ISSN 0308 - 5589

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
DIRECTORATE OF FISHERIES RESEARCH

FISHERIES RESEARCH TECHNICAL REPORT No. 79

The techniques and practicability of year-round production of lobsters, *Homarus gammarus* (L.), in laboratory recirculation systems

T. W. BEARD, P. R. RICHARDS and J. F. WICKINS

LOWESTOFT, 1985

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
DIRECTORATE OF FISHERIES RESEARCH

FISHERIES RESEARCH TECHNICAL REPORT
NUMBER 79

The techniques and practicability of year-round production of lobsters, *Homarus gammarus* (L.), in laboratory recirculation systems

T W BEARD, P R RICHARDS and J F WICKINS

LOWESTOFT, 1985

The authors:

T W Beard is a Higher Scientific Officer and J F Wickins, BSc, is a Senior Scientific Officer. Both are based at the Fisheries Experiment Station, Conwy.

P R Richards, at the time of the investigations was a Research Officer employed by the Honourable Company of Fishmongers and was stationed at the Fisheries Experiment Station, Conwy. He has since left the laboratory.

Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft, (79), 22 pp.

CONTENTS

1. Introduction

The intensive culture of lobsters (*Homarus gammarus*) has been studied at the MAFF Fisheries Experiment Station, Conwy, since 1973. Financial support was provided by the Honourable Company of Fishmongers, London, who sponsored a 3½ year programme to investigate environmental and nutritional factors affecting the growth and survival of juvenile lobsters (Richards and Wickins, 1979; Richards, 1981). On the basis of the preliminary findings, the programme was extended to study the technical feasibility of culturing lobsters to marketable size (about 340 g live weight) on a continuous production basis (Richards, 1980). Three controlled environment tank systems were designed and built (for broodstock, larvae-rearing and on-growing, respectively) to produce 200 lobsters of 80 mm carapace length per year from batches of 80 juveniles reared every 3 months.

This report describes the main components of the production unit, the production of larvae and juveniles and the survival and growth rates achieved by juveniles and adults during the 3½ years of the project, and considers improvements and further research needed before commercial application can hope to be viable.

2. Methods

2.1 Description of the culture programme and tank systems

For convenience, the programme was divided into three parts:

(a) broodstock and supply of larvae;
(b) culture of larvae;
(c) on-growing,

each of which was conducted in a separate recirculation system.

Supplies of wild-caught, egg-bearing females were purchased from a lobster merchant and individually housed in the first recirculation system through which there was a continuous flow of natural sea water (Figure 1). When their eggs hatched, the newly-hatched larvae were transferred to glass-fibre reinforced plastic bins (Hughes *et al.*, 1974) in the second recirculation system and cultured communally (Figure 2). After their third moult, juvenile or stage IV lobsters were transferred to individual containers (to prevent fighting and cannibalism) in the third recirculation system which was of 8,000 l capacity (Figure 3). During on-growing, which was in four phases, four appropriate sizes of individual container were used. The container sizes and the time spent in each size are set out in Table 1, the number of lobsters in the second, third and fourth phases being governed by the size of the tanks available.

2.1.1 Materials

The recirculation systems have been described by Richards and Wickins (1979). All tanks were of grey glassfibre and supported on a timber framework protected with black bituminous paint. Pipework, valves and fittings were of unplasticized P.V.C. and centrifugal pumps incorporating plastic housings and impellers on stainless steel shafts were used throughout. Percolating biological filters were cylindrical and made by joining curved sections of

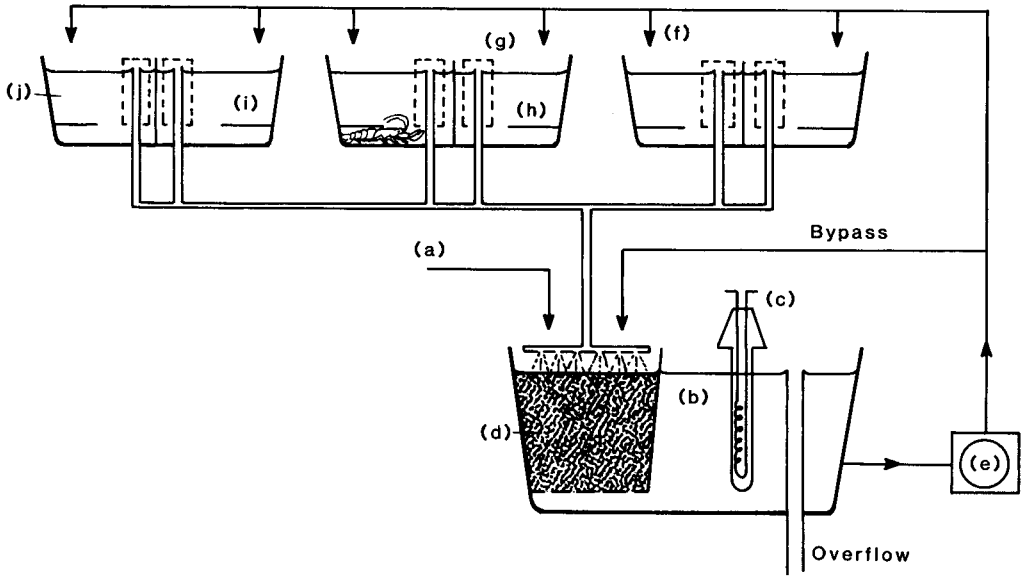


Figure 1 Recirculation system (900 l capacity) used for the maintenance of egg-bearing female lobsters. Key: (a) continuous flow of natural sea water, 2–3 l min^{-1}, at 5–15°C, 28–34°/oo salinity; (b) reservoir, water volume 228 l; (c) immersion heater, 3 kW; (d) submerged biological filter of plastic media, specific surface area 164 m^2 m^{-3}, volume 75 l; (e) centrifugal pump, capacity 900 l h^{-1}; (f) flow rate 4–6 l min^{-1} to each compartment; (g) overflow screen, 2 mm mesh; (h) tile and brick shelter; (i) one of two compartments each 86 x 48 x 41 cm; (j) tank, volume 250 l.

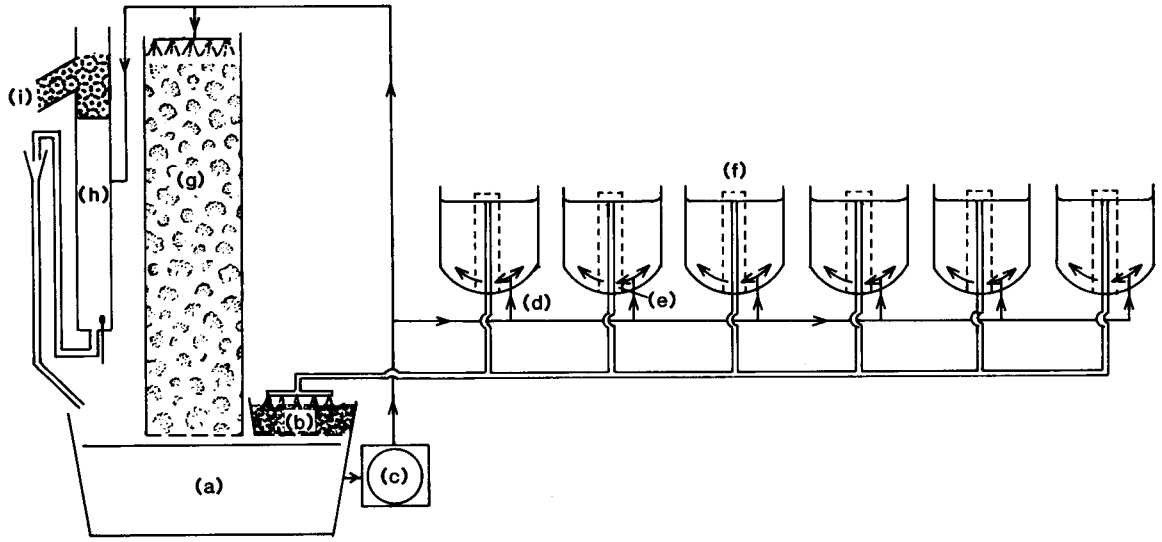


Figure 2 Recirculation system (500 l capacity) used for the culture of lobster larvae. Key: (a) reservoir, water volume 250 l; sea water at 20–22°C; 30–34°/oo salinity; (b) washable Terylene wadding; (c) centrifugal pump, capacity 2,300 l h^{-1}; (d) flow rate 3–4 l min^{-1} to each 40 l culture bin; (e) radial water distributor (see Richards and Wickins, 1979); (f) overflowscreen, 2 mm mesh; (g) percolating biological filter of plastic media, specific surface area 164 m^2 m^{-3}, volume 0.1 m^3, hydraulic load 95 m^3 m^{-3} d^{-1}; (h) foam separation tower, volume 22 l, water flow 3 l min^{-1}; (i) foam discharge pipe.

