Fisken og havet, nummer 6 - 2004

Development of methods for intensive farming of European lobster in recirculated seawater

Results from experiments conducted at Kvitsøy lobster hatchery from 2000 to 2004

Tore S Kristiansen, Asbjørn Drengstig, Asbjørn Bergheim,
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ISSN 0071 - 5638

PROSJEKTRAPPORT

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Distribusjon: Åpen
HI-prosjektnr.: 140402
Oppdragsgiver(e): Norwegian Lobster Farm AS
Oppdragsgivers referanse:

Dato: 10.05.04
Program: Havbruk
Forskningsgruppe: FG -16 Fiskevelferd og oppdrettsmiljø
Antall sider totalt: 52

Rapport: FISKEN OG HAVET
Nr. - År 6 - 2004

Tittel (norsk/engelsk):
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Sammendrag (norsk):
Et brukerstyrt prosjekt med mål om å evaluere potensialet for intensiv produksjon av porsjonshummer i resirkulert sjøvann har blitt gjennomført ved Kvitsøy hummerklekkeri i regi av selskapet Norwegian Lobster farm AS. Prosjektet har omfattet av utprøving av ulike enheter for oppdrett av hummer i enkeltbur, testing av vannkvalitet, vekstforsøk under ulike betingelser (diett, substrat, areal), evaluering av fôr med ulik mengde astaxanthin (pigment), utvikling av prototyper for storskala produksjon, karakterisering av hummer vha billedanalyse, markedsundersøkelser og testing av av produktkvalitet.

Summary (English):
The goal of this project has been to evaluate the biological, technical and economical potential for production of plate sized lobsters in recirculated sea water. The project was carried out at Kvitsøy lobster hatchery and has been led by the company Norwegian Lobster farm AS. The experiments have included studies of various rearing units, water quality, growth rates, rearing environment, testing of feed (fresh,dry, astaxanthin contents), development of prototypes for large scale production, characterisation of lobsters by image analysis, market studies and testing of product quality

Emneord (norsk):	Subject heading (English):
1. hummeroppdrett	1. lobster aquaculture
2. resirkulert sjøvann	2. recirculated sea water
3. diett	3. diet

ISSN 0071 - 5638

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prosjektleder

forskningsgruppeleder

Development of methods for intensive farming of European lobster in recirculated seawater

Results from experiments conducted at Kvitsøy lobster hatchery from 2000 to 2004

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Contents

TECHNICAL DRAWINGS ARE PREPARED BY TORMOD DRENGSTIG. PHOTOS BY ASBJØRN DRENGSTIG, RUDOLF SVENSEN AND EVA FARESTVEIT.

Idi Amin II – One of the two first portion sized lobsters produced at Kvitsøy lobster hatchery in 2001 – here weighing approximately 150 g. Lobsters with this patterned pigmentation is a type of lobster called "Scotsmen" by the local fishermen, and are believed to be descendant of imported live lobsters from Scotland

Preface

The present project was initiated in 2000 and has been managed by Norwegian Lobster Farm AS in Stavanger in close co-operation with the Institute of Marine Research, Stavanger University College and RF-Rogaland Research. In addition, the Norwegian Institute of Fisheries and Aquaculture Ltd. (Bergen division) contributed with feed formulation. Moreover, several private companies contributed to the project. These were Procean Technology AS, HOBAS Tropical Aquaculture AS, Stavanger Rørhandel AS, BioServe AS, ITT Flygt, Synergia AS and AC DesignTech AS. We are indebted to these companies.

The entire R&D project was partial funded by the Norwegian Industrial and Regional Development Fund (SND-Rogaland). Moreover, Rogaland Regional County contributed with financial support to develop a feed formulation and to conduct the formulated feed experiments. We are especially grateful to Knut N. Nilsen at SND-Rogaland (Innovation Norway) and to Johan Livastøl at Rogaland Regional County for valuable support.

The research assistance from the Institute of Marine Research in 2001 was financed by the FUNN program (Norwegian Research Council). This was originally a project financed for three years, but due to change in the governmental policy, the FUNN program was terminated after only one year. Since this part of the project lost its financial support, the scientific results are more limited than originally planned.

Norwegian Lobster Farm AS is currently in a transfer phase between research and development, and semi-commercial production. During the project, the company has developed and patented a new innovative farming solution for cannibalistic crustaceans. The new technology has lower investment costs, enables higher densities and is more area-intensive than other known production technologies available. Thus, the company is now in position to build a land-based plate sized lobster factory under highly viable commercial terms. Moreover, the results from the present project have generated an exceptional opportunity to establish a new aquaculture industry both in Norway and internationally. The new technological concept will be commercially available in 2005 after thorough testing and documentation in 2004.

Reference to this report is given as:
Kristiansen, T. S., A. Drengstig, A. Bergheim, T. Drengstig, R. Svensen, I. Kollsgård, E. Nøstvoll, E. Farestveit & L. Aardal (2004). Development of methods for intensive farming of European lobster (*Homarus gammarus* L.) in recirculated seawater. Results from experiments conducted at Kvitsøy lobster hatchery from 2000 to 2004. Fisken og Havet, 6 - 2004: 52 pp.

Bergen, 7 May 2004

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Summary

The European lobster, *Homarus gammarus*, is today one of the most valuable and preferred seafood in the world. The goal of this project was to evaluate the potential of producing the European lobster in land-based facilities using re-circulation of seawater. However, in order to do this, it was necessary to start the development almost from scratch, since there was no suitable technology, no formulated feed, no proper market studies and finally little documentation on farming of lobster in re-circulated seawater. It was also considered important to actually produce portion-sized lobsters to get hands-on experience with production methods in order to identify bottlenecks and risk factors, and not least to be able to document the culinary quality of the product for customers and investors.

The experiments were conducted at Kvitsøy, in southwestern Norway at a lobster hatchery rented from Kvitsøy municipality. The hatchery consisted of a hatching and an on-growing section, that were equipped with sea water pumps, mechanical water filtration units, ultra violet filters, recirculation systems with bio-filters, titanium heaters, header tanks, rearing tanks, larval incubators and accessories. The building was insulated to prevent heat loss. The total water volume in the system has varied between 19 – 30 m^3 dependent on the various rearing tanks employed. Three recirculation loops supplied 100 l/min of filtered (30µm) and aerated 18 – 20ºC seawater each. The fluidised bed bio-filters were heavily aerated by air ejectors driven by the recirculation pumps. One litre per minute of UV-treated seawater was added per loop, corresponding to approximately one complete renewal of the seawater in the loop each week. The monitored water quality parameters were all within the ranges reported optimal for lobster.

Six different systems and concepts for rearing of juvenile lobsters were tested, and the practical experiments have revealed important risk factors and design details. One of the systems, a stack system for industrial rearing of lobsters at high densities, has been patented. Based on these results a new system for high density rearing in deep tanks have been developed and patented and is now under testing.

The rearing trials with juvenile lobsters in single compartments included studying the effects of rearing substrate, shelter, rearing space, feed types and family variations. Berried females were bought from local fishermen the previous fishing season and stored in a lobster park. When the eggs were close to hatching, the females were transferred from the sea to the hatching tanks. The larvae selected for ongrowing were reared in 40 L upstream incubators and were fed frozen *Artemia* and frozen mysids twice a day. When they reached the IV-stage the larvae were transferred from the incubators to the individual rearing units. Lobsters reared the three first months in individual compartments with sand substrate and fed a rotational diet of fresh crustaceans had the best growth rates, but also lobsters given dry marine fish feed, and only a little supplement of frozen crustaceans once a week, had relatively high growth rates and survival. There were also significant effects of family on growth rate. Around 90% of the lobsters reared with sand-substrate and/or given an empty shell as shelter developed crusher claws. Sand substrate had a strong positive effect on survival in communal tanks. We found no significant effect of compartment size in the studied size intervals.

The growth rates of the lobsters reared under the best conditions were equal to the best growth rates published from other studies. The production time from hatching to portion sized lobster were estimated based on growth trials with larger juvenile lobsters, and was estimated to be between 800 to 900 days. The large juveniles grew well on dry marin fish feed, but lost their pigmentation. By adding 50 mg or more astaxanthin to the feed the lobsters changed colour from almost transparent to dark blue after few moults. With this feed, average feed conversion

rate was as low as 1.0-1.17. Moreover, the newly hatched larvae maintained natural pigmentation in addition to obtaining good growth rates and high survival during the pelagic stages. Further development of lobster feed is however necessary to obtain the better growth rates and improved product quality.

