first generation was on April 20–28; the last reproductive peak was on September 12 to 17. The nauplii that hatched after September 1 (with the converse integral method) cannot complete the development from nauplii to adults because of insufficient habitat effective accumulative temperature.

3.4.3 Population productive potential

Based on the changes in water temperature with time (Eq.8) and the relationships between parameters and temperature (Table 4), the r_m, R_o, T, l, and t were converted into the relation of time distribution.

The results indicated that during the period from July 11 to September 20, there was a relatively high productivity of the population. In this case, doubling the population (t) would take less than 30 d; the intrinsic rate of natural increase (r_m) was over 0.02/d. Therefore, the period from July 11 to September 20 would be the best season for commercial exploitation of the *Artemia* in the Gahai Salt Lake.

4 Discussion

4.1 Importance of dividing the generation time of *A. parthenogenetica Gahai*

Because the age structure of the population and related water temperature in the Gahai Salt Lake vary with season, it is difficult to calculate the reproduction of *Artemia* based on water temperature. Whereas, using generation time as a time unit, it is easier to estimate the reproduction precisely with the integral method based on the curves of simulated reproductive rate and temperature combined with time.

Defining the generations and their borderline time in natural habitats is useful for exact estimation of the quantity of *Artemia* resource and establishment of the strategy of exploitation. For example, the first generation in a year comes from the overwintered eggs; the population size is limited without complement until it is sex mature. In the first generation, the peak of nauplii was on April 20–28, and the sex maturation was during the first 20 days of June. In order to keep the quantity of the population for sustainable increase, the eggs before the middle of July should be banned. The last reproductive peak was on September 12–17. Because the last generation provides the basis of producing the first generation of the next year; to assure enough eggs for the population of the next year, the diapause eggs of the last generation after September 12–17 should be exploited moderately. The other generations, except the first and last ones, provide relative greater potentials of resource exploitation because they are just in the growth period.

4.2 Reliability of experimental temperature and salinity

In nature, the major factors related to the productivity of *Artemia* are temperature, salinity, nutrient salt, primary productivity, and biological characteristics of *Artemia* (population dynamics and life history characteristics). Dana et al. (1993) reported that the salinity effected obviously on hatching success, survival, length, weight, ovigery, brood size, time to hatching, reproduction, and other life history characteristics of *Artemia*.

Our studies showed that temperature influenced mainly the developmental rate, generation time, doubling time of the population, and intrinsic rate of natural increase of *Artemia* under adaptive temperature conditions. Salinity influenced mainly the reproductive characteristics (oviparous or ovoviviparous), survival, length, and weight. If both salinity and temperature are within the adaptive range, the complex influence of these two factors does not appear obviously. If one or both of them are close to the range of limits, the interaction and correlation between them were remarkable (Calobres 1969). In our other study (unpublished data), it showed that the complex influence of salinity and temperature on ecological feature was not significant in the range of 8°C–32°C. This result is similar

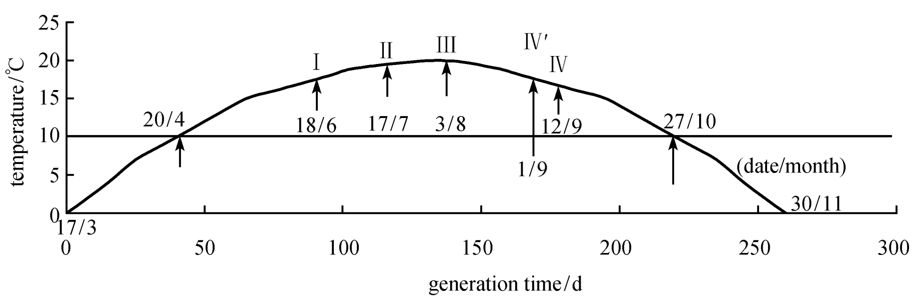

Fig. 2 The reproductive peak time of *Artemia* in the Gahai Salt Lake. I–IV: first to fourth reproductive peak; IV': reproductive peak in the last whole generation.

to that of Calobres (1969). In addition, food influenced mainly the reproductive number.

Newmark (1991) excluded the close relationship between biomass (using biomass to estimate the quantity of resource) with hydrological parameters such as evapotranspiration, rainfall, pH and salinity, and with reproductive characteristics (oviparous or ovoviviparous) in their studies of population biomass predictive models of *Artemia*.

In large temperate-zone salt lakes like the Gahai, the annual salinity is less changed, and seasonal features of *Artemia* basically rely on the period of temperature, which can be predicted. Lenz (1987) found the dynamics of populations mainly depended on temperature characters within the range of adaptive salinity. Therefore, the constant area and depth, regular annual variations in water temperature and salinity in the Gahai Salt Lake showed that the population features of *Artemia* could be predicted.

In this study, we fixed the experimental salinity at 60‰ and the experimental temperature range at 0°C–38°C, which was close to that of the Gahai Salt Lake. Therefore, the results obtained could basically reflect the biological characters of *A. parthenogenetica Gahai* under natural conditions.

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