Table 1 Disposition and size of lobsters in on-growing system

On-growing phase	Number of lobsters held	No. of batches	Duration of phase (months)	Container size (cm)	Age range (months)	Size range (g)	Total weight (kg)
1	80	0–1	1	5 x 5	0– 1	0 – 0.2	0.016
2	64	1	3	10 x 11.5	1– 3	0.2– 1.4	0.062
3	56	3	8	20 x 23	3–12	1.4– 26.9	2.4
4	56	6	18	23 x 46	12–30	26.9–358.7	59.7

corrugated plastic roofing sheet, filled with a random arrangement of proprietary plastic rings. Foam separation towers were made of 110 mm P.V.C. drainpipe.

2.1.2 Food

The broadstock females were fed fresh mussel (*Mytilus edulis*) flesh at approximately 1% body weight per day. Larvae were fed *ad libitum* with deep frozen mysid shrimp purchased from local aquarist shops. Juveniles up to 4-months old were fed a daily ration of fresh mussel of approximately 10% body weight d^{-1}; older lobsters received 5% d^{-1}; both these groups received a supplement of frozen shrimp (*Crangon crangon*) twice each week.

2.1.3 Heating and cleaning

Natural sea water was heated prior to use by electric immersion heaters in laboratory storage reservoirs. Immersion heaters were also used in the broodstock system (see section 2.2.1) but the temperature of the recirculated sea water in the larvae culture and on-growing systems was maintained (20 ± 2°C) by a gas-fired, ducted, hot air room heating system.

In each recirculation system 12.5% of the water was replaced every Monday and Friday with warm sea water which had been filtered through a diatomaceous earth pressure filter and sterilized by ultra-violet irradiation. The filter removed 90% of suspended particles above 2.5 μm diameter. Salinity was adjusted to 30 ± 2°/oo by the addition of artificialsea salts or tap water to each recirculating system or to the reservoirs as required. Generally, all pipework and tank floors were cleaned every 2–4 weeks.

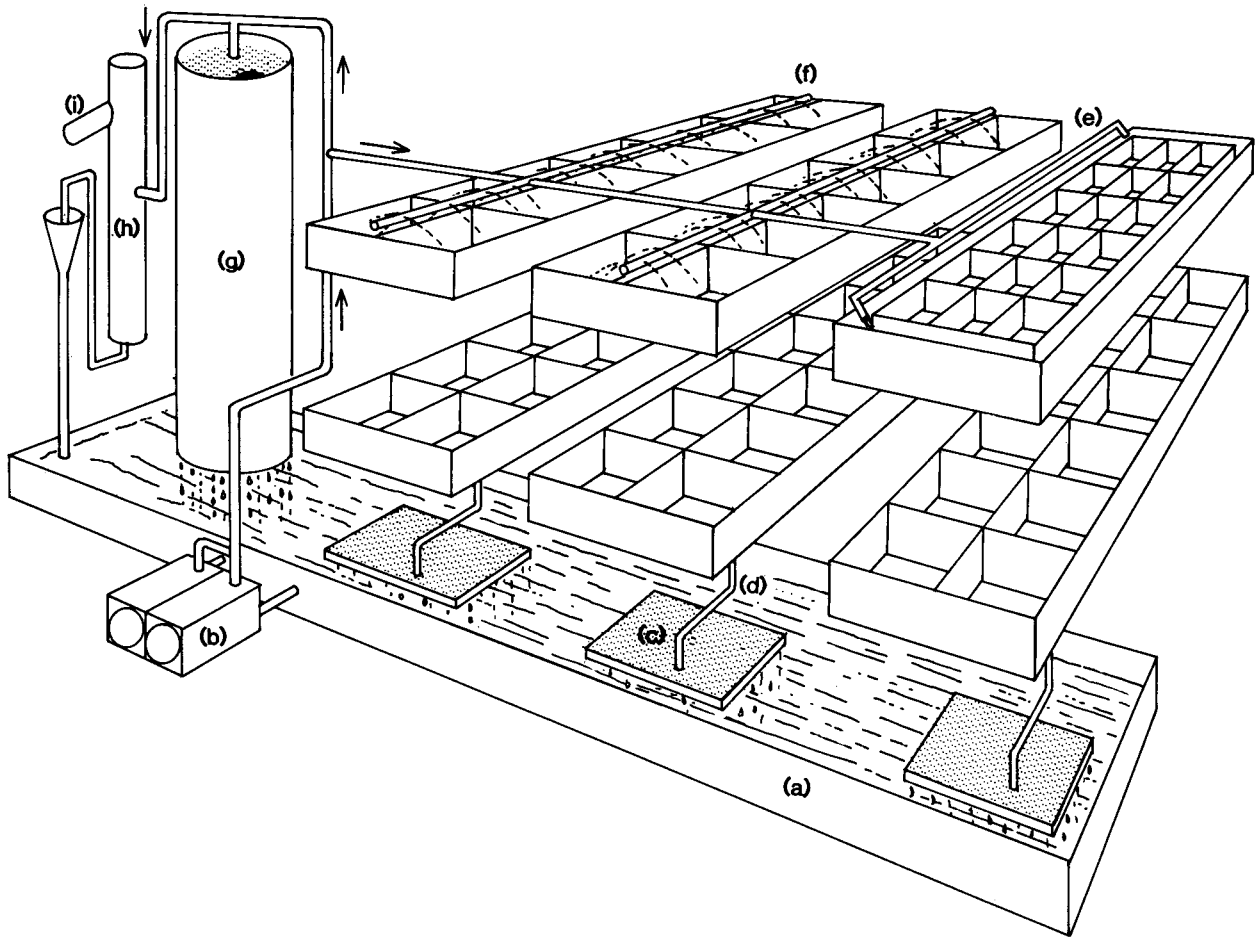


Figure 3 Recirculation system used for the culture of lobsters from stage IV to 80 mm carapace length (ca ¾ lb). Arrows indicate direction of flow. Key: (a) three reservoirs (shown as one in the diagram), total volume 900 l; sea water at 19–21°C, 29–32°/oo salinity; (b) six centrifugal pumps (two only shown), capacity 2,300 l h^{-1} each; (c) washable Terylene wadding; (d) drains; (e) flow to each rearing tray 6.3 l min^{-1}, automatic siphons, operating every 6–8 min (on-growing phases 1–3); (f) flow to each compartment 0.6 l min^{-1} (on-growing phase 4); (g) percolating biological filter of plastic media, specific surface area 164m^2 m^{-3}, volume 0.76 m^3, hydraulic load 114 m^3 m^{-3} d^{-1}; (h) foam separation tower, volume 22 l, water flow 3 l min^{-1}; (i) foam discharge pipe.

2.1.4 Lighting

Lobsters were exposed to a natural photoperiod (because of windows in the culture building) at a light intensity of up to 10 lx at the water surface. During normal husbandry operations (0830 h to 1230 h daily) fluorescent strip lights increased the intensity in exposed tanks to about 200 lx.

2.1.5 Monitoring water quality

Satisfactory functioning of the water treatment plant in the recirculation systems was monitored regularly by the methods shown in Table 2.

2.2 Animal management and the collection of data

2.2.1 Broodstock and supply of larvae

Egg development was monitored in broodstock females by measuring the increase in size of the oval embryonic eye in a small sample of eggs taken from each female every two weeks. In order to produce larvae during January, April, July and October, the rate of egg development was increased when necessary by raising the water temperature from ambient (4–12°C) to 13–15°C. Table 3 shows the time taken at this temperature for eggs with an eye index (half the sum of its greatest length and breadth) between 50 and 620 μm to hatch. For example, newly purchased females carrying eggs with an eye index of 250–300 μm would, if held at 13–15°C, hatch their eggs in 10 weeks.

No attempt was made to estimate the number of eggs carried by the females but larvae were counted as they were transferred to the larvae culture bins. After the eggs had hatched the females were exchanged for further ovigerous females.