The market studies support the establishment of controlled land-based factories to supply and meet the existing demand in the market. Prices vary between markets, but the so-called emerging markets in the high end segment seem to have a lucrative potenstial. However, at the current price level of approximately 200NOK/kg, the global market demand was quantified:

- Frozen plate-sized lobster: 50,000 MT annually
- Fresh, bigger (> 500 g) lobster: 1,000 MT annually
- Live lobster (≥ 250 – 300 g): 60,000 – 70,000 MT annually

It was also detected that continuous deliveries could actually increase both price and quantity demand in the market.

Results from the culinary tests were indeed positive, however, a minor drawback was the lack of natural pigmentation. Nevertheless, the representatives from various restaurants and the Culinary Institute want to commercialise this product in the market. Thus, a new test is planned in 2004 were the lobsters with natural pigmentation after being fed the newly developed feed will be included.

Norwegian Lobster Farm is now building a prototype of a patented system for intensive rearing of lobsters (IV-stage up to 300 g) that will be tested and evaluated in 2004-2005.

1 Introduction

The European lobster, *Homarus gammarus*,, is today one of the most valuable and preferred seafood in the world. Despite a vast distribution from Northern Norway to Greece, the annual landings are only 2,000-2,500 metric tons (MT), mainly from Ireland and Great Britain. The Norwegian lobster fishery has an almost four hundred years tradition (Boeck 1869; Dannevig 1936; Jørstad *et al.* 2001a), with a record catch exceeding 1300 tonnes in 1933. Norway was before 1960 one of the major fishing areas for European lobsters, but between 1960 and 1980 the landings declined by more than 90% to only around 50 tonnes (Dow 1980; Jørstad *et al.* 2001a). The lobster stocks in Norway have since not recovered and the spawning stock is probably at a historical low and critical level.

The other Atlantic clawed lobster species, the American lobster, *Homarus americanus*, is distributed along the eastern coast of USA and Canada, from Virginia to Labrador. The lobster fishery is the most valuable fishery on the Atlantic coast of both the United States and Canada. In 2002 37,000 tons and 45,000 tons of American lobster were landed in USA and Canada, respectively (http://www.st.nmfs.gov/st1/fus/current/02_commercial2002.pdf; http://www.dfo-mpo.gc.ca/media/infocus/2003/20031205/shellfish_e.htm). The lobster is exported to more than 50 countries, as live, fresh and frozen products. The two *Homarus* species have a very similar morphology, but the European lobster is more valued. This may be due to its scarceness, however, most consumers consider the European lobster to be a better product with a superior taste. Nevertheless, there is a worldwide market demand for lobsters today, and especially the European lobster is subject to ever increasing prices and demand in the market.

1.1 Lobster biology

The European Lobster and the American Lobster are the two members of the genus *Homarus*; distinctively recognized by their large anterior claws. The largest documented American lobster was caught in Nova Scotia and this specimen was more than 44 pounds (20 kg) and believed to be 100 years old (Hughes 1968). There are no exact methods to measure age in lobsters. The European lobster record is 10 kg, a lobster caught on the western coast of Norway. Clawed lobsters are generally solitary animals, hiding in burrows under stones or in crevices between rocks, and are both aggressive and cannibalistic if kept at high densities. As all crustaceans the lobster has a stepwise growth. Growth in size occurs when they shed their external shell with subsequent uptake of seawater before the new shell hardens. The rate of growth is a function of the frequency of moulting and the increase in size at each moult. Temperature is the main regulating factor and optimal temperature for growth is around 20°C. The lobsters do not feed during the coldest Norwegian winter months (January - March) and growth only occurs during summer (April – September). Due to these seasonal patterns, growth is slow and it may take anywhere from 5 to 9 years to reach legal size of 25cm total length (ca. 450 g), depending on environmental conditions, food availability and social interactions (Agnalt *et al.* 2001, in press).

In western Norway, the female lobster matures at around 80 mm carapace length (23 cm total length) and has usually a two-year spawning and moulting cycle. The mating occurs usually in late summer just after moulting when the shell still is soft. The males transfers the sperm “packages” to the females oviducts, where the sperm is stored for almost a year until the next autumn when the females spawn and fertilize their eggs and attach them between the pleopods under their tail. The eggs develop slowly and needs around 11 months before hatching (dependent of temperature). In Norway the main hatching season is in July – August. After hatching, the females moult and mate again.

The first three stages after hatching are spent in the free water masses (pelagic stages), where they prey on copepods and other plankton organisms. At the fourth moulting stage, when they metamorphose to miniature clawed lobsters, they settle at the bottom and hide in the bottom substrate where they live a very cryptic life the next 2 – 3 years. Almost no wild lobsters less than 10 cm have been observed in Europe and their ecology in this period is practically unknown (Mercer *et al.* 2001). To reach a size of 300g (75 mm carapace length), they have to moult around 20 times after settling at the bottom. After settling the lobsters are very stationary and live within a range of few thousand meters the rest of their life.

1.2 Lobster aquaculture

Lobster aquaculture can be conducted in three forms: resource enhancement, product enhancement and full grow out. Interest in the resource enhancement aspect began more than a century ago and many hatcheries were built in Europe and North-America for the purpose of hatching eggs and releasing I or IV stage larvae into the wild (Nicosia & Lavalli 1999). In product enhancement, lobsters are kept in captivity in holding pounds and fed until their quality or prices increases (Aiken & Waddy 1995). Full grow out or closed-cycle culture is independent of fishery and involves rearing of lobsters from egg to market size. Interest in full grow out culture peaked in the 1970s, when government funded research programs on intensive culture of American lobster were conducted in USA and Canada. As a result of this research and earlier studies, lobster biology is reasonably well understood (Factor 1995), seed stock can be produced on demand, and systems and strategies are in place for rearing lobster from larvae to market size (see reviews by van Olst *et al*. 1988; Aiken & Waddy 1995; Nicosia & Lavalli 1999). Several private companies in America started lobster production, but none of these projects proved to be commercially viable (Nicosia & Lavalli 1999). A large increase in landings of wild lobsters and an abrupt termination of governmental research programs before rearing technology and formulated lobster feeds were sufficiently developed contributed to this scenario (Aiken & Waddy 1995). Besides, the necessary computer and automation technology was too poorly developed in the 1970 – 1980s to achieve a sufficient automation level at a reasonable production costs. However, during the 1990s there were some significant breakthroughs in the development of automation and land-based aquaculture technology. Especially in the field of recirculation technology major progress occurred, making land-based aquaculture using heated water more economical realistic. Today, there are no commercial land-based lobster farms in America due to too high production costs.

Compared to other lobster species, the *Homarus* species are considered very hardy with a simple and abbreviated larval period. They feed readily on natural and artificial feeds, are resistant to disease and exhibit a very rapid and accelerated growth in warmed water (van Olst *et al*., 1980). Thus, temperature is the primary controller of growth and optimum water temperature has been found to be 20 – 22^{o}C (van Olst *et al*. 1980; Richards 1981; D'Abramo & Conklin 1985; Waddy 1988; Aiken and Waddy 1995). Larval period in 20^{o}C water is around 12 days (Waddy 1988) compared to 35 days at 15^{o}C (van Olst *et al*. 1980). Furthermore, *H. gammarus* can reach 250-300g (total length 210 mm; carapace length 75mm) in 24-30 months as long as constant 20^{o}C water is provided (Wickins & Beard 1991). The extreme difference in growth rate experienced in heated seawater is a result of removing winter growth inhibition allowing for year-round growth and moulting.

Factors that influence growth in lobsters include handling, stocking density, habitat size, social interactions and water quality (Aiken & Waddy 1995). Because of large growth variation and high losses due to cannibalism and injuries when kept communally, the cultured lobsters have to be kept in individual containers. Communal rearing has been used in grow-out of juveniles, however due to uneven growth rates and high mortalities, the practice is not recommended in

intensive culture, but may be a method for producing predator trained small juveniles for release (Jørstad *et al.* 2001a; *Kristiansen et al. 2002*[*]).

Several different methods have been developed for culturing lobsters individually. All of them attempt to provide a separate compartment for each lobster, a constant supply of oxygen saturated seawater to each individual, a method of providing food and removing solid and dissolved wastes, and in general an environment that will promote rapid, uniform growth and high survival (van Olst *et al*. 1980; Grimsen *et al*. 1987). Aiken & Waddy (1995) characterise and summarise the technological development like this: "The ideal tank for rearing lobsters individually would be inexpensive to construct and operate and simple to maintain. It would be self-cleaning, use space in three dimensions, conserve water, and permit access to the livestock for inspection and feeding. So far, no one has successfully incorporated all of these features into a single design". Bottlenecks for commercial culture of lobsters have also been lack of high quality dry feed and technology that can solve the problems related to rearing in individual containers in an effective and profitable way.

