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Improvement of rearing conditions for juvenile lobsters (*Homarus gammarus*) by co-culturing with juvenile isopods (*Idotea emarginata*)

Isabel Schmalenbach *, Friedrich Buchholz, Heinz-Dieter Franke, Reinhard Saborowski

Biologische Anstalt Helgoland, Stiftung Alfred-Wegener-Institut für Polar-und Meeresforschung, 27498 Helgoland, Germany

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ABSTRACT

Growth conditions of the juvenile lobsters, *Homarus gammarus*, were optimized in view of a restocking project of the lobster population at Helgoland (German Bight, North Sea) aimed to produce more than ten thousand juvenile lobsters per year. Growth and survival rates of juvenile lobsters depend on diet, temperature and water quality. In the present study, diet at optimum temperature was considered, but special emphasis was placed on the optimization of cleaning and feeding methods from both an economical and ecological point of view. Six dietary treatments of juvenile lobsters (each $n=99$) were tested in individual compartments in a semi-closed re-circulation system at around 20 °C. Lobsters were fed with combinations of two diets, newly hatched *Artemia* sp. nauplii and minced crabs *Cancer pagurus* (whole carcasses), every 2 or 4 days until a carapace length of 10 mm was reached. During the experiment (max. 105 d), juvenile isopods, *Idotea emarginata*, were constantly present in the lobster boxes. More frequent feeding significantly increased growth rates of the juvenile lobsters while different feeding combinations had no effect. The highest growth rate (0.091 ± 0.02 mm CL day^{-1}) was at a feeding frequency of every 2 days for each diet. At this rate the carapace length of 10 mm was reached in 68–71 days. The survival rate of the juvenile lobsters ranged from 90–97%. The diet consisting of *C. pagurus* was most cost-efficient and was obtained as discards from the crab fishery at Helgoland. The co-culture of juvenile lobsters with juvenile isopods *I. emarginata* as "cleaning organisms" was ideally suited for the rearing of lobsters and reduced the maintenance time by 50%. The isopods also served as supplementary diet.

1. Introduction

European lobsters (*Homarus gammarus* Linnaeus, 1758) form valuable fisheries along the coastline of the northeast Atlantic. In 2006, the annual European landings from the major lobster exporting countries, i.e. UK, Norway, Greece, Ireland and France reached approximately 3400 metric tons (t) with a value of 45 million Euros (Fishery Statistics, 1999–2006). Along the German coast, a sustainable lobster population is only present at the rocky subtidal of the island of Helgoland (North Sea, German Bight), where the lobster fishery was important during the 1920s and 1930s with catches of up to 80,000 animals (38 t) per year (Klimpel, 1965). Since the 1960s, the catch rates decreased drastically and reached a minimum of a few hundred lobsters per year in the 1980s (Goemann, 1990; Anonymus, 1980–2008). The reasons for the collapse of the Helgoland lobster population may include the destruction of the habitat by the bombing of the island during and after the second world-war, extensive fishing pressure in the 1950s and 1960s, pollution of the North Sea waters by oil spills, chemicals, and industrial wastes, and interspecific competition for food and shelter with the crabs, *Cancer pagurus* (Linnaeus, 1758) (Klimpel, 1965; Anger and Harms, 1994; Harms et al., 1995).

In order to provide specimens for biological research, a lobster rearing facility was established in 1997 at the Marine Station at Helgoland. Berried females were provided by local fishermen and kept in aquaria until the larvae hatched. The larvae were raised to post-larvae and juveniles. Based on the experience in lobster rearing, a restocking programme was initiated to enhance the natural lobster population around Helgoland with laboratory raised juveniles. Within a 5-year programme it is anticipated to raise and release more than ten thousand juveniles per year. The local rearing capacities have to be extended accordingly.

Since the maintenance of lobsters is time and cost intensive, the present work was aimed to optimize the breeding conditions for juveniles to reach maximum productivity at lowest cost. A principal goal of our study was to utilize local resources. In this respect discards of the crab fishery around the island of Helgoland provide a suitable and cheap food for the juvenile lobsters. Preliminary feeding trials with minced crab meat showed good acceptance and satisfactory growth rates. However, remains of the crab meat frequently blocked the water circulation system and drastically increased the effort for cleaning and maintenance of the rearing facilities and sometimes caused complete loss of the lobster stock. Despite the initial failure,

* Corresponding author. Tel.: +49 4725 8193342; fax: +49 4725 8193369.
E-mail address: Isabel.Schmalenbach@awi.de (I. Schmalenbach).