Table 2 Water quality measurements made during the culture of lobsters in recycled sea water

Factor	Frequency of sampling	Time of sampling	Origin of sample	Method
Temperature	Continuous	–	Reservoir	Thermograph
Salinity	Twice weekly	0800–1000 h	Phase 4 on-growing container	Optical refractometer
Oxygen	Occasional	0800–1700 h	Various positions throughout the system	Dissolved oxygen electrode
pH	Daily	0800–1000 h*	Phase 4 on-growing container	Electrode (Wickins and Helm, 1981)
Total ammonia plus ammonium ion	Weekly	0800–1000 h*	Phase 4 on-growing container	Spectrophotometric (Wickins and Helm, 1981)
Nitrite	Weekly	0800–1000 h*	Phase 4 on-growing container	Spectrophotometric (Wickins and Helm, 1981)

* before feeding

Table 3 The relation between the embryonic eye index and the time to hatching at 13–15°C

Embryonic eye index (μm)	Time to hatching (weeks ± 2)
50–100	15
100–150	14
150–200	13
200–250	12
250–300	10
300–350	8
350–400	7
400–450	5
450–500	4
500–550	2
600–620	At hatch

2.2.2 Larvae culture

Each larvae culture bin was stocked with 1,500–2,000 larvae from a single parent and, to reduce cannibalism, all hatched within a period of not more than 2–3 days. As soon as stage IV lobsters were seen (Nichols and Lawton, 1978) they were removed by hand-net, counted and placed in individual containers. At least 80 juveniles were retained from each batch. Juveniles with deformities or missing appendages were rejected.

2.2.3 On-growing

When fully stocked, the on-growing system held ten or eleven batches of lobsters at any one time (Table 1).

The growth of individual lobsters was monitored by measuring the length of the cast carapace at each moult and noting the date of the moult. Each cast shell was returned to the container for the lobster to eat. Every 6 months the individual lobsters were weighed after removal of surface water with paper tissue.

Food consumption was regularly monitored by weighing the total amount of food to be fed to each batch on any one day and then subtracting the weight of uneaten food recovered the next day.

Lobsters that died were dissected and the condition of the following tissues noted: midgut gland, gill, digestive tract, muscle, gastrolith, old and new exoskeleton. Growths, wounds and lost or damaged appendages were recorded. At intervals, specimens were sent to the MAFF Fish Diseases Laboratory, Weymouth for histological examination and to the Ministry's Fisheries Laboratory, Burnham-on-Crouch for analysis of heavy metal and pesticide content. Of the first lobsters to reach marketable size, six were sent live to the Ministry's Torry Research Station, Aberdeen for determination of edible meat yield and sensory acceptability (see section 3.8) and several were eaten by project staff to confirm their palatability.

3. Results

3.1 Production of larvae from captive broodstock

Altogether 55 egg-bearing females of around 1.5 kg live weight were held at one time or another during the $3\frac{1}{2}$ years of the project. Their performance is shown in Table 4. Category (a) females produced, on average, 4,000 larvae per female, but when the results from categories (a) and (b) females were combined the overall average was 2,500 larvae per female. Since a wild-caught female of equivalent size (1.5 kg) would be expected to be carrying some 14,000 eggs (Hepper and Gough, 1978), it would appear that from the time of capture from the sea as ovigerous females, through commercial empoundment, and up to the point of hatching, some 82% of the eggs were being lost.

3.2 Survival and growth of larvae

Over 66,000 larvae were cultured in thirty-eight separate batches to yield a total of 6,500 stage IV juveniles for production trials and experiments described by Richards (1981). Survival was therefore roughly 10% overall, but there seemed to be seasonal differences: survival was generally poor between November and March (average 4%) when incubation at elevated temperatures lasted up to 4 months, and better between April and September (average 16%) when incubation lasted less than 2 months (Figure 4).

The time required to reach stage IV varied from 9 to 26 (average 16) days (Figure 5): 63% reached stage IV between days 13 and 17.

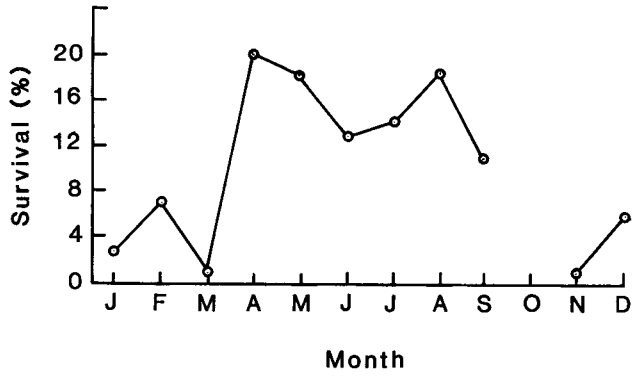


Figure 4 Average survival of lobster larvae reared during different months of the year (no data for October).

Table 4 Performance of female broodstock

Category		No. of females	Percentage
(a)	Females producing more than 1,000 larvae	22	40
(b)	Females producing less than 1,000 larvae	17	31
(c)	Females dying before eggs hatched (including those accidentally killed by thermostat malfunction)	7	13
(d)	No data	9	16
Total		55	100

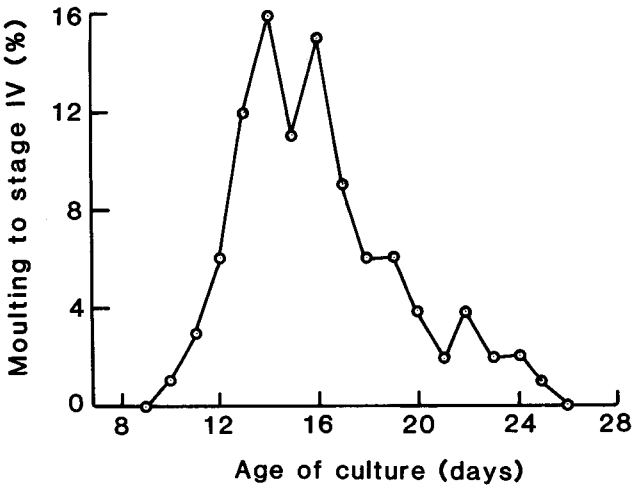


Figure 5 Time taken for lobster larvae to reach stage IV at 20°C.

3.3 Survival of stage IV juveniles

Usually, only the first 80 juveniles to moult successfully to stage IV were retained for the production unit. Their survival may not therefore have been representative of all the larvae cultured. On several occasions, however, more juveniles were required for other experiments and among twelve batches of 80–400 lobsters held for one month survival was 82%. About 15% died before or during the moult to stage V and a further 3% died over the next two stages. Thereafter, mortality was negligible up to 12 months of age, with the exception of batch 8.

3.4 Survival of one- and two-year-old lobsters

Survival from age 12 months onwards was very disappointing (Table 5) and, on average, only 14% of the first three batches reached 80 mm carpace length. The pattern of mortality for each batch is shown in Figure 6: in all batches the good survival up to 12 months old was followed by losses in the late summer and autumn of both 1978 and 1979. In 1978 most deaths occurred in the older animals (that is, in the first three batches) between September and the end of December. In 1979 losses occurred in all nine batches, beginning in June among the older animals and progressively later among the younger animals. From January to May 1980 (when the project finished) there were only seven deaths among the total stock of 240 animals.

We were unable to identify the cause of the mortalities. There were no significant correlations between mortality and any of growth rate, age (after 12 months), size (over 25–30 mm carapace length) and sex: the deaths appeared to be random. Although mortalities were clearly related to the time of year, they were not related to diet or space limitations. It was noticed that many lobsters showed reduced appetite from June 1979 until early 1980. No evidence was found of either Gaffkaemia or shell disease, which can be important in commercial lobster storage.