Production of lobster juveniles for sea-ranching and stock enhancement has again high actuality in Norway. In the early 1980s the Tiedeman company established a factory for large scale production of lobster juveniles for sea ranching in Norway, but due to lack of legal protection of released lobsters the company gave up the idea and handed over the hatchery to Institute of Marine Research (IMR) in 1989. During the 1990's IMR conducted a research program on lobster sea-ranching which gave promising results (Agnalt *et al*. 1999; in press) and a new law ensuring property rights to released sedentary invertebrates was approved by the Norwegian Parliament in 2000 and put into effect 1 January 2004. This law ensures exclusive harvesting rights in specific areas for decapods, molluscs and sea urchins to persons holding a proper license. This new act has promoted an increasing commercial interest in lobster sea-ranching in Norway, and several companies are now ready to apply for licenses and start commercial sea-ranching. Deadline for applications was 26 April 2004. An important prerequisite for sea-ranching success is, among others, access to a large amount of cheap and high quality lobster juveniles for release.

1.3 Risk of disease in aquaculture

With more than a century of experimental and commercial hatchery operations only a few incidents of disease have been recorded (van Olst *et al*. 1980). Intensive culture does however increase the chance for, and diversity of, potential disease outbreak. High temperatures, possible physiological stressors, periods with poor water quality and inadequate nutrition are predisposing factors for disease (Waddy 1988). Normally, the use of recirculation in aquaculture represents an environmentally friendly production method that ensures stable water quality and proper welfare of fish and shellfish. However, once a disease is introduced into a closed circulation system with high stocking density and circulation of water, a more rapid infection rate may occur. The most predominant lobster disease is *Gaffkemia*, a filamentous bacterial disease of larva, shell disease and two fungal diseases (van Olst *et al.* 1980, Jørstad *et al.* 2001b). Disease is best avoided in aquaculture systems through preventive action and a thorough control over the key water quality parameters. The present project has developed protocols for water management and mitigating measures in order to reduce the risk of disease outbreaks during culture (Drengstig in prep.). Moreover, brood-stock should be quarantined before being introduced into the facilities and proper water quality, adequate feeds and minimal stress should be provided. As such, disease should not be a problem in a well-managed re-circulation system (van Olst *et al*. 1980; Waddy 1988).

[*] *References written in cursive are found in the list of reports from the project.*

1.4 The "Plate sized lobster project" at Kvitsøy

During the last two decades with experiments with juvenile production and sea-ranching of lobster in Norway, significant know-how has been revealed related to lobster juvenile production and lobster biology and ecology. In addition, the recent development of intensive aquaculture methods based on re-circulation of seawater and low cost industrial automation technology have opened up new possibilities for solving the special demands related to lobster farming (Agnalt *et al.* 1999; Wickins & Lee 2002; KPMG 2003; *Drengstig et al. 2002*; *Drengstig & Drengstig 2003*). Norwegian Lobster Farm AS initiated in 2000 the first R&D project in Norway on land-based production of plate-sized lobsters. The aims of the project were to evaluate the potential of producing the European lobster in land-based facilities using re-circulation of seawater. However, in order to be able to evaluate this, it was necessary to start the development almost from scratch, since there was no suitable technology, no formulated feed, no proper market studies and finally little documentation on re-circulation of seawater as a production method for farming plate sized lobsters. It was also considered important to actually produce portion-sized lobsters to get hands-on experience with production methods in order to identify bottlenecks and risk factors, and not least to be able to show the product to investors and financing institutions and document the culinary quality of the product.

The project has included studies of the following areas and activities:

- build-up of the hatchery and preparing the hatchery for small scale ongrowing study trials
- general maintenance, feeding of lobsters, cleaning of cages, pipes and tanks, weighing and measuring
- documentation of the relationship between growth and rearing environment, feed, and family
- estimation of production time to market size
- documentation of recirculation of seawater as a production method for lobster and monitoring of the water quality dynamics is such systems
- water management – mass balance
- quantification of Food Conversion Ratio (FCR)
- quantification of oxygen consumption rates and excretion rates
- development of a new formulated feed including revealing the necessary pigment content in a dry feed diet for lobsters
- development and testing of severeal new farming technologies
- software development
- development of larval selection robot, feeding robot and harvesting robot
- development of image processing programmes
- market studies
- culinary analysis
- health management and veterinary training
- trace systems for food safety
- establishment of a national network for lobster farmers
- development of business plan for a lobster factory with an annual capacity of 15 MT (metric tons)
- technical and biological dimensioning of the 15 MT factory
- visualising the factory through 3 dimensional drawings

This report presents the experiment and the results obtained in the period 2001-2003. Some of the results have already been published else where, however, summaries of these results are

included (i.e. water quality, re-circulation, feed development, market studies, automatic farming procedures, image processing, etc.). Thus, the report is sectioned in chapters, where each activity is presented and discussed separately. The report also includes presentation of future challenges and prospects for industrial development. For further information, contact the corresponding author.

1.5 Research and innovation price 2002

Norwegian Lobster Farm AS received the Research and Innovation Award 2002 for Rogaland County in 2002. The price was awarded by Rogaland Regional County, RF-Rogaland Research and NHO-Rogaland.

2 Kvitsøy Lobster Hatchery

Kvitsøy Lobster Hatchery is located in Fiskernes hus (Fishermen's House) in Kvitsøy harbour (Figure 2.1). The hatchery was established by the Kvitsøy municipality in 1998, and several projects have since been run at the hatchery in cooperation with the Institute of Marine Research. From 2000 and onwards, the hatchery has been managed by Norwegian Lobster Farm AS. The building is 150m^2 and contains a lobster fishery museum, a lobster hatchery with hatching and larval rearing section, and an on-growing section. The hatching and on-growing section are each equipped with water filtration units, bio-filters, titanium heaters, ultra violet filters, header tanks, rearing tanks, larval incubators, and re-circulation pipes, pumps and accessories. The building was also insulated to prevent heat loss, and thus the hatchery is today an advanced technological facility suited to carry out any small-scale scientific experiment.

Figure 2.1. Kvitsøy Lobster Hatchery

The water supply consists of three separate, but interchangeable recirculation loops, each equipped with an embedded biofilter (Eikebrokk 1990) and a 30 micron drum filter (Figure 2.2).

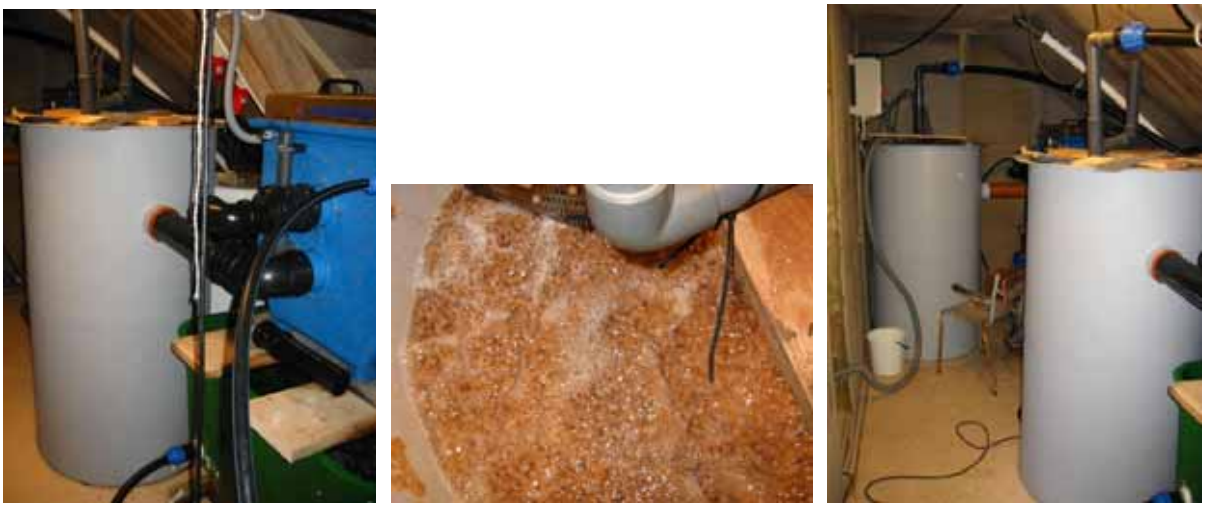


Figure 2.2. The embedded biofilters (BIOFISH^{TM} and Kaldnes plastic media) with air ejector and mechanical filter (Hydrotech)

A principle sketch of the re-cycling loops is given in Figure 2.3. The bio-filters are heavily aerated by air ejectors driven by the recirculation pumps. Each recirculation unit can supply 100 l/min of filtered and aerated 18 – 20ºC seawater. Approximately 1.0 litre per minute of new filtered and UV-treated seawater was added per loop, corresponding to one complete renewal of the seawater in the loop each week. The total water volume in the system has varied between 19 – 30 m^3 dependent on the various rearing tanks employed during the project (the on-growing section has been rebuilt and reorganised three times during the project period). Water temperature was raised and adjusted by titanium heaters equipped with thermostats. The salinity was stable at 33‰.