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crab meat from *C. pagurus* seems to be a suitable, abundant, and inexpensive feed for lobsters at Helgoland. Therefore, we focussed our attempts on improving the rearing systems and rearing conditions to minimise the adverse effects when feeding minced crab meat. In order to increase the survival rates we tried to reduce food waste and other debris by co-culturing juvenile lobsters with live juvenile isopods, *Idotea emarginata* (Fabricius, 1793). These isopods are known as debris feeders and thus appeared useful to keep the rearing system clean and thus to maintain water quality.

2. Materials and methods

The experiments were carried out in summer 2006 at the Marine Station at Helgoland. The feeding experiments were run at 20.5 ± 0.6 °C, at ca. 33 psu and maintained under the natural light/dark-cycle.

2.1. Origin of animals

The post-larval lobsters used in the experiments were raised in the laboratory as reported by Ulrich (1998). The larvae were a mix from the eggs of eight different ovigerous females. The females were captured by local fishermen from the rocky subtidal at Helgoland (North Sea, 54°11.3′N, 7°54.0′E). The newly hatched larvae were reared in specific semi-flow through tanks (Hughes et al., 1974) in ambient seawater (17–19 °C). The larvae were fed daily with newly hatched *Artemia* sp. nauplii and every other day with minced crabs (whole carcasses of *C. pagurus*). The larvae reached the post-larval stage (stage IV) approximately 17 days after hatching. After moulting to post-larvae the specimens were separated in 40 ml glass containers. Everyday, the water was exchanged and the post-larvae were fed with newly hatched *Artemia* sp. nauplii. After 5 days, the carapace of the post-larval lobsters hardened and the initial weights and the carapace lengths (CL-R = without rostrum) were determined.

2.2. The culture system

The semi-closed recirculation system was developed and built in the Marine Station of Helgoland (Fig. 1). It consisted of three tanks (34 × 95 × 150 cm). In each tank a rectangular polyvinylchloride frame (140 × 90 × 9 cm) was adjusted which was partitioned in 198 single compartments (9 × 7 cm, height of water level: 7 cm). The bottom of the frame was made of nylon gauze (300 µm mesh size). The rectangular frames were covered with sprinklers and a light shield. The flow rate of fresh seawater into the semi-closed recirculation system was at 4–5 l min^{-1}. This system allowed for separation of animals and provided a constant circulation of sea water. The water quality was not monitored within the compartments but within the seawater supply system of the institute. The flow rate through each cubicle allowed for complete water exchange every 15 min. Therefore, the juveniles received the best possible water quality close to natural conditions. The juvenile lobsters were maintained at 20.5 ± 0.6 °C. Each post-larva was placed in a separate compartment. A short plastic tube (1.5 × 3.5 cm) provided shelter.

2.3. The diets

The principal diets offered to the post-larvae were live *Artemia* sp. nauplii and minced crab. Juvenile isopods, *I. emarginata*, were supplemented. They served as an additional food source and kept the rearing system clear of accumulated debris. Newly hatched *Artemia* sp. nauplii from cysts (Sanders Brine Shrimp Company, USA) were reared in a temperature controlled room (25 °C). *C. pagurus* (discards of the crab-fisheries on Helgoland) were provided by local fishermen. The whole crabs, including shells, muscle tissue, and internal organs, were minced, divided in portions and stored deep frozen. The live juvenile isopods *I. emarginata* (3–4 mm total length) were taken from mass cultures which are established since several years at the Marine Station at Helgoland (Franke and Janke, 1998).

The gross composition (CHN) of the diets was analysed with a CHN Analyser (Fision EA 1108). Samples of the diets were lyophylised for 48 h. Subsamples were weighed on a microbalance (Mettler UMT2, precision: ±0.1 µg) and used for CHN analysis. Acetanilide (HEKAtech, 141 d) was used as a standard. The carbon content was used to calculate the energy content of the samples according to Salonen et al. (1976).

2.4. The experimental design

The growth and the survival of juvenile lobsters were studied under six dietary treatments. In each treatment 99 juvenile lobsters (initial mean weight of 38.5 ± 16.8 mg and carapace length (CL-R) of 4.0 ± 0.4 mm) were fed with combinations of the diets described above. Three groups were fed every 2 days while the other three groups were fed every 4 days. The lobsters received food *ad libitum* (ca. 200–300 *Artemia* sp., 300–400 mg minced crabs, and ca. 20–30 juvenile isopods). Additionally, the lobsters were allowed to eat their moults.