Of the dead lobsters which were examined, 70% were judged to be close to a moult. Judgment was made on the basis of large gastrolith size, formation of the new shell and softening of the base of the large chelae. The other 30%, although not in a condition associated with moulting,

Table 5 The survival of ten batches of 50 lobsters reared in individual compartments

Batch	Date stocked into on-growing system	Percentage survival to week					
		16	26	52	78	104	130
1	5/4/77	98	98	91	87	60	24
2	30/6/77	80	78	76	44	22	7
3	15/9/77	98	98	95	63	33	12
4	24/1/78	100	100	94	72	47	
5	9/3/78	98	98	98	73	55	
6	13/6/78	100	98	96	62		
7	22/9/78	100	100	93			
8	16/12/78	100	84	58			
9	9/7/79	91	89				
10	27/12/79	100					
	Mean	96.5	93.7	87.6	66.8	43.4	14.3

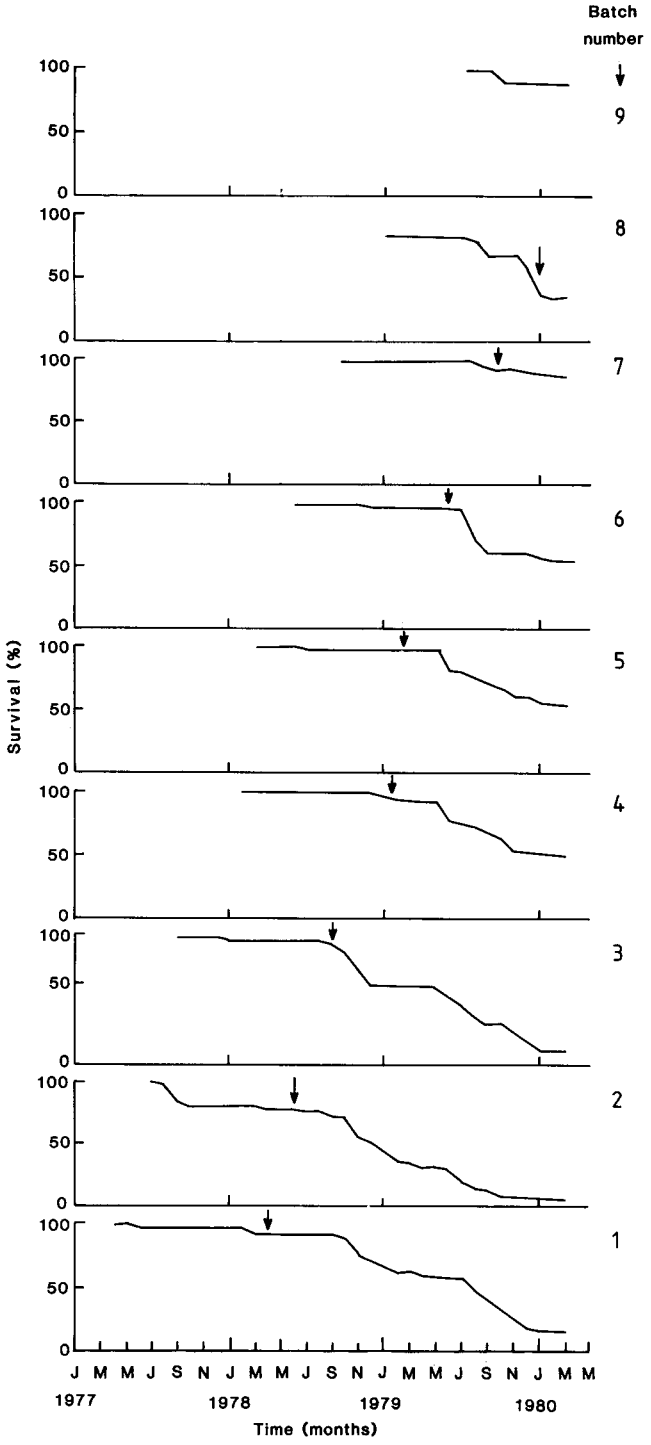


Figure 6 Effect of year, season and age on survival of ten batches of cultured lobsters. Arrows denote 12-months of age.

also died at the time of expected moult (see section 3.5.4). Less than 1% of all deaths occurred during ecdysis, although the incidence of claw loss during ecdysis was high (2–3% of entire lobster stock) particularly during the period of high mortalities in 1979.

Post-mortem examinations were carried out on 138 dead lobsters but only 24 of these showed any evidence of tissue abnormality (Table 6).

Table 6 Tissue abnormalities observed in the 138 dead lobsters examined in 1979–80

Observations	Number of lobsters
Intracellular inclusions similar to those caused by mycoplasms (bacteria-like organisms of the order Chlamydea – highly specific parasites)	1
Abdominal muscle degeneration producing a milky-white dehydrated appearance (cause unknown)	1
Granulomatous lesion in the mid-gut gland; no evidence of causative organism	1
Hypertrophy of the mid-gut which may have restricted passage of food and faecal material	2
General degeneration of body tissues typical of starved lobsters	5
Swollen gill lamellae which may have been a post-mortem change	14

Although a rigorous survey was not possible, four dead and eight healthy lobsters were analysed for selected heavy metals and organochlorine compounds. With the exception of lead, mercury and copper, all metals and organochlorine compounds were well within the ranges expected from wild-caught lobsters (Portmann, 1979; Murray, 1981). The average and maximum values of lead, mercury and copper (copper was surprisingly low in cultured lobsters) are compared with published values for wild-caught lobsters in Table 7. Also included in Table 7 are the results of spot checks made on the lobsters' food (mussel and shrimp) and on a sample of sediment from the floor of a rearing tank. Particularly noticeable are the high levels of lead recorded from the sediment sample (183 mg/kg) and dead lobster tail muscle (up to 29 mg/kg). Average copper levels were between two and six times lower in cultured lobsters than in wild specimens, but the true toxicological significance of these findings cannot be judged in the absence of more detailed comparisons.

3.5 Growth of lobsters to marketable size

3.5.1 Growth rate

Among the ten batches of lobsters stocked into the on-

Table 7 Levels of mercury, lead and copper in wild lobsters, cultured lobsters, their food and tank sediment (mg kg^{-1} fresh weight)

		Date	Mercury		Lead		Copper	
			Mean	Max	Mean	Max	Mean	Max
Wild lobster*	body	1970–73	< 0.10	0.52	< 1.1	4.5	254	1,600
	tail		0.29	0.84	< 1.1	4.0	19	46
	claw		0.30	0.86	< 1.8	5.5	26	50
Wild mussel*		1970–73	0.15	1.10	< 2.3	10.0	4.6	29
Wild shrimp*		1970–73	0.15	0.32	3.6	7.5	26	45
Wild lobster†	body	1975	0.20	0.76	< 0.2	0.4	180	430
	tail		0.45	1.40	< 0.2	0.3	15	81
	claw		0.21	0.58	< 0.2	0.2	25	45
Wild mussel†		1975	0.05	0.06	0.9	2.0	1.2	2.0
Wild shrimp†		1975	0.18	0.30	3.0	6.0	28	31
Cultured lobsters (live)	body	1979–80	0.30	0.32	1.8	2.0	38	50
	tail		0.85	1.00	5.0	5.5	4.3	5.2
	claw		0.61	0.80	3.6	4.5	15	18
Cultured lobsters (dead)	body	1979–80	0.39	0.67	< 2.3	5.5	39.4	130
	tail		1.36	2.20	11.4	29.0	3.2	16
	claw		0.40	0.49	2.5	3.0	9.7	32
Lobster food								
N. Wales mussel		Nov. 1979	0.27		2.1		1.0	
		Dec. 1979	0.06		1.8		1.7	
N. Wales shrimp		Nov. 1979	0.05		1.5		30	
		Dec. 1979	0.08		0.4		11	
Tank sediment (mg kg^{-1} dry weight)		1979	0.86		183			

* Portmann (1979)
† Murray (1981)

Table 8 The increase of carapace length with time in cultured lobsters, as described by the predictive regression equation: Carapace length (mm) = a + (b × age in weeks)

Batch Number	Intercept (a)	Slope (b)	95% confidence limits of slope	*r*	d.f.	Maximum age recorded (weeks)
1	2.84	0.58	0.56–0.59	0.998	31	130
2	4.96	0.56	0.55–0.57	0.999	32	130
3	5.84	0.58	0.55–0.60	0.995	29	130
4	3.11	0.65	0.63–0.67	0.997	25	112
5	5.06	0.58	0.57–0.59	0.999	23	104
6	3.96	0.66	0.65–0.68	0.999	19	96
7	1.08	0.72	0.69–0.76	0.997	12	68
8	1.59	0.72	0.69–0.75	0.998	11	64
9	1.85	0.59	0.52–0.65	0.996	5	40