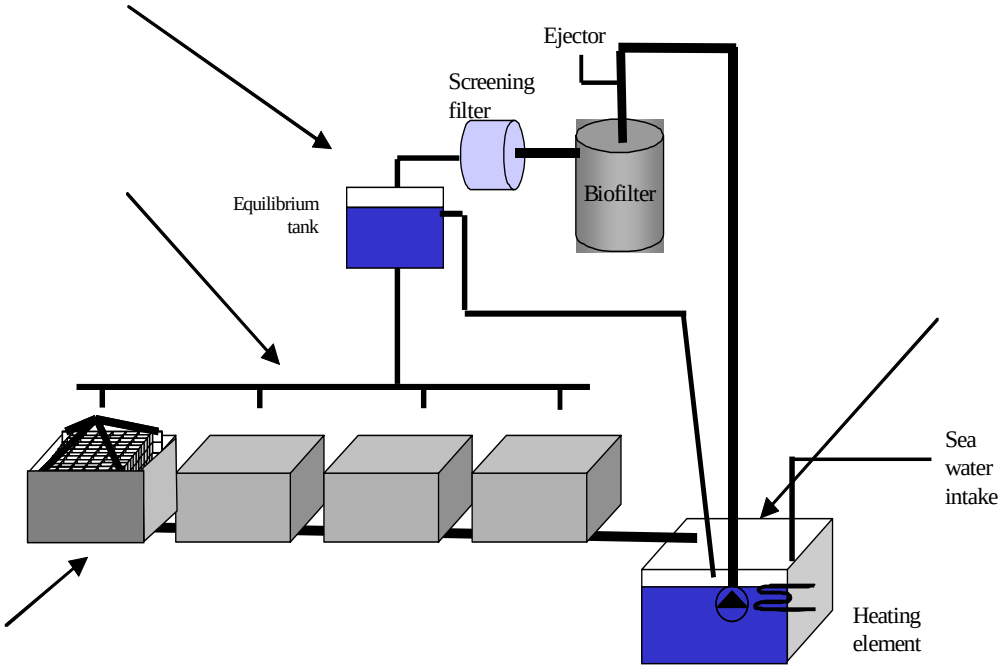


Figure 2.3. Principle layout of a recirculation loop at the lobster hatchery at Kvitsøy. Arrows indicate sampling points for water quality analysis.

3 Water quality

3.1 Introduction

A system that supplies water of good quality is an essential factor if we want to obtain good welfare and growth, and reduce stress and disease. Especially in closed recirculation systems, where there is little or no exchange of water, a build-up of toxic metabolites and reduction in oxygen concentrations may happen very rapidly (Timmons & Losordo 1995). However, re-circulation of water is necessary to reduce heating costs, if no other external warm water supply is available. In any occasion, it is important to understand what the optimal as well as limiting culture conditions are for lobsters. van Olst *et al.* (1980) reviewed the water quality parameters for *Homarus* sp. (Table 3.1) and while the optimal conditions (except for temperature) lies within the natural water conditions of lobsters, they can tolerate relatively extreme environmental fluctuations.

Table 3.1. Desirable levels for key water quality parameters for *Homarus* sp. (van Olst *et al.* 1980; Wickins & Lee 2002)

Parameter	Optimal Condition	Natural Condition	Lethal levels
Temperature (^oC)	18 – 22	1 – 25	<0, >31
Salinity (‰)	28 – 35	28 – 35	<8, >45
Dissolved oxygen (mg/L)	6.4	4.0 -- 7.3	<1, >saturation
pH	8	7.8 -- 8.2	<5, >9
NH_3-N (mg/L)	<0.14	0 -- 0.3	>1.4

Whiteley *et al.* (1990) found lobsters to be tolerable of dissolved oxygen concentration as low as 0.2 mg/l in 5^{o}C seawater (33‰) and 1.72mg/l in 25^{o}C brackish water (20‰). Oxygen supersaturated water has on the other hand been shown to cause serious damage as gas bubbles can develop in the hemolymph and restrict blood flow (Aiken & Waddy 1995). Furthermore, while lobster may tolerate wide fluctuations in salinity, optimal conditions ranges between 28 – 35 ‰ (van Olst *et al.* 1980; Richards 1981; D'Abramo & Conklin 1985), which means that some dilution of seawater may occur (e.g. flushing of mechanical filters with warm freshwater). Ammonia concentration is most likely the most limiting water quality parameter in recirculation systems for seawater, and while the optimal concentration given by van Olst *et al.* (1980) is rather higher than that recommended by D'Abramo & Conklin (1985) (<1.5mg/l), there is no doubt that *Homarus* sp. are more tolerable than most finfish.

3.2 Material and methods

Water quality monitoring during the project (*Drengstig et al. 2003a*) was performed by two YSI-556^{TM} MPS (Multi-Probe-System) instruments. These instruments were used to measure DO, temperature, pH and salinity. Analysis of pH, CO_2 and TAN were conducted at Rogaland Research's certified QA-lab in Stavanger (Norwegian Standard, NS 4720 & NS 4744).

pH readings in-situ were compared with pH values measured in water samples at the laboratory. During specific sub-projects on water quality (*Drengstig et al. 2003a*), water samples were collected from five different points in each of the two recirculation loops for further analysis (Figure 3).

Concentration of free carbon dioxide (CO_2) was calculated from pH, temperature and total alkalinity/bicarbonate alkalinity based on a method described in Standard Methods (1998).

Concentration of un-ionized ammonia (NH_3) as per cent of total ammonia nitrogen (TAN) was calculated according to the following equation:

$$\% \ NH_3 = \frac{100}{(1 + \text{antilog}\ (pKa - pH))}$$

where the dissociation constant, pKa, ranges from 9.09 to 9.90 dependent on temperature and salinity (Alabaster & Lloyd 1982).

3.3 Results and discussion

During these investigations of water quality dynamics, the water quality was found to be favourable for growth of lobster. The emphasised parameters, pH (7.6 – 8.1), temperature (18 – 19°C) dissolved oxygen (> 6.2 mg/L), CO_2 (< 3 mg/L), salinity (33‰), TAN (50 – 300 µg/L) and NH_3 (< 5 µg/L) were all within the ranges reported optimal for lobster (Table 3.1). The results prove that use of recirculation of seawater as a production method for lobsters is highly recommendable.

A limiting water quality parameter in seawater recirculation systems is the concentration of un-ionized ammonia (NH_3). Under optimum conditions for European lobster, NH_3 should be permanently kept below 14 µg N/L. Generally, the NH_3 concentration is a result of the total ammonia excretion in the lobsters and the ammonia removal of the biofilter. In the present trial at low-moderate loading, the removal rate of ammonia (TAN) in the biofilters was found to be 50 – 70% at an inflowing concentration of 100 – 200 µg/L.

In all tanks, the individual weight variation was rather high at stocking (CV: 22 – 34 %) as the lobsters were randomly picked out for the trial. Throughout the test, the individual size variation was gradually reduced in most tanks.