The lobsters were examined daily for mortality and moults. Dead animals were removed from the culture system but were not replaced by new lobsters. When lobsters moulted their new carapace length

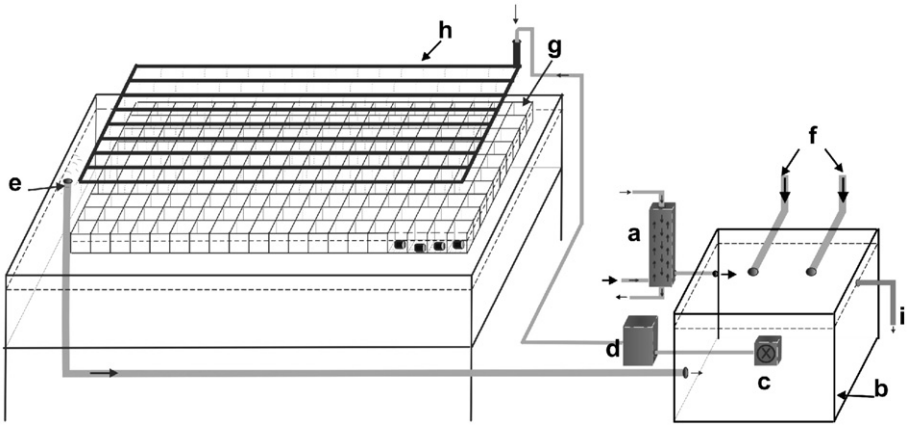

Fig. 1. Semi-closed recirculation system used for the culture of juvenile lobsters. The figure shows only one of three culture systems which were run in parallel. Key: (a) continuous flow heater of fresh sea water (gravel filter), flow rate 4.8 l min^{-1}, sea water at 20 °C and 33 psu (b) tank reservoir, volume 170 l; (c) centrifugal pump, capacity 1900 l h^{-1}; flow rate 8.8 l min^{-1} (d) wadding filter, volume 18 l; (e) overflow, (f) overflow of two additional culture systems; (g) PVC-frame (140 × 90 × 90 cm) with 198 compartments (9 × 7 × 9 cm, volume 440 ml, gauze 300 µm mesh size) and shelters (approx. 1.5 × 3.5 cm); (h) sprinkling; (i) discharge.

was not measured until 7 days after their moult to avoid injuries of the soft bodies. The carapace lengths and weights were not measured in all experimental animals but 20 individuals of each treatment were randomly selected to be measured after their next moult.

The experiment continued until the animals reached a size of 10 mm carapace length. Specific growth rates and moult increments were used to evaluate growth. The specific growth rate was calculated from the weight data and the carapace length after each post-moult stage from the beginning to the end of the experiment according to Hopkins (1992). The specific growth rate (SGR, % day^{-1}) in post-moult wet weight and in carapace length (CL-R) is described as

$$\mathrm{SGR} = \ln\left(\frac{final\ weight, length}{initial\ weight, length}\right) \times \frac{100}{\text{number of days}}. \quad (1)$$

2.5. The cleaning effect of isopods

The accumulation of feeding remains, debris, and faeces in the lobster compartments was investigated in a separate experiment. Three treatments with 10 replicates each were run in the culture system described above. In treatment 1 each of the lobster compartments was stocked with one juvenile lobster of 3 cm total length (10 mm CL-R) and 20–30 juvenile isopods (3–4 mm total length). In treatment 2 only juvenile lobsters was placed in the compartments while in treatment 3 only 20–30 juvenile isopods were used. The animals of all treatments were fed every other day with about 340 mg of minced crabs. Everyday the numbers of juvenile isopods in the compartments were controlled and if necessary restocked. The experiment was terminated after 20 days. The accumulated remains of food and debris in the compartments were aspirated and collected on cellulose nitrate filters, 12 µm pore size. The filters were dried for 48 h at 60 °C and then weighed on a microbalance.

2.6. Statistics

All data sets, presented as mean±standard deviation (S.D.), were first examined for normal distribution and similarity of variances using the statistical software package, Statistica 7.1 (StatSoft). The data were subjected to a one-way or two-way ANOVA. Multiple comparisons of data sets were performed with a Tukey's post-hoc test at a significance level of α=0.05 (Sokal and Rohlf, 1995). The size increments were plotted and linear and curvilinear regressions were applied to calculate the growth rate and the time when the juvenile lobsters reached a carapace length of 10 mm. The time course of the specific growth rates (SGR) in % day^{-1} was best described by the equation

$$\mathrm{SGR} = a\ \exp\left(-0.5(\ln(x/x0)/b)^2\right), \quad (2)$$

where a, b, and x_0 are the coefficient of variation, and x are the days from stage IV. Data obtained within intervals of 10 days were averaged and statistically analysed.