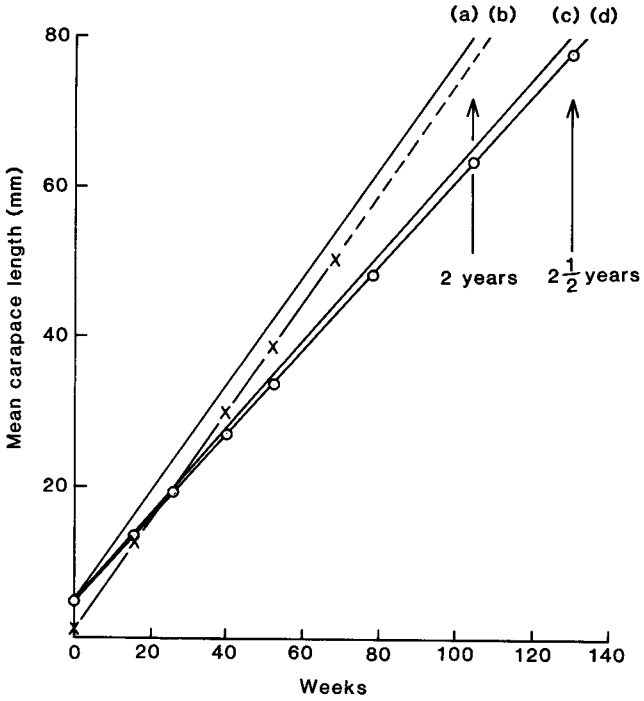


Figure 7 Time taken for captive lobsters to attain 80 mm carapace length: (a) predicted growth rate to attain 80 mm carapace length size in 2 years; (b) best growth achieved (batch 7) up to 68 weeks (broken line represents anticipated growth rate); (c) predicted growth rate to attain 80 mm carapace length in 2½ years; (d) slowest growth achieved (batch 2) up to 130 weeks (broken line represents anticipated growth rate).

growing system, only the growth of the first eight batches could be followed beyond one year. Comparison of the slopes obtained by plotting mean carapace length against lobster age for each batch (Table 8) showed that, of these eight batches, four (batches 4, 6, 7 and 8) grew significantly faster than the rest, and batches 7 and 8 grew faster than 4 and 6. Figure 7 shows estimates of the growth rates needed to attain 80 mm carapace length in 2 and 2½ years, alongside the growth actually achieved by the best (batch 7) and worst (batch 2) lobsters. The results indicated that, on average, the slowest growing batches would reach 80 mm carapace length in about 2 years 7 months and the fastest in 2 years 1 month. Even within a batch, however, some individuals grew faster than others, so, in a commercial operation, some lobsters would become saleable before others of the same age.

Table 9 shows that the coefficient of variation about the mean live weight of lobsters of different ages from each batch, with few exceptions, was around 20–30%. In practical terms this means that the percentages of each batch that were expected to attain 80 mm carapace length after specified growth period were as in Table 10.

3.5.2 Sex

There was a slight tendency for males to grow more rapidly than females although the differences between the mean weights of the sexes after 1- and 2-years growth (Table 11) were not significant statistically ($P > 0.05$). There were no significant departures from a sex ratio of 1:1 in any of the batches.

Table 9 The increase in mean weight (g) of cultured lobsters

	Weeks											
	16		40		52		78		104		130	
Batch	Weight	C.V. (%)	Weight	C.V. (%)	Weight	C.V. (%)	Weight	C.V. (%)	Weight	C.V. (%)	Weight	C.V. (%)
1	1.25	29	9.20	33	18.34	29	80.9	32	194.0	39	285.6	29
2	1.42	21	10.85	25	23.70	23	75.3	22	166.0	34	339.5	33
3	1.56	18	13.67	26	30.16	22	95.4	29	208.6	24	334.0	25
4	1.66	20	15.61	27	29.52	32	110.7	30	255.4	38		
5	1.75	18	13.59	31	27.43	34	85.3	35	223.0	36		
6	1.35	17	13.97	23	29.04	24	112.4	25				
7	1.48	22	17.67	23	33.85	25						
8	1.47	20	15.87	24	36.65	25						
9	0.90	14	10.38	29								
10	1.13	24										
Target for 2½ year grow-out	1.43		13.22		26.89		85.9		186.5		358.7	

Table 10 Time taken for cultured lobsters to reach marketable size (calculated from size range of the first six batches at 78 weeks old)

Culture period (years)	Percentage of batch reaching market size
1.75–2.00	3
2.00–2.25	18
2.25–2.50	38
2.50–2.75	22
2.75–3.00	12
3.00–3.25	6
3.25–3.50	1

3.5.3 Length:weight relationship

The relationship between the live weight of a lobster and its carapace length is described by the equation:

$$\log_e \text{weight (g)} = \log_e a + b \log_e \text{carapace length (mm)},$$

where a and b are respectively the intercept and slope constants. Values of the constants were calculated for each of the first nine batches separately (Table 12) but there were no marked differences in the carapace length:weight relationship between batches.

3.5.4 Moult frequency

Small, juvenile lobsters (4 mm carapace length) moulted every 2 weeks and the intermoult period increased as the lobsters grew until at about 75 mm carapace length they were moulting approximately every 14 weeks. Plots of $\log_e$ intermoult period against $\log_e$ carapace length gave consistently high correlation coefficients and therefore accurately described the moulting pattern of captive lobsters (Table 13). The general equation is:

$$\log_e \text{intermoult period (days)} = \log_e a + b \log_e \text{carapace length (mm)}$$

where a and b are respectively the intercept and slope constants.

The low value of the constant b for batch 7 indicates that, on average, lobsters in this, the fastest growing batch, were moulting more frequently than the others.

3.6 Feeding

3.6.1 Larvae

The daily ration of mysid shrimp fed to each fully-stocked bin of larvae is shown in Figure 8. From day-14 onwards the ration was reduced as stage IV juveniles were removed.

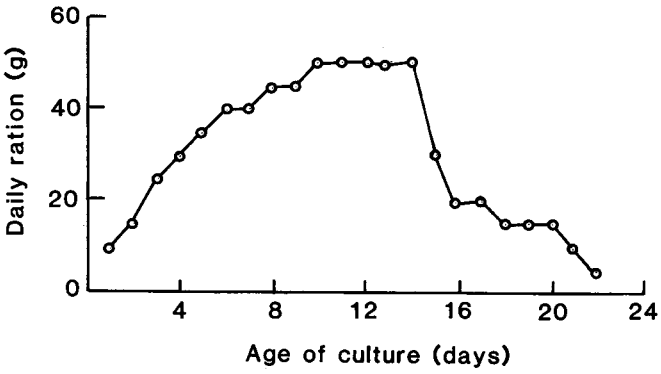


Figure 8 Typical daily ration of mysid shrimp fed into a 40 l culture bin initially stocked with 1,500–2,000 lobster larvae. The earliest stage IV juveniles appeared and were removed at about day 10.

Table 11 The numbers (n) and mean live weights ($\bar{w}$) (g) of males and females that developed in eight batches of cultured lobsters

	Weeks							
	52				104			
Batch	Males		Females		Males		Females	
	n	$\bar{w}$	n	$\bar{w}$	n	$\bar{w}$	n	$\bar{w}$
1	25	20.5	21	15.7	20	217.4	12	155.0
2	20	23.1	19	24.4	5	179.6	7	156.4
3	25	31.5	28	29.0	12	206.4	7	212.4
4	18	32.7	11	24.5	8	308.5	7	194.7
5	28	28.6	26	26.2	13	223.2	14	210.2
6	25	31.8	23	26.2				
7	25	35.2	26	32.1				
8	16	36.3	13	37.1				

Table 12 Predictive regression equation constants (see text sub-section 3.5.3) describing the relationship between live weight and carapace length in cultured lobsters. Data were obtained from 20–30 animals from each of the first nine batches grown for 40 weeks or more.