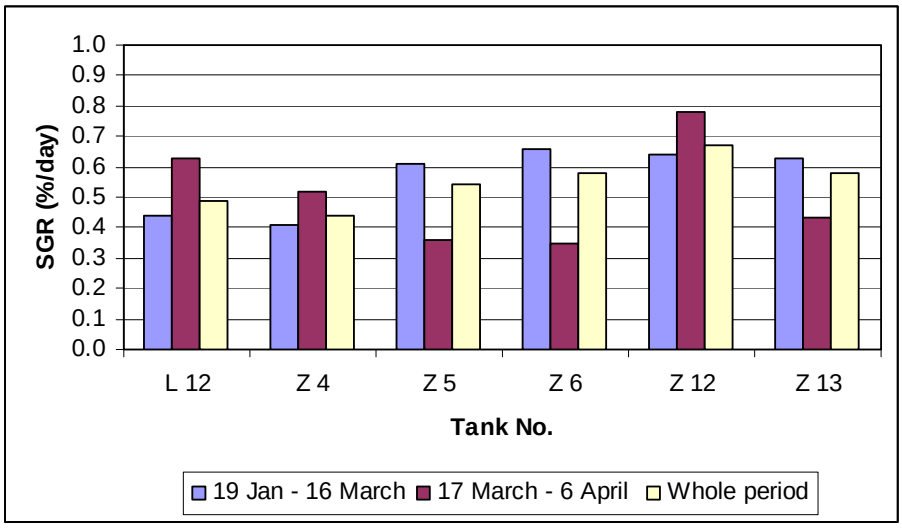


Figure 3.1. Specific growth rate of lobsters in six tanks at Norwegian Lobster Farm's hatchery based on three samplings, 19 January – 6 April 2003

The specific growth rate was calculated for each tank during the three periods (Figure 4). Throughout the whole period, the SGR fluctuated between 0.43 (Z4) and 0.67 %/day (Z12). Typically, the lowest SGR was found in Tank Z4 stocked with the largest individuals (about 2 times the average lobster size of the other tanks).

Lobsters of 10 g initial weight on average doubled their size in two months, while lobsters of 40 g initial weight increased their size by about 50% (to approximately 60 g) in the same period. Most of the small lobsters (<10g) moulted two times during the period, while the larger moulted only one.

Both carapace length (CL) and total length (TL) were measured at start on 19 January 2003 (Figure 3.2). However, calculations showed a consistent ratio between CL and TL with a correlation of 0.97 and, thus, only TL was measured afterwards.

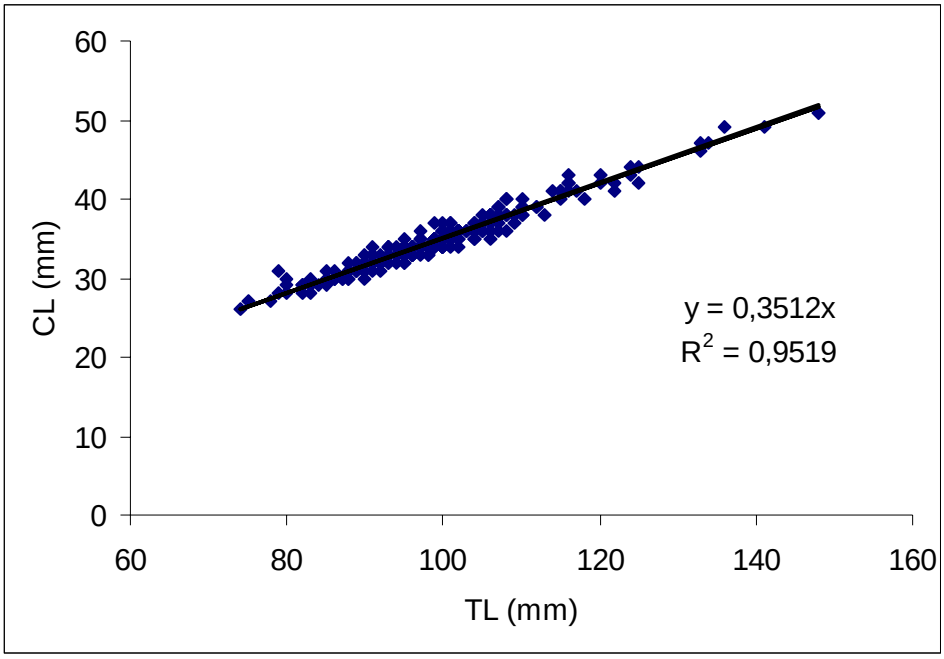


Figure 3.2. Correlation between carapace length and total length

4 Brood-stock and post-larvae production

4.1 Introduction

Keeping a brood-stock from wild caught lobsters is currently the safest way to meet the demand for juveniles in intensive aquaculture. It is however important to ensure that the gravid females are exposed to the correct temperature regime before hatching in order to increase survival of IV-stage larvae. However, according to Aiken & Waddy (1985), the ability to condition wild pre-ovigerous females with a high degree of reliability has been developed which minimises the social and legal opposition to taking berried females from the fisheries. These procedures have been used with success during the current project, and Norwegian Lobster Farm is able to produce IV-stage larvae from February to November.

Lobsters grown rapidly to maturity at 20°C have been shown not to perform well as brood-stock, and both egg production (approximately 5% spawned) and egg attachment were poor (Aiken & Waddy 1995; Wickens & Lee 2002). Moreover, the males produced fewer sperm and spermatophores. Brood-stock should be selected from genetic selection criteria over generations. Control over mating of captive brood-stock utilises either natural copulation between selected animals (which sometimes involves mating with intermoult females) or artificial insemination (Talbot & Helluy 1995). The latter offers little control over egg extrusion and fertilisation. Additionally, eggs spawned after artificial insemination frequently do not attach well to females (Wickens & Lee 2002).

Figure 4.1. Left: A berried lobster female - the eggs turns from black to red before hatching. Right: The lobster park.

4.2 Materials and methods

In this project, berried females were bought from local fishermen the previous fishing season and stored in a lobster park (Fig 4.1). When the eggs were close to hatching, the females were transferred from the sea to the hatching tanks inside the hatchery. The hatching facilities consisted of 16 black polyethylene tanks (70 x 40 x 25 cm; 7.000 cm^3), all with an overflow through a 20 mm water hose leading to separate containers equipped with a filter to retain the larvae (Figure 4.3). The tanks were supplied with 2 – 3 L/min filtered and UV-treated seawater with ambient sea surface temperature**.** Since the larvae hatch mainly in darkness, the light was kept on from 08:00 – 22:00 to concentrate the hatching period and shorten the stay in the larvae collectors.

Figure 4.2. Brood-stock hatching tanks and larvae collectors (left) and incubators for rearing larvae from I-IV- stage (right).

The newly hatched larvae were every morning harvested from the larvae collectors, and the ones selected for on-growing were counted and transferred to 40 L upstream incubators (plankton kreisels; Hughes *et al*. 1974; Figure 4.2) supplied with ca.10 L/min aerated 18 – 20ºC seawater. Only larvae from one female were reared in each larval tank and maximum 1500 larvae were added to each tank. The larvae were fed frozen *Artemia* and frozen mysids twice a day. Although, growth seemed to be slightly inhibited, some successful experiments were also conducted where the newly hatched larvae were fed formulated pellets from day one.

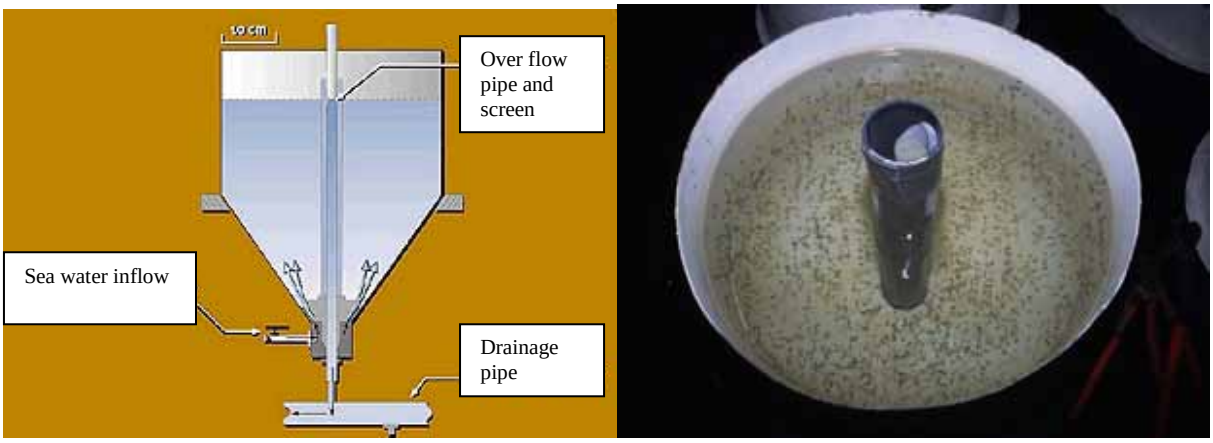


Figure 4.3. Principle sketch and a photo of an upstream larval incubator with lobster larvae

The outflow screens of the incubators were changed every morning and evening due to clogging of *Artemia* on the screen. The larvae needed approximately 12 days before reaching the IV-stage (Figure 4.4). The IV-stage larvae were harvested (one by one) and transferred to individual compartments as soon as practically possible after moulting to the IV-stage to avoid claw loss and cannibalism.