Table 1
Gross compositions (carbon, hydrogen, nitrogen) and energy contents (mean±S.D.) of diets (*Artemia* sp. nauplii, minced crabs (*Cancer pagurus*) and juvenile *Idotea emarginata*)

Diet	*Artemia* sp.	*C. pagurus*	*I. emarginata*
n	25	24	25
C (%)	47.5±0.5^a	40.5±1.7^b	29.8±1.1^c
H (%)	6.9±0.1^a	6.1±0.3^b	4.1±0.2^c
N (%)	9.7±0.5^a	7.9±0.4^b	5.2±0.3^c
C:N — ratio	4.9±0.1^a	5.1±0.1^b	5.7±0.1^c
J mg^{-1} AFDW	454±10^a	330±26^b	179±13^c

Different superscripts denote statistically significant differences (one-way ANOVA and paired comparisons post hoc test (P=0.05)). n=Number of lobsters, AFDW=Ash-free dry weight.

Table 2
Survival and growth rates (mean±S.D.) of juvenile lobsters (*Homarus gammarus*) kept at 20.5±0.6 °C

Treatment	Survival (%)	*n*	Growth CL-R (mm day^{-1})	Growth weight (mg day^{-1})	SGR_CL-R (% day^{-1})	SGR_Weight (% day^{-1})
2 AI	96	95	0.088±0.024^a	5.93±2.28^a	1.47±0.42^a	4.04±1.05^a
2 ACI	90	91	0.091±0.020^a	6.65±2.40^a	1.51±0.31^a	4.25±0.84^a
2 CI	92	99	0.087±0.022^a	6.17±2.50^a	1.44±0.34^a	4.00±1.03^a
4 AI	97	110	0.071±0.014^b	4.98±1.30^b	1.17±0.30^b	3.25±0.79^b
4 ACI	93	126	0.069±0.022^b	4.67±1.79^b	1.17±0.41^b	3.20±1.08^b
4 CI	95	108	0.073±0.025^b	5.00±1.97^b	1.22±0.46^b	3.40±1.17^b

Growth rates were calculated after each moult from the beginning to the end of the experiment. Initial mean weight was 38.45±16.78 mg and initial carapace length (CL-R) 4.0±0.4 mm. Juvenile lobsters were fed every 2 or every 4 days with two main diets (*Artemia* sp. nauplii and minced crabs (*C. pagurus*) and everyday with *I. emarginata*. Key: AI = *Artemia* sp. nauplii and *I. emarginata*; CI: *C. pagurus* and *I. emarginata*; ACI = *Artemia* sp. nauplii, *C. pagurus* and *I. emarginata*.
Different superscripts denote statistically significant differences (one-way ANOVA and paired comparisons post hoc test (P=0.05)). n=Number of measured lobsters, CL-R=Carapace length without rostrum, SGR=Specific growth rate (SGR=((ln postmoult weight, length−ln initial weight, length)*100/experimental time)).

Survival analyses were carried out after Kaplan and Meier (1958). The Kaplan–Meier estimator of S is given by

$$\hat{S}(t) = \prod_{t_i \le t}\left(1-\frac{d_i}{n_i}\right), \quad (3)$$

where n_i is the number of the risk set at t, and d_i the number of observed events at t_i, i=1, 2, …, N.

3. Results

3.1. Diet

The gross compositions and energy contents of the three diets (*Artemia* sp. nauplii, minced crabs (whole carcasses of *C. pagurus*) and juvenile *I. emarginata*) were significantly different (P<0.001, Table 1). *Artemia* sp. nauplii showed the highest carbon and nitrogen contents and, thus, the highest energy content of 454 J mg^{-1}AFDW. All parameters were significantly higher than in *C. pagurus* and *I. emarginata*.

3.2. Growth and survival

The growth rates of all juvenile lobsters ranged from 0.069 to 0.091 mm day^{-1} CL-R^{-1} or 4.67 to 6.65 mg day^{-1}. This corresponds to a

Table 3
The specific growth rates of length (A) and specific growth rates of weight (B) of juvenile lobsters (*Homarus gammarus*) were determined on FF=feeding frequency in day and diet

Source of variation	Analysis of variance				
	df	SS	MS	*F*	*P*
(A) Length-SRG					
Main effects					
FF	1	15.87	15.869	104.73	<0.0001
Diet	2	0.08	0.039	0.26	0.7749
First-order interactions					
FF×Diet	2	0.45	0.223	1.47	0.2308
(B) Weight-SRG					
Main effects					
FF	1	120.36	120.36	110.18	<0.0001
Diet	2	0.45	0.22	0.20	0.8159
First-order interactions					
FF×Diet	2	6.23	3.12	2.86	0.0584

Six dietary treatments with each 99 replicate experiments were run. Key: *df*=degrees of freedom, SS=sum of squares, MS=mean squares, *F*=variance ratio, *P*=probability of rejecting a correct null hypothesis ($P \le 0.05$).