Batch	Intercept (a)	Slope (b)	*r*	d.f.	Maximum live weight (g)
1	0.0004	3.15	0.998	123	406
2	0.0003	3.16	0.999	117	447
3	0.0003	3.15	0.998	114	330
4	0.0004	3.14	0.997	117	401
5	0.0004	3.13	0.998	111	310
6	0.0003	3.21	0.996	101	181
7	0.0004	3.10	0.998	90	57
8	0.0005	3.08	0.999	79	55
9	0.0004	3.12	0.998	71	19

Table 13 Predictive regression equation constants (see text sub-section 3.5.4) describing the increase in mean intermoult period with increase in mean carapace length in seven batches of cultured lobsters

Batch	Intercept (a)	Slope (b)	*r*	d.f.	Maximum carapace length (mm)
1	4.399	0.705	0.971	57	75
2	3.614	0.748	0.979	61	75
3	3.184	0.797	0.974	47	75
4	3.059	0.812	0.978	59	74
5	3.843	0.755	0.943	43	57
6	3.086	0.803	0.967	45	54
7	5.834	0.597	0.982	35	46

Their prompt removal reduced cannibalism. By day 18, 75–80% of the lobsters had been transferred to individual containers. Typically, a total of 670 g of food was added to each bin of larvae during the culture period.

3.6.2 Juveniles and adults

Three measurements of particular interest in the culture of lobsters in recycled sea water were:

(a) the weight of food put into the system;
(b) the weight of food eaten by the lobsters;
(c) the food conversion ratio (FCR).

The weights in (a) and (b) will differ because that given to the lobsters or put into the system is related to the size of the lobsters in a given batch, while that actually eaten will depend upon the numbers within the batch that are not feeding well, for example, because of moulting.

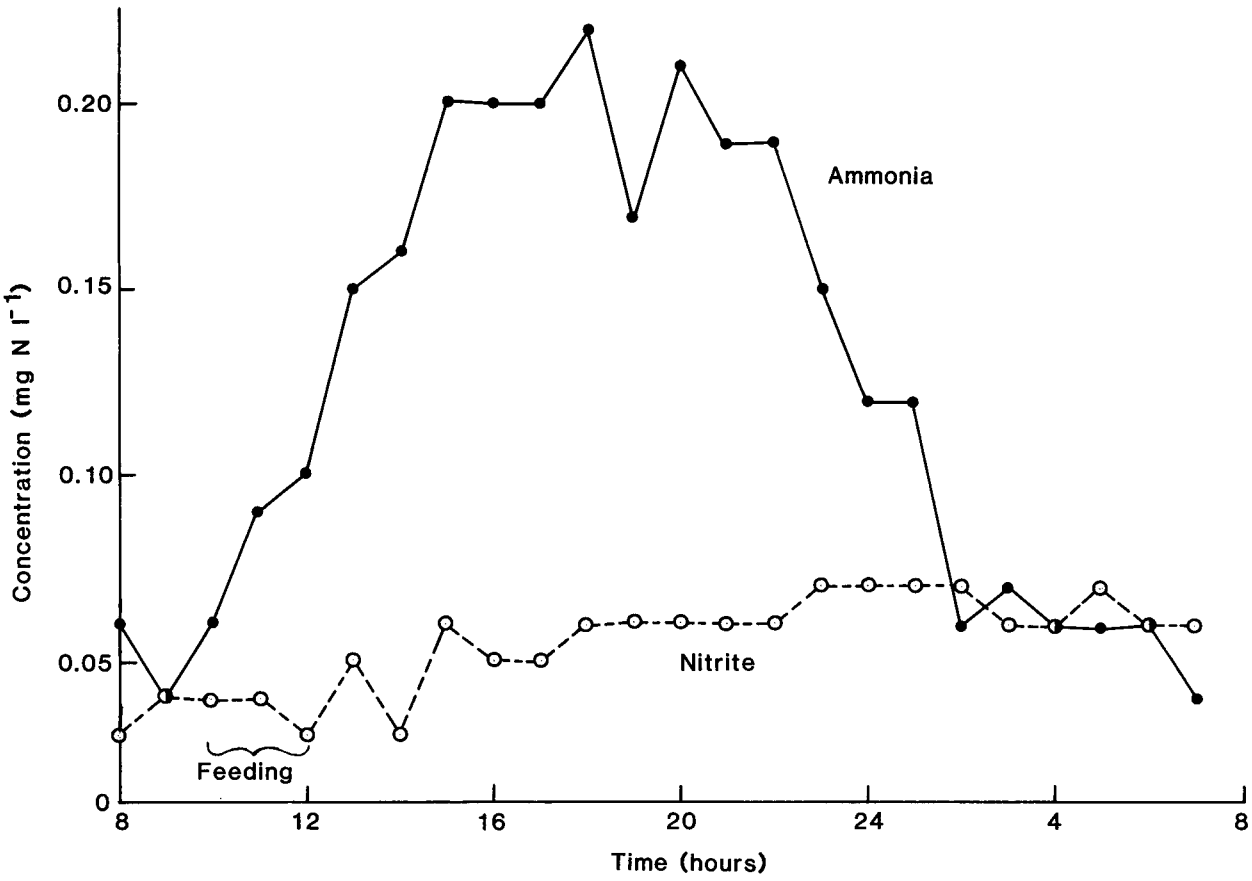
Measurements of food given and food eaten throughout the production cycle were used to prepare the feeding guide shown in Table 14. The gross FCR for lobsters fed with mussel flesh for $2\frac{1}{2}$ years and reaching a final size of 350 g was calculated from observed food consumption measurements to be 5.9:1 wet weight of mussel eaten to live weight of lobster produced. Equivalent figures for the ratio based on the amount of food given are 8.8:1 wet food to live lobster, indicating some 33% wastage of food.

3.7 Water quality

Hourly measurements of total ammonia + ammonium nitrogen and nitrite nitrogen were made over 16–24 h periods on ten separate occasions in an 8-month period one year after the project had started. The results were combined to produce Figure 9a and showed that from a minimum of about 0.05 mg total NH_4-N l^{-1} at 0900 h ammonia rose following feeding at 1000–1200 h to around 0.2 mg total NH_4-N l^{-1} between 1500 and 2200 h. Concentrations remained low from about 0200 to 1000 h the next day. Calculated concentrations of un-ionised ammonia nitrogen (Wickins and Helm, 1981) did not exceed 0.1 mg NH_3-N l^{-1}. In contrast, there was less variation in nitrite levels which remained between 0.03 and 0.07 mg NO_2-N l^{-1}. Excretion in adult lobsters (ca 300 g) was monitored over 24 h periods on two occasions and showed that the pattern of ammonia levels in the recirculation system water (Figure 9b) closely followed that of ammonia production.

Table 14 The daily ration of mussel given to and eaten by lobsters of selected ages in the laboratory on-growing system.

Age range (months)	Median weight of lobsters in a batch (g)	Food given (% body weight per day)	Food eaten
0– 3	0.5	14.9	8.1
3– 6	2.7	11.7	6.4
6– 9	8.4	9.5	5.3
9–12	19.3	7.9	4.5
12–15	37.6	6.6	3.8
15–18	65.1	5.6	3.3
18–21	104.2	4.7	2.8
21–24	156.7	3.9	2.4
24–27	225.0	3.2	2.1
27–30	311.2	2.6	1.8