Figure 4.4. Stage I, II, III and stage IV larvae (from upper left to lower right). The relative sizes of the different stages are not correct. Total length of the I-stage larvae is 9 mm, while the IV-stage larvae is 14.5 mm.

5 Testing of different rearing units

5.1 Introduction

Due to the lack of available, adequate and cost effective technology for farming lobster in intensive systems, the project had to include testing and development of various technological solutions to pursue a commercially acceptable farming concept. This concept should incorporate all features described by Aiken & Waddy (1995) into one single design. If such solution were to be achieved successfully, a major step towards a sustainable economical, technological and biological farming concept would be made. During the project a total of six different technological farming solutions were tested, whereof the final solution enables all the required features in one single design (*Drengstig & Drengstig 2003*). This system has been patented.

5.2 The trays

Trays with individual compartments, earlier used in the juvenile production conducted by IMR at Kyrksæterøra, were used as to produce experimental animals in earlier projects conducted by IMR. These units were made of white plastic, with 1mm perforated holes in the bottom. Each compartment was 6x13 cm (78 cm^2), and is suitable for rearing lobsters up to 80 mm TL. The units were originally made for circulating in circular channels (Figure 5.1), where the lobsters were fed when passing a feeding bridge (Grimsen *et al.* 1987; Uglem 1995). These units are easy to inspect and feed, but the water circulation is poor and vulnerable to degradation of water quality if the animals are large or given to much food. The units are also very area demanding.

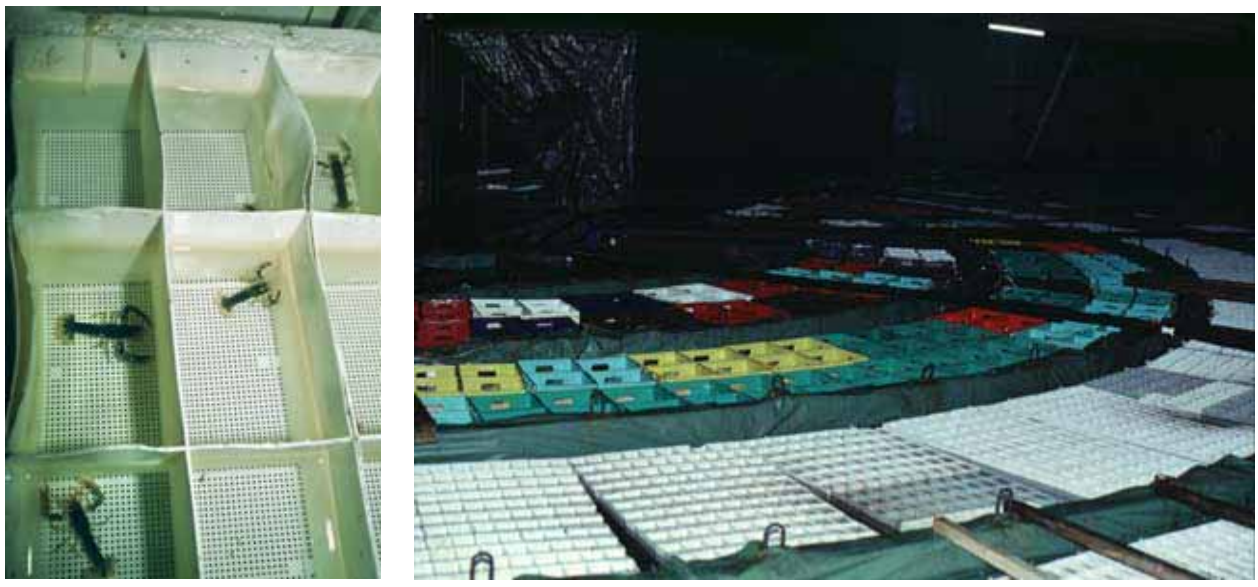


Figure 5.1. Trays with individual compartments made of white plastic with perforated bottom. The photo to the right is taken at the Tiedeman lobster hatchery at Kyrksæterøra.

5.3 The car-o-cells/horizontal wheels

For the first on-growing experiments in single confinements, vertical circular shaped (d: 95 cm; area 6.200 cm^2) enclosures were employed, which could be divided into 28 sectors, where

each sector could be divided into three compartments of three different sizes (Small 46 cm^2; Medium 74 cm^2; Large 99 cm^2); all max length 11 cm (Figure 5.2). In total, up to 84 single confinements could be made, 28 of each size. For the communal rearing experiment the wheel was divided in only four large compartments of 1550 cm^2 each. Water was supplied in the centre of the wheel and ran from the centre through perforated walls to the compartment. By making an overpressure in the centre compartment, an even water distribution through all compartments was achieved. The wheel could be turned, and it was therefore possible to inspect all compartments from a single position at the tank wall. These units were initially made especially for experimental purposes, as they were easy to inspect and rebuild to different sized compartments. Some mortality occurred during the IV-V stages due to small openings between the compartment walls and/or the compartment floor, where the animal fastened their claws or entered into the neighbour compartment. In the first trials lobsters were seen climbing up the perforated walls and out of the water and some were even seen sitting on top of the circles when inspected in the morning. To prevent the escapes, not perforated, slippery, extensions were mounted on every compartment and a cover was placed on top of each car-o-cell.

Figure 5.2. The wheels with up to 84 compartments used for the feeding experiments in 2001 and 2002

5.4 The stacks

In 2002, a new system for mass production was developed and tested and the grow-out section was rebuilt. The system was a stack concept, with 5 – 7 trays in each stack, placed in $1m^2$ square tanks with 70 cm water depth. Each tray could house from 12 (compartment size 540 cm^2) to 180 lobsters (compartment size 36 cm^2). Thus the highest density was 60 plate-sized lobsters/m^2 or 1260 lobster juveniles/m^2, respectively. In the biggest compartments it was possible to rear the juveniles up to commercial size (21 cm TL; 300g), and the maximum size of juveniles in the smallest trays were TL = 9 cm (Figure 5.3).

Despite the small size of the lobster hatchery at Kvitsøy, it was possible to farm between 30,000 and 40,000 lobster juveniles (TL = 9cm) annually using this type of farming concept. The water flow through the stacks was maintained by an over pressure in the top tray, which gave equal water flow into each compartment. During feeding and inspection the stacks were dismantled. The main weakness of the system was that the trays had to be taken out of water during this process. This was stressing the individuals that were in the moulting process, and this led to some mortality. Another weakness was inadequate self-cleaning mechanism were heavy sedimentation of feed and organic materials occurred in the tanks. The survival when

using *Artemia* (the units were then in water at all time) was approximately 80% from IV-stage up to 9 cm TL.

Figure 5.3. Stacks for high density rearing of lobsters (left: compartments for juveniles up to 9 cm TL; right compartments for plate-sized lobsters).

5.5 The rotator/vertical wheels

Another experiment included the use of a horizontal circular unit (Figure 5.4). The units were placed in the 1x1 m tanks (0.7m^3) and two different sized compartments were used. The small compartments had the following measures: length: 6 cm, height: 6 cm, width: 3 cm (108 cm^3). The big compartments were 6 x 6 x 6cm (216 cm^3). The lobsters were fed on top, and the car-o-cells rotated discharging the faeces and feed wastes on the bottom.

The overall average survival was poor in this system, ranging from 20 – 30%. Moreover, to avoid that the small juveniles were able to escape from the cages, the green mesh consisted of 1.5 mm holes. Thus, only granulated feed could be used. The use of granulated feed lead to local pollution in the cages causing sub-optimal water quality conditions in the tanks. In addition, the vertical wheels were difficult to maintain properly, especially within the cages. The system was also handicapped by not achieving a proper water exchange in the cages. Moreover, the cages were not square or rectangular in shape, thus making it difficult for the biggest lobsters to position themselves in the cages at the top position. Whether or not this

represents a significant stressor to lobsters is not know, but due to heavy mortality this concept was discharged. However, the use of *Artemia* would probably increase the survival.

Figure 5.4. Vertical car-o-cells with big compartments (left) and small compartments (right)

5.6 The artificial polyethylene substrate

This experiment was a test of an artificial polyethylene substrate (Figure 5.5) used to grow freshwater crayfish in many sub-tropical (i.e. Israel and Egypt) and tropical countries (i.e. Malaysia) with great success. The initial stocking densities during the trials were approximately 500 IV-stage larvae per net (Figure 5.5). The size of each basket was 25x25x35 cm (21,875 cm^3), and two baskets were placed in a 1m^2 tank (40 cm water depth). Each tank had then an effective stocking density of 1,000 larvae. The juveniles were fed dry marine fish feed once a day. The tanks were harvested and the survivors were counted and measured after 2.5 months.