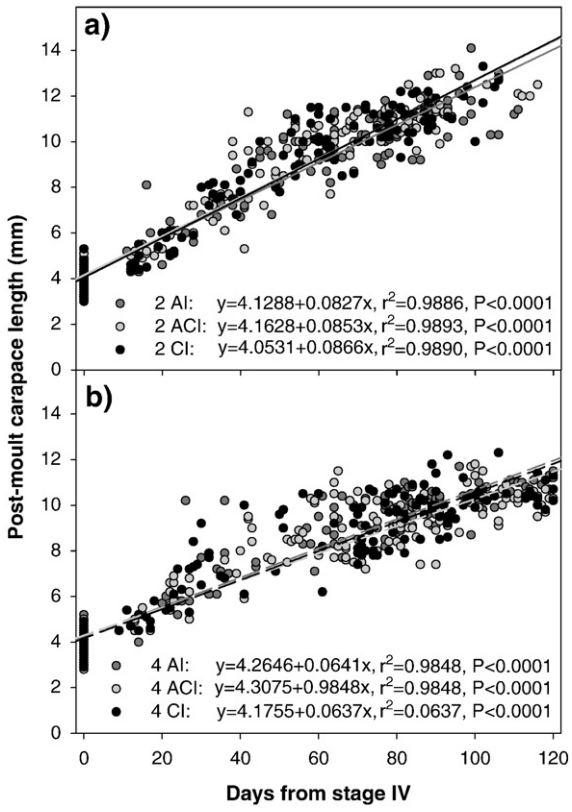

Fig. 2. Growth over time of juvenile lobsters (*Homarus gammarus*). The lobsters were kept at 20 °C and were fed with two main diets (*Artemia* sp. nauplii and/or minced crab carcasses (*C. pagurus*), separately and in combination) (a) every 2 or (b) every 4 days and were fed with live juvenile *I. emarginata* everyday. Key: AI = *Artemia* sp. nauplii and *I. emarginata*; CI = *C. pagurus* and *I. emarginata*; ACI = *Artemia* sp. nauplii, *C. pagurus* and *I. emarginata*.

specific length increase of 1.17 to 1.51% day^{-1} and a weight increase of 3.20 to 4.25% day^{-1}. The diets given had no significant effect on the growth rates of the lobsters. However, the feeding frequency significantly influenced growth rates (Tables 2 and 3). The growth rates of lobsters which were fed every 4 days were approximately 20% lower than those of lobsters fed every 2 days.

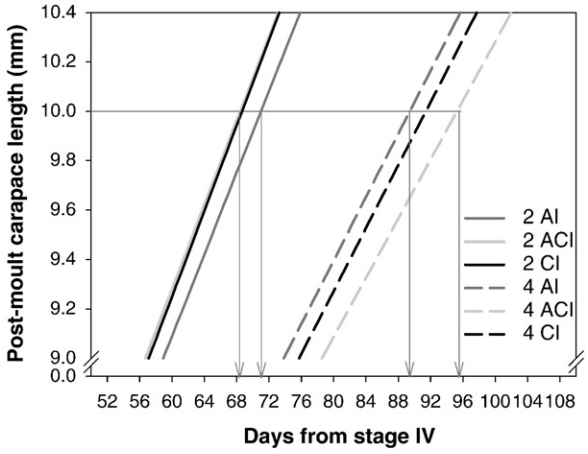

Fig. 3. Growth over time of juvenile lobsters (*Homarus gammarus*). Juvenile lobsters were kept at 20 °C and were fed with two main diets (*Artemia* sp. nauplii and/or minced crabs (*C. pagurus*), separately and in combination) every 2 or every 4 days and were fed with live juvenile *I. emarginata* everyday. Key: AI = *Artemia* sp. nauplii and *I. emarginata*; CI = *C. pagurus* and *I. emarginata*; ACI = *Artemia* sp. nauplii, *C. pagurus* and *I. emarginata*. For the juvenile lobsters, the experiment was terminated when a carapace size of 10 mm was reached. The horizontal reference lines designate the end size of the lobsters at 10 mm carapace length.