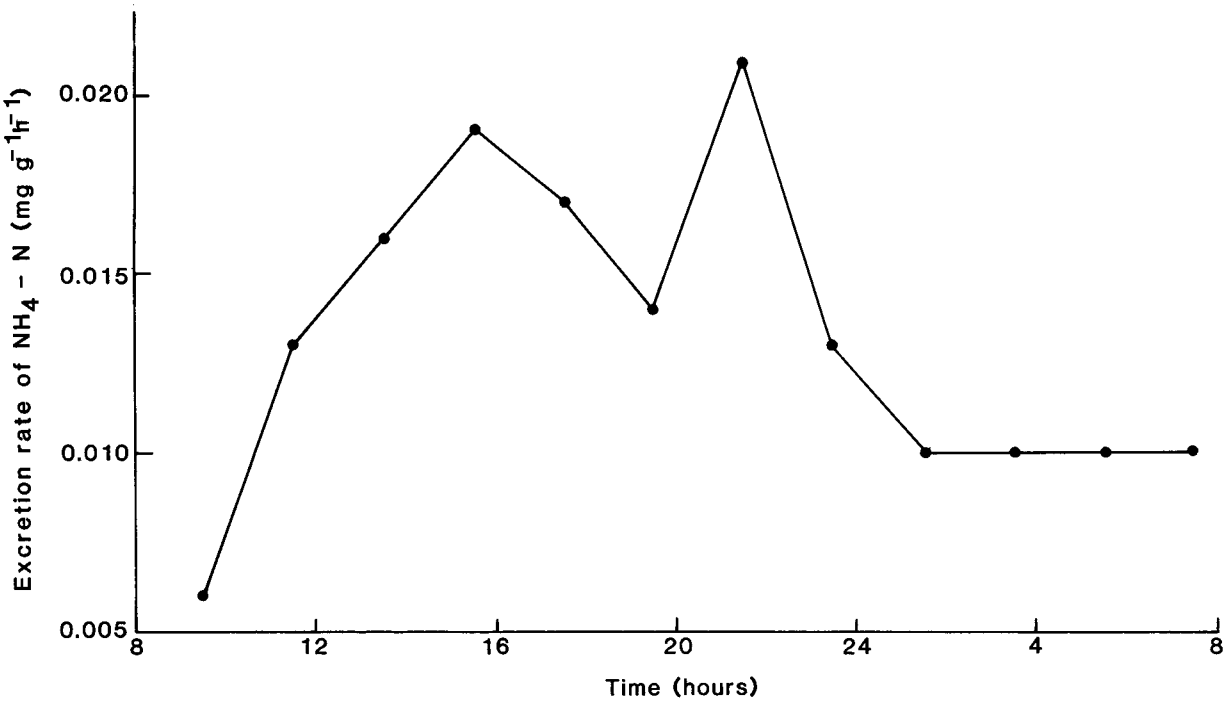


Figure 9 Nitrogen in recycled sea water during the culture of lobsters: (a) concentrations (mg N l^{-1}) of total ammonia plus ammonium nitrogen and of nitrite nitrogen; (b) excretion rate of ammonia + ammonium nitrogen in adult lobsters.

3.8 Product quality

Although cultured lobsters were not test marketed, six of the first to reach marketable size were compared by the Torry Research Station to six specimens caught from the North Wales coast. The results (Stroud and Dalgarno, 1982) indicated that there were no major differences in eating quality, yield of meat and gross meat composition between the cultured and wild samples. Significantly higher percentage yields of white meat from claws and tails were obtained from the cultured lobsters (Table 15).

Table 15 Boiled meat yields (percentage of boiled weight of whole animals) of cultured and wild lobster samples

	Mean total weight (g)	Meat yield (%)	
		Claw	Tail
Wild	269	12.2	17.6
Cultured	373	14.2	21.3
Significance of difference between means: $P <$	.001	.05	.01

Differences in the colour of the shells of the whole boiled animals made the cultured lobster less attractive than the wild lobster, the panel judges preferring the brighter red shells of the wild specimens. Discrimination against the appearance of the cultured lobster was not apparent after the shell was removed.

4 Discussion

The major achievements of the culture project were:

(a) the year-round production of post-larvae;
(b) the rapid growth of lobsters to marketable size in $2\frac{1}{2}$ years;
(c) the rapid growth of lobsters held in individual containers in recycled sea water;
(d) identification of technical problems.

The high mortalities during 1978 and 1979, while extremely distressing, did not detract from the general lessons learned. The mortalities were thought to have been related to the condition of the sea water in the Conwy estuary which, then, was unusual in that, for the first time in ten years, normal algal blooms did not occur. It is perhaps relevant that oysters cultured around our shores also suffered high mortalities during 1979 (Utting, 1983).

The high levels of lead and mercury and the low level of copper found in the samples analysed were unexpected. It is not known if they were in any way related to the estuary water, to materials in the culture system, to the food or even to the mortalities observed.

It was our original intention (Richards and Wickins, 1979) to include in this report estimates of the time required for the various culture operations – food preparation, water changing, plant maintenance. However, these were so greatly influenced by or dependent upon the constraints imposed by the laboratory infrastructure and research requirements that it was felt that no potential investor would consider our figures in making an assessment of commercial viability. Even so, the most simplistic estimates showed that the culture of lobsters to marketable size in our systems would not be commercially attractive without substantial improvements being made to increase yields and reduce the requirement for labour. For example, a conservative estimate of the annual running cost of the on-growing phase alone equalled the market value of the lobsters produced, and the capital costs of building our tank systems were some ten times higher. Labour accounted for 70–80% of the running costs.

The research needed on the biological problems associated with survival and growth should not be underestimated, although their solution will directly affect basic feasibility rather than costs. As a result of our experience at Conwy we feel that basic biological studies are required on:

(a) establishment of 'safe' levels of metabolic wastes, and the maintenance of optimum conditions over long periods in recycled water;
(b) determination of the effects of variation in the natural sea water supply;
(c) assessment of the nutritional value of the fresh food diets used at Conwy and development of a suitable artificial diet;
(d) pathology of lobsters, including disease studies.

A number of other aspects where further research and development are considered desirable were highlighted by our study and are described in sub-sections 4.1–4.3.

4.1 Broodstock and supply of larvae

Obtaining sufficient numbers of broodstock females carrying eggs at an appropriate stage of development was sometimes difficult from January to April because of reduced commercial fishing activity.

Breeding from captive stock was achieved but to adopt this method would require large areas of tank space for broodstock maintenance, and results to date have been sporadic (Wickins, 1983).

Although no precise records were kept, it was felt that prolonged incubation at the elevated temperatures needed to induce out-of-season spawning adversely affected the viability of eggs and possibly larvae. In general, the larger hatches and best survival of larvae occurred between April and September close to the natural breeding season, when incubation periods in the laboratory were short. To produce the out-of-season broods, perhaps it would have been better to retard egg development rates by cooling during incubation rather than to accelerate them by heating.

4.2 Larvae culture

An overall survival rate of 10% among larvae was adequate for the present study, as only 80 juveniles were needed from each batch. Those selected for on-growing were the first to reach stage 4 successfully. The juveniles which developed more slowly tended to be smaller, were sometimes unable to free themselves from the cast skin at moulting, and occasionally lost one or both claws. High mortalities during stages IV and V have also occurred in lobster hatcheries in France (Y. Henocque, personal communication) and were thought to be mainly associated with slow-developing larvae. We believe that a diet of live *Artemia,* although expensive, would have alleviated this problem.

4.3 On-growing

The two most important aspects of on-growing that require further research and development if large-scale lobster culture is to progress are container design and diet/feeding.

4.3.1 Container design

Lobsters are cannibalistic at all stages of their life cycle, but it is practicable to rear them individually only from stage IV onwards. Attempts have been made to grow juveniles communally from stage IV to about 6 months old in America (Carlberg *et al.*, 1979) and in Japan (Y. Henocque, personal communication), but the methods seem to depend upon the provision of such considerable numbers of shelters that stock assessment and husbandry is impaired. Some workers have suggested that surgical and hormonal treatments might be effective in reducing losses in communally-reared juveniles (Aiken and Young-Lai, 1981; Kendall *et al.*, 1982) but these methods are unlikely to be publicly acceptable in the U.K.

Since we were dealing with batches of only 80 lobsters, early individual confinement was entirely practical. The size of each individual container, and the number of different sizes to be used, are important aspects of system design. If the individual containers are too small, growth and survival will be adversely affected; if too large, expensive space will be wasted. The actual shape of the container does not appear to be as critical as the floor area available (Shleser, 1974) and, for practical purposes, squares and rectangles are often more suitable for container fabrication. Ideally, the lobster should always be maintained in the optimum container size (Richards, 1981) but this would require many different sizes of container with frequent transfer of each animal. Holding each lobster in the optimum size of container for a market-sized animal would result in excessive use of space during the early stages.

Preliminary experiments at Conwy showed that the slower growth of lobsters grown in containers that were too small was brought about by a reduced growth rate from an early stage, rather than by a sudden limitation after a period of normal growth (Richards, 1981). This was an important finding since it indicated that over-zealous space saving was likely to be a false economy. Our lobsters were transferred to larger containers when they had reached a size for which the container they were in was optimal (Richards and Wickins, 1979). This did not represent the most economic use of space but ensured that the growth-rate was not affected by the container size. In fact, for the majority of the time, the amount of space provided was probably in excess of the optimum values. Of far greater importance was the considerable labour involved in feeding and cleaning individually-held lobsters, and we believe that the design of a satisfactory production plant will include the following features:

(a) adequate water exchange with automatic flushing of detritus;
(b) arrangement and design of individual containers for maximum space utilisation and adequate stock inspection;
(c) limited number of container sizes to reduce manufacturing costs;
(d) facilities to transfer lobsters, or to enlarge containers easily, as few times as possible in order to reduce both labour costs and unnecessary stress;
(e) automatic feeding.