Figure 5.5. Artificial polyethylene substrate for tested for communal rearing of IV-VIII stage lobsters

The survival in these systems was extremely poor, ranging from 1 – 8 %. Due to the lobster aggressive behaviour, the lack of physical barriers probably leads to heavy cannibalism. The use artificial polyethylene substrate is not an adequate way of farming lobsters communally.

6 Effects of diet, substrate and family on growth of juvenile lobsters reared in single compartments

6.1 Introduction

The rearing trials of juvenile lobsters in single compartments included studying the effects of rearing substrate, shelter, rearing space and feed type. In this experiment, we first wanted to look at the first three months of the production phase, from the 14 mm long post-larvae (IV-stage) settle at the bottom to it reach a total length of around 30 mm (12 mm CL; stage VIII-IX). In nature, these stages of the European lobster have a very cryptic behaviour and have never been found in the sea (Mercer *et al*. 2001). Most probably they hide in burrows in the substrate where they filter feed or act as ambushers at the shelter entrance. To develop a crusher claw, the lobster juveniles need to have access to shell sand or similar substrate (crushed shell) in the V-stage (Wickins 1986). In empty plastic compartments all lobsters will develop two scissor claws. The main goal with these experiments was to document growth and survival rates in our rearing system under assumed optimal conditions, and produce lobster juveniles for further on-growing. From other studies it was known that a mixed diet of natural food gave the best growth rates, but also that a relative small supplement of fresh food significantly improve the growth rates of lobster fed compounded diets (Ali & Wickins 1994). In this study, we wanted to compare growth rates of lobsters given a mixed diet of frozen mysids, krill and lobster larvae (I-stage), with groups given a pure diet of frozen mysids, frozen krill or dry marine fish feed, with a supplement of lobster larva one day a week. We also wanted to assess if sand substrate and shelter were important for the juveniles, and if there were any effects of compartment sizes in these larval stages. In addition, an estimated effect of family group variations influenced the growth performance.

6.2 Materials and methods

The experiment lasted from 06.08.01 to 01.11.01. Focus was put on testing if addition of shell sand and an empty shell as shelter improved growth and survival in the first bottom stages and if sand and shelter should be essential elements in further design of rearing units. We also wanted to compare growth rates between groups given three different natural food types and a dry marine fish food. We used a split-plot factorial design with four food types, four substrate types, six families and three compartment sizes. Each food type was tested in all substrate types and all families were tested in all combinations of food, substrate and compartment size. Regrettably, the results from tank 3 and 13 had to be excluded due to technical accidents (escapements due to overflow of water with subsequent cannibalism).

Table 6.1. Experimental design Experiment 1 (Tank no: Food; Substrate):

1: Food A; Sand	5: Food B; Sand	9: Food C; Sand	13: Food D; Sand*
2: Food A; Sand+shell	6: Food B; Sand+shell	10: Food C; Sand+shell	14: Food D; Sand +shell
3: Food A; Little sand*	7: Food B; Little sand	11: Food C; Little sand	15: Food D; Little sand
4: Food A; Shell + little sand	8: Food B; Shell + little sand	12: Food C; Shell + little sand	16: Food D; Shell + little sand

To each tank (horizontal wheel), one of four substrate types were added: *Sand*: a 1cm thick layer of fine shell sand; *Shelter*: a small empty scallop shell (*Pecten maximus*) or large blue mussel shell (*Mytilus edulis*) in each compartment; *Sand + shelter:* Both sand and shell; *Little sand*: two teaspoons of shell sand (believed to be enough to secure development of crusher claws); *Little sand+shelter*: two teaspoons of shell sand and an empty shell. The relationship

between substrate in the first period and crusher claw development was evaluated after 10 months (29 June 2002), when the lobster had grown to around 80 mm TL and the crusher claws easily could be identified.

The four food types were: *Food A*: rotational feeding with frozen locally caught mysids (*Praunus flexousus*), frozen krill (*Thysanoessa* sp.) and frozen I-stage lobster larvae; *Food B*: frozen mysids; *Food C*: frozen krill; *Food D*: 2mm pellets of commercial dry food made for marine fish + one ration per week with frozen lobster larvae. Feeding was done once a day in excess and the ration size was increased during the period according to the lobster size. Uneaten food was removed or flushed out of the confinements every day. The lobsters were allowed to eat their cast shells.

Larvae from six berried females (families) (CL 89-107mm; 497-830g) were chosen for the experiment. Within 24h after the larvae moulted to the IV-stage (ca. 14 d after hatching), 14 larvae (with two claws) from each of the 6 families were placed in the 84 single compartments in a "wheel" in 16 tanks (in total 1344 IV-stage larvae, 224 from each family). In each tank the compartments were numbered from 1-84, and family 1 was placed in confinements 1-14, family 2 in confinements 15-28, and so on. Confinements 1, 4, 7, etc. were of large size (99 cm^2); 2, 5, 8, etc. medium (74 cm^2); 3, 6, 9 small size (46 cm^2). The water current ran from the centre of the wheel, first into all the small confinements, then the medium and so on (direction small-medium large).

6.3 Results and discussion

Diet

There were significant effects of diet on mean size after three months. The growth rates were highest on the rotational diet followed by frozen mysids (Figure 6.1). The groups fed dry feed, with supplement of frozen lobster larvae once a week, were significantly smaller than the mysid group, but only about 0.5 mm CL. The dry feed groups had also a more pale blue-grey pigmentation (Figure 6.2) The groups fed only krill were significantly smaller than the other and had also the highest mortality (49%), and we suspected that the frozen krill had become stale and of low nutritional quality (to old).

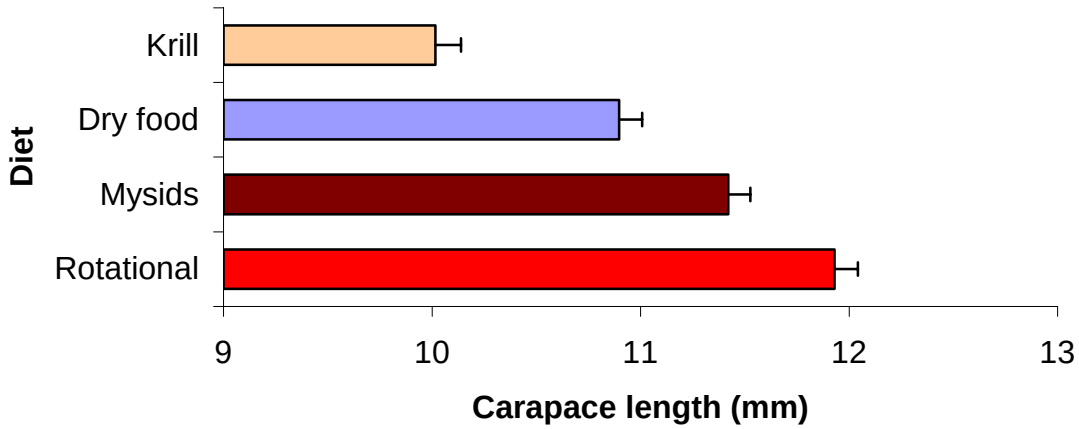


Figure 6.1. Mean carapace length after three months of the groups (pooled) fed the four diet types. Error bars show 95% conf. int. for the mean. Note that x-axis does not start in origo.

The mean growth rate of the groups with rotational diet were 0.085 mm CL/day, which was similar to average growth values found by Wickins & Beard (1991) on a similar diet. The growth rate of the dry feed group was 86% of the best group and the survival was the same or better. This was a surprisingly good result, given that this was a marine fish feed (considered nutritional insignificant). Earlier studies of lobsters given formulated feed have generated a much poorer growth performance (Nicosia & Lavalli 1999). From February the next year all groups were only given dry marine fish feed (Cod feed), and the growth rates were than reduced to 66% compared to the results of Wickins & Beard (1991). In addition, the juveniles turned to light blue in colour and the juveniles became less vital, showing severe deficiencies with the food. The juveniles finally became transparent in colour (Figure 6.3). However, the good results with only supplement with a few lobster larvae once a week in the first period, indicated that relatively small changes in the composition of the marine fish feed were necessary. Especially the lack of pigments (probably astaxanthin) was evident.