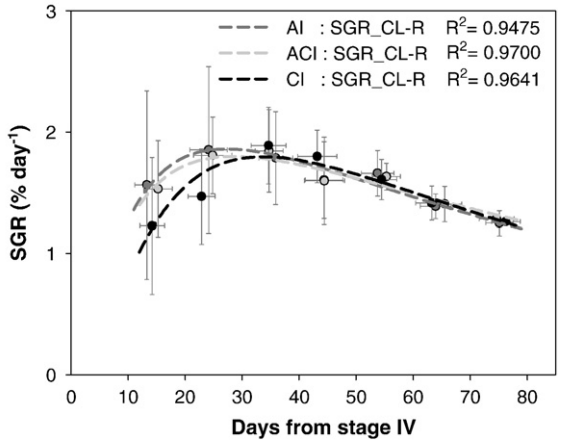

Fig. 4. Specific growth rates (SGR_CL-R, mean±S.D.) of juvenile lobsters (*Homarus gammarus*) which were kept at 20 °C and were fed with two main diets (*Artemia* sp. nauplii and/or minced crabs (*C. pagurus*)) every 2 days and were fed with live juvenile *I. emarginata* everyday. Key: CL-R = Carapace length without rostrum, AI = *Artemia* sp. nauplii and *I. emarginata*; CI = *C. pagurus* and *I. emarginata*; ACI = *Artemia* sp. nauplii, *C. pagurus* and *I. emarginata*. Data obtained within intervals of 10 days were averaged and statistically analysed. Nonlinear regressions showed the development of the growth rates during the experiment.

The feeding experiment was terminated when the lobsters reached a carapace length of 10 mm (Figs. 2 and 3). The lobsters which were fed every 2 days reached 10 mm carapace length after 68 to 71 days. Those lobsters which were fed every 4 days reached the same length after 89 to 95 days. The linear regressions and equations are shown in Fig. 2, along with the coefficients of determination, r^2 (all ≥0.98). The slopes of these regressions were significantly higher for lobsters which were fed every 2 days than for lobsters which were fed every 4 days (ANOVA, $P<0.001$). At the end of the experiment the average live body weight of all six dietary treatments was 524±83 mg.

The specific growth rates (SGR_CL-R) varied significantly ($P<0.05$) during the experiment (Fig. 4). At the beginning the growth rates increased. They reached their maximum of 1.9% day^{-1} at 35 days in the group which was fed with minced crabs (2CI). The other treatments (2AI and 2ACI) showed a maximum of 1.8% day^{-1} at 25 days. Thereafter, the growth rates continuously decreased towards 1.3% day^{-1} after 75 days of experiment.

The survival rates of juvenile lobsters ranged from 90 to 97%. The Kaplan–Meier survival curves are shown in Fig. 5. The experimental

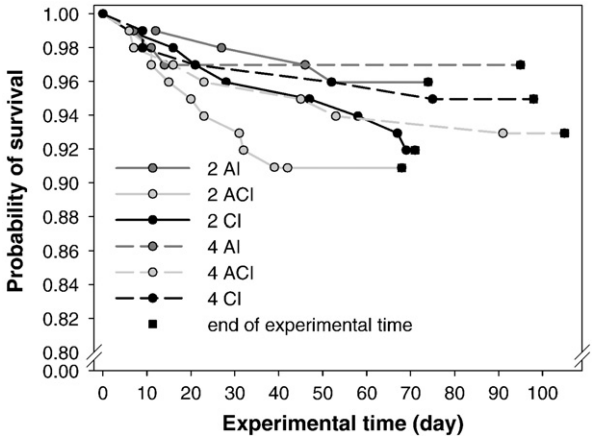

Fig. 5. Kaplan–Meier survival curve of juvenile lobsters (*Homarus gammarus*) which were kept at 20 °C and were fed with two main diets (*Artemia* sp. nauplii and/or minced crabs (*C. pagurus*), separately and in combination) every 2 or every 4 days and were fed with live juvenile *I. emarginata* everyday. Key: AI = *Artemia* sp. nauplii and *I. emarginata*; CI = *C. pagurus* and *I. emarginata*; ACI = *Artemia* sp. nauplii, *C. pagurus* and *I. emarginata*. For the lobsters, the experiment was terminated when a carapace length of 10 mm was reached.

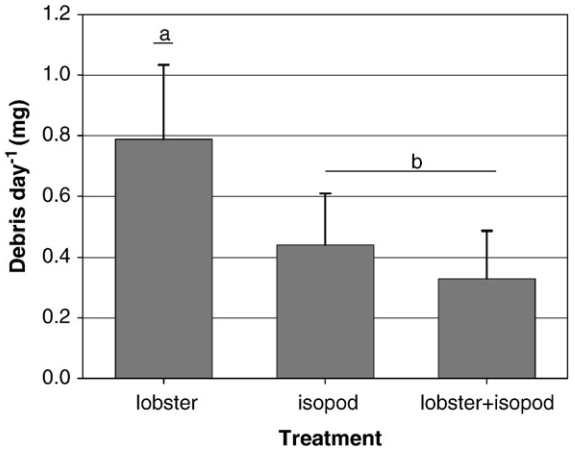

Fig. 6. Debris accumulates per day (mean ± S.D.) in lobster compartments ($n = 10$). The animals of all treatments were fed every other day with minced crabs (*C. pagurus*). Different superscripts denote statistically significant differences (one-way ANOVA and paired comparisons post hoc test ($P = 0.05$)).

treatments had an effect on the mortality. Juveniles fed every 4 days showed better survival than those fed every 2 days. Lobsters fed the main diet of *Artemia* sp. nauplii showed the highest survival rates. The earliest mortality in the dietary treatments occurred after 6 days.