These design problems fall largely within the provinces of hydraulic and materials engineers; solution of them will substantially affect costs (Van Olst *et al.*, 1977; Mickelsen *et al.*, 1978).

4.3.2 Diet and feeding

The diet of fresh mussel and frozen shrimp was chosen for lobsters because it gave good growth and survival among fourteen other species of Crustacea reared at Conwy (Wickins, 1982). Such a diet is never likely to be economic and a dry, compounded diet mechanically dispensed is a prerequisite for a successful intensive culture system. Considerable effort has been expended, particularly in North America, on the formulation of lobster diets (Conklin, 1980. Conklin *et al.*, 1980; Bayer and D'Agostino, 1980; D'Abramo *et al.*, 1981; Conklin *et al.*, 1983).

The amount of food consumed each day by 10 g lobsters varied from 0 to about 5% of the body weight per day through the moult cycle (Richards and Wickins, 1979). It was impracticable, therefore, to feed a consistently appropriate ration to each individual and, in practice, the daily ration size was determined from the average weight of all the lobsters in a batch. This meant that smaller than average animals were often overfed and that the larger than average lobsters were underfed. Clearly, there is a need for further study, of the effects of ration size and feeding frequency on lobster growth and survival.

4.4 Harvesting

At the time of the culture project, lobsters were legally marketable once they had achieved 80 mm carapace length. In 1981 the minimum size of a saleable lobster was increased to 83 mm and it may yet be raised to 85 mm. We judge that this will effectively increase the time required for on-growing by 6–12 months. Premium prices are paid for 1–1¼ lb lobsters (86–93 mm carapace length).

Lobsters, however, are not suitable for eating until the shell hardens and the flesh has been fully reconstituted. The time this takes depends on diet and culture conditions and may delay harvesting for as long as 2–3 months beyond the nominal growth period of 2–2½ years.

4.5 The future

At present, the high cost of creating a controlled environment and of maintaining and feeding individually housed lobsters remains an obstacle to commercial lobster culture (Anon, 1980; Wickins, 1982). Any future progress to overcome these problems will probably depend upon the financial initiative and inventiveness of industrial entrepreneurs. In the meantime, however, our lobster culture experience is being applied in a study of the prospects for enhancing our natural lobster resources by restocking selected coastal areas with hatchery-reared, internally-tagged, juvenile lobsters (Anon, 1982; Wickins, 1983).

5. References

AIKEN, D. E. and YOUNG-LAI, W. W., 1981. Dactylotomy, chelotomy, and dactylostasis: methods for enhancing survival and growth of small lobsters (*Homarus americanus*) in communal conditions. Aquaculture, *22*: 45–52.

ANON, 1980. High cost is still an obstacle to lobster culture. Fish Farmer, *3* (4), 40–41.

ANON, 1982. New techniques look set to boost production in lobster fisheries. Wld Fishg, *31* (11), 37.

BAYER, R. C. and D'AGOSTINO, A. (Eds.), 1980. 1980 Lobster Nutrition Workshop Proceedings, January 15 and 16. University of Maine at Orono. Tech. Rep., Maine Sea Grant Publs, (58), 57 pp.

CARLBERG, J. M., VAN OLST, J. C. and FORD, R. F., 1979. Potential for communal rearing of the nephropid lobsters (*Homarus* spp.). Proc. 10th Ann. Meet. Wld Maricult. Soc., Honolulu, Hawaii, 22–26 January, Louisiana State Univ., Baton Rouge, 840–853.

CONKLIN, D. E., 1980. Nutrition. pp. 277–293. In: Cobb, J. S. and Phillips, B. F. (Eds.), Biology and Management of Lobsters, Vol. 1. Academic Press, London, 463 pp.

CONKLIN, D. E., D'ABRAMO, L. R., BORDNER, C. E. and BAUM, N.A., 1980. A successful purified diet for the culture of juvenile lobsters: the effect of lecithin. Aquaculture, *21*: 243–249.

CONKLIN, D. E., D'ABRAMO, L. R. and NORMAN-BOUDREAU, K., 1983. Lobster nutrition. pp. 413–423. In: McVey, J. P. (Ed.), Handbook of Mariculture. *1*: Crustacean Aquaculture. CRC Press, Boca Raton, Florida, 442 pp.

D'ABRAMO, L. R., CONKLIN, D. E., BORDNER, C. E. BAUM, N. A. and NORMAN BOUDREAU, K. A., 1981. Successful artificial diets for the culture of juvenile lobsters. J. Wld Maricult. Soc., *12*: 325–332.

HEPPER, B. T. and GOUGH, C. J., 1978. Fecundity and rate of embryonic development of the lobster, *Homarus gammarus* (L.), off the coast of North Wales. J. Cons. int. Explor. Mer, *38:* 54–57.

HUGHES, J. T., SHLESER, R. A. and TCHOBANOGLOUS, G., 1974. A rearing tank for lobster larvae and other aquatic species. Progve. Fish. Cult., *36*: 129–132.

KENDALL, R. A., VAN OLST, J. C. and CARLBERG, J. M., 1982. Effects of chelae immobilization on growth and survivorship for individually and communally raised lobsters, *Homarus americanus.* Aquaculture, *29*: 359–372.

MICKELSEN, R. W., INFANGER, R. C. and HECKMANN, R. A., 1978. Culturing the American lobster (*Homarus americanus*) using a vertically stacked cage system. Proc. 9th Ann. Meet. Wld Maricult. Soc., Atlanta, Georgia, 3–6 January, Louisiana State Univ., Baton Rouge, 723–730.

MURRAY, A. J., 1981. Metals, organochlorine pesticides and P. C. B. residue levels in fish and shellfish landed in England and Wales during 1975. Aquat. Environ. Monit. Rep., MAFF Direct. Fish. Res., Lowestoft, (5), 7 pp., appendices.

NICHOLS, J. H. and LAWTON, P., 1978. The occurrence of the larval stages of the lobster *Homarus gammarus* (Linnaeus 1758) off the north east coast of England in 1976. J. Cons. Int. Explor. Mer, *38*: 234–243.

PORTMANN, J. E., 1979. Chemical monitoring of residue levels in fish and shellfish landed in England and Wales, 1970–73. Aquat. Environ. Monit. Rep., MAFF Direct. Fish. Res., Lowestoft, (1), 21 pp., appendices.

RICHARDS, P. R., 1980. Prawn culture and lobster culture. Pt 2: Lobster culture. Proc. Ann. Conf., Shellf. Assoc. G.B., (11), 10-23.

RICHARDS, P. R., 1981. Some aspects of growth and behaviour in the juvenile lobster, *Homarus gammarus* (Linnaeus). Ph.D. Thesis, University College of North Wales, 209 pp.

RICHARDS, P. R. and WICKINS, J. F., 1979. Ministry of Agriculture, Fisheries and Food lobster culture research. Lab. Leafl., MAFF Direct. Fish. Res., Lowestoft (47), 33 pp.

SHLESER, R. A., 1974. The effects of feeding frequency and space on the growth of the American lobster, *Homarus americanus*. Proc. 5th Ann. Workshop Wld Maricult. Soc., Charleston, South Carolina, 21–25 January, Louisiana State Univ., Baton Rouge, 149–155.

STROUD, G. D. and DALGARNO, E. J., 1982. Wild and farmed lobsters (*Homarus gammarus*). A comparison of yield, proximate chemical composition and sensory properties. Aquaculture, *29*: 147–154.

UTTING, S. D., 1983. Watch on water to save oysters. Fish Farmer, *6* (2), 6–7.

VAN OLST, J. C., CARLBERG, J. M. and FORD, R. F., 1977. A description of intensive culture systems for the American lobster (*Homarus americanus*) and other cannibalistic crustaceans. Proc. 8th Ann. Meet. Wld Maricult. Soc., San José, Costa Rica, 9–13 January. Louisiana State Univ., Baton Rouge, 271–292.

WICKINS, J. F. 1982. Opportunities for farming crustaceans in western temperate regions. pp. 87–177. In: Muir, J. F. and Roberts, R. J. (Eds.). Recent Advances in Aquaculture. Croom-Helm, London, 453 pp.

WICKINS, J. F., 1983. On the track of profits from lobsters. Fish Farmer, *6* (1), 20–21.

WICKINS, J. F. and HELM, M. M., 1981. Sea water treatment. pp. 63–128. In: Hawkins, A. D. (Ed.), Aquarium Systems. Academic Press, London, 452 pp.