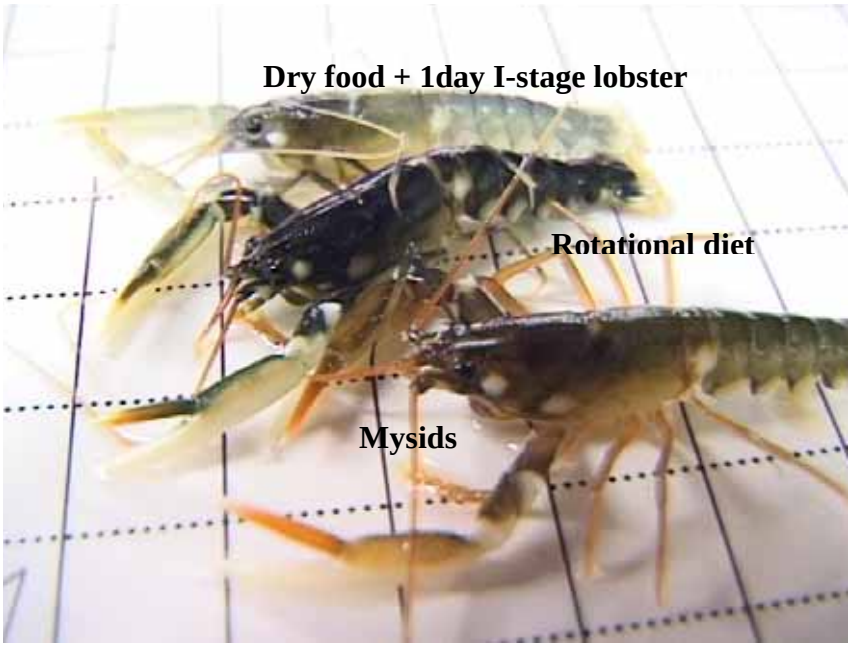


Figure 6.2. Effect of diet on colour of shell pigmentation of the three months old lobsters. A square on the paper is 1 cm^2.

Figure 6.3. Effect of a diet without astaxanthin on shell pigmentation of lobsters.

Substrate

If we look at all groups pooled given the same substrate, a significant effect of substrate type was found ($F(3.838)=35.37$; $p<0.0001$), where the largest lobsters were on average found in "sand" and the smallest in "little sand" (Figure 6.4).

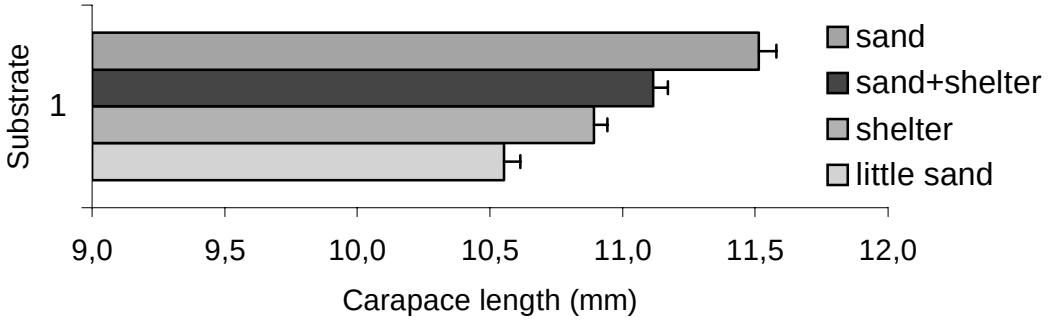


Figure 6.4. Mean size after three months of pooled groups reared on the same substrate.

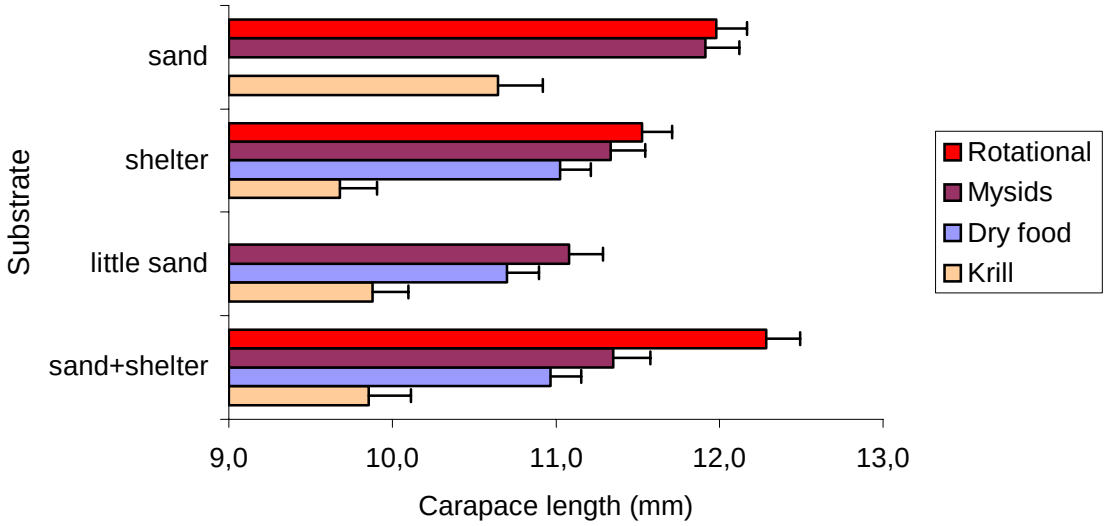


Figure 6.5. Interaction between feed and substrate. Mean carapace length of pooled groups after three months.

However, there were significant interaction effects between feed types and substrates ($F(7.848)=5.67$; $p<0.0001$) and when we look at the mean size of the groups given different feeds the picture become less clear (Figure 6.5). E.g. the group given rotational food and both "sand and shelter" had the largest mean size. The krill group had a much larger mean size in sand substrate compared to other substrates, but there were small differences between other substrates.

At 10 months of age, 93 – 95% of the lobster reared in sand or both sand and shelter as substrate in the first three months had developed crusher claws. Of the groups given only two teaspoons of sand, 63% had developed crusher claws. However, when an empty shell was

added as a shelter in addition to the teaspoons of sand, a total of 87% developed crusher claws. There was an equal distribution of left and right crusher claws (483 right vs. 475 left). These results indicate that the amount of sand substrate influences the crusher claw development, and also that the empty shells in the compartment stimulates to the crusher claw development.

Compartment size

Compartment size had no significant effect on carapace length after three months (Figure 6.6). The lobsters were on average slightly smaller in the smallest compartment and there were significant interaction between diet and compartment size. In the krill group, the lobsters were smallest in the large compartments, but in all other diet groups the lobsters were smallest in the smallest compartment.

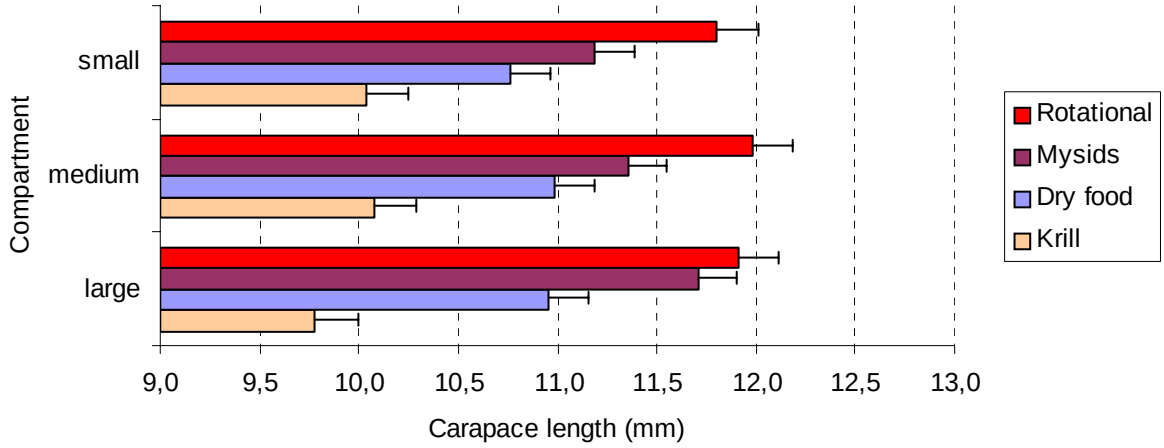


Figure 6.6. Mean carapace length (mm) with 95% Conf. int. of the four diet groups reared in the three compartment sizes.

Two of the dry food tanks and three of the rotational diet tanks were followed until 29 June 2002. In this period the size difference between lobsters reared in the three compartments did not increase significantly (Figure 6.7). Since the compartments were all 110 mm long, but had different width, this indicates that compartment length may be more important than area. However, Schleser (1974), found no difference in growth rates between circular, rectangular or square containers with the same area for American lobster.