3.3. Cleaning effect of isopods

The amount of debris in the lobster compartments differed significantly between the three treatments (ANOVA, $P < 0.0001$, Fig. 6). The food remains in the lobster boxes amounted to 0.79 ± 0.25 mg day^{-1} in treatment 1 (only lobsters), and 0.44 ± 0.17 mg day^{-1} in treatment 2 (only isopods). In the boxes of treatment 3 (lobsters and isopods), the amount of the debris was 0.33 ± 0.16 mg day^{-1}. The treatments which included isopods showed significantly lower amounts of debris than the treatment with lobsters only. The water in the compartments without juvenile isopods flow over because the fine nylon gauze of the compartments was blocked.

4. Discussion

The major challenges in rearing juvenile lobsters (*H. gammarus*) are the supply with clean seawater, feeding with high quality but reasonable food, and the prevention of cannibalisms. These aspects require expensive or technically ambitious solutions and may entail high staff costs. We established a cost-efficient rearing and feeding method for easiest handling and maintenance but highest possible productivity of juvenile lobsters.

4.1. Separation of animals

Clawed lobsters are agonistic and cannibalistic when kept at high densities. Therefore, mass cultures often suffer from high mortality (Van Olst et al., 1975; Sastry and Zeitlin-Hale, 1977; Aiken and Waddy, 1995; Jørstad et al., 2001). In contrast, individually reared juveniles showed higher survival rates (Beard et al., 1985; Aiken and Waddy, 1988; Waddy, 1988) but they may exhibit lower growth rates due to space limitation. Aiken and Waddy (1978) showed that the growth of lobsters strongly depends on container size. An area of approximately 75 cm^2 is required to allow for unrestricted growth of juvenile lobsters up to 3 cm total length. To grow up to the double size, a total length of 6 cm, juvenile lobsters need a four times larger area. In our rearing system the area for each juvenile lobster amounted to 63 cm^2. This area is sufficient to maintain juvenile lobsters to up to 10 mm carapace length which corresponds with a total length of 3 cm. After reaching this length the juvenile lobsters were released into the wild. The system allows for the rearing of 140 juvenile lobsters per square meter at high survival rates of more than 90%. Accordingly, this system provides a suitable trade-off between demand of space, the final size of the juveniles, and the duration of intensive maintenance period.

4.2. Diets

The best diet for optimum growth, survival, and normal coloration is natural food such as fresh and fresh-frozen marine molluscs, crustacean and macroalgae (Waddy, 1988). We chose in our experiment three food types: newly hatched *Artemia* sp. nauplii, minced *C. pagurus* and live juvenile isopods, *I. emarginata*. Except *Artemia* sp., the crab *C. pagurus* and the isopod *I. emarginata* occur in the same habitat as the lobsters and, thus, form a potential natural prey.

Newly hatched *Artemia* nauplii provide all nutrients required by juvenile lobsters for growth and health (Shleser and Gallagher, 1974). Moreover, no accumulation of debris occurred and, therefore, *Artemia* sp. nauplii do not excessively deteriorate water quality. However, since feeding with *Artemia* sp. nauplii is costly and work intensive, it is not suitable as the exclusive diet.

The best protein sources for crustaceans are from other crustaceans (Boghen and Castell, 1981). Discards of the edible crab *C. pagurus* can be cheaply obtained from local fishermen. Lobsters which were fed in a preliminary experiment with minced crab carcasses showed high growth rates. However, a disadvantage of this diet is the lack of natural pigments which results in poorly pigmented lobsters. Therefore, *C. pagurus* is not suitable as exclusive diet but must be given in combination with diets that contain pigments. Moreover, minced crab meat blocked the fine nylon gauze which formed the bottom of the maintenance compartments and, thus, impaired water exchange and water quality.

Live isopods, e.g. *I. emarginata*, are easily produced in mass culture (Franke and Janke, 1998). Preliminary feeding attempts showed good acceptance by juvenile lobsters and satisfactory growth rates. The presence of live isopods encouraged the predatory behaviour and increased the feeding activity of the lobsters. The juvenile isopods were available for the juvenile lobsters at any time and provided pigments for full coloration of the lobsters.

A preliminary experiment showed that feeding with either *Artemia* sp. nauplii, or *C. pagurus* or live juvenile isopods alone resulted in poorer growth than feeding a combined diet. Similar results were reported by Beard et al. (1985) and Waddy (1988). In their experiments, too, the combination of different natural foods, i.e. a mixed diet, gave better growth and survival rates. Lobsters which were fed with artificial diets had lower growth rates (0.05 mm day^{-1}; Conklin et al., 1980; D'Abramo and Conklin, 1985) than with natural foods (0.01 mm day^{-1}; Waddy, 1988). In comparison to natural mixed diets, artificial feeds must be supplemented with balanced nutrients which make them expensive.

4.3. Growth and survival

Juvenile lobsters grow best at 20 °C (Beard et al., 1985; Waddy, 1988; Wray, 2005; Schmalenbach unpubl.). This corresponds to about the highest summer water temperature around Helgoland. Rearing at 20 °C and feeding every 2 days a combination of natural diets resulted in highest growth rates of almost 0.1 mm CL-R per day. The juvenile lobsters reached a carapace length of 10 mm after 69 days of post-larval development with a survival rate of 90–96% at a feeding frequency of every 2 days. Similar growth rates of juvenile lobsters were reported by Waddy (1988) and Kristiansen et al. (2004). The juvenile lobsters in our experiment which were fed every 4 days needed an additional 2 to 3 weeks to reach 10 mm carapace length at a survival rate of 93–97%. This might suggest that the highest feeding frequency of every 2 days would result in the highest growth rates

with adequate survival rates. Other studies have shown that there are already significant differences in growth between feeding every 2 days and every 3 days (Richards and Wickins, 1979). Feeding less frequently helps to reduce the accumulation of debris and to maintain good water quality and higher survival rates. Indeed, our rearing experiments showed not only good growth rates, but also high yield of juvenile lobsters at survival rates of 90 to 97%.

4.4. Co-culture with isopods

The well-being, health, and the survival of juvenile lobsters strongly depend on clean water. However, accumulation of food remains, excrements, or other waste products significantly impairs water quality. Accordingly, a major burden in our lobster rearing facility was the frequent manual cleaning of each of the single compartments. Manual cleaning is time and personnel-intensive and, therefore, expensive. The addition of live juvenile isopods into the single compartments of the juvenile lobsters significantly improved the rearing conditions. The isopods consumed remaining food and, thus, prevented the gauze which formed the bottom of the compartments from becoming blocked. This, in turn, ensured a constant water flow through each of the compartments and, thus, guaranteed best water quality for the juvenile lobsters. The juvenile isopods, moreover, provided a permanently available prey for the lobsters and could stimulate their foraging behaviour. Studies about the spiny lobster *Jasus edwardsii* have shown that a daytime-dependent feeding rhythms by the presence or absence of predators influenced the growth and trained patterns of foraging and emergence (Oliver et al., 2006). A preliminary experiment showed that feeding with either *Artemia* sp. nauplii, or minced crabs or live juvenile isopods alone and in combination resulted in different shell pigmentations. Feeding with isopods improved the pigmentation of the lobsters. Watt and Arthur (1996) added into the lobster box a few mussel spat for the proper development of their crusher claws. In the present study, substrates were avoided because it would cause further cleaning efforts. The live isopods encouraged the lobsters to actively hunt for prey. This, again, appears to be favourable for the proper development of their crusher claws (e.g. Wickins, 1986).

Another advantage of the co-culture of lobsters and isopods is that the lobsters can feed on the isopods when desired. Lobsters are active during the night (Mehrtens et al., 2005) but in the rearing facilities the food is usually offered during the daytime at working hours. Foraging and feeding during the night may increase the assimilation efficiency because it better matches with the natural diurnal activity rhythms of the lobsters. Foraging in darkness influences the growth rate of juvenile lobsters. Bordner and Conklin (1981) observed that juvenile lobster grew significantly faster when kept in dimmed light or long periods of darkness. Therefore, we covered the basins with a dark Perspex lid.

5. Conclusions

An extensive restocking programme for the endangered Helgoland lobster population requires laboratory rearing and subsequent release of large numbers of juveniles lobsters. For the implementation of such a programme we developed a rearing method which is optimized from both economic and ecological viewpoints.

Minced crab meat from discards of the Helgoland crab fisheries proved to be a suitable and inexpensive food for juvenile lobsters but it blocked the rearing system and impaired water circulation. The co-culture of juvenile lobsters with juvenile isopods provided significant advantages in terms of feeding as well as cleaning of the rearing facilities. The maintenance of a conventional culture system for 600 juveniles, including feed preparation, feeding, and cleaning, takes about 14 man hours/week. The use of isopods as cleaning organisms and supplementary diet reduced the maintenance time by 50% to 7 man hours/week. The isopods served as a permanently available food for the juvenile lobsters, and simultaneously, the isopods fed on food remains and reduced the amount of debris which, in turn, ensured a continuous water flow through the maintenance compartments.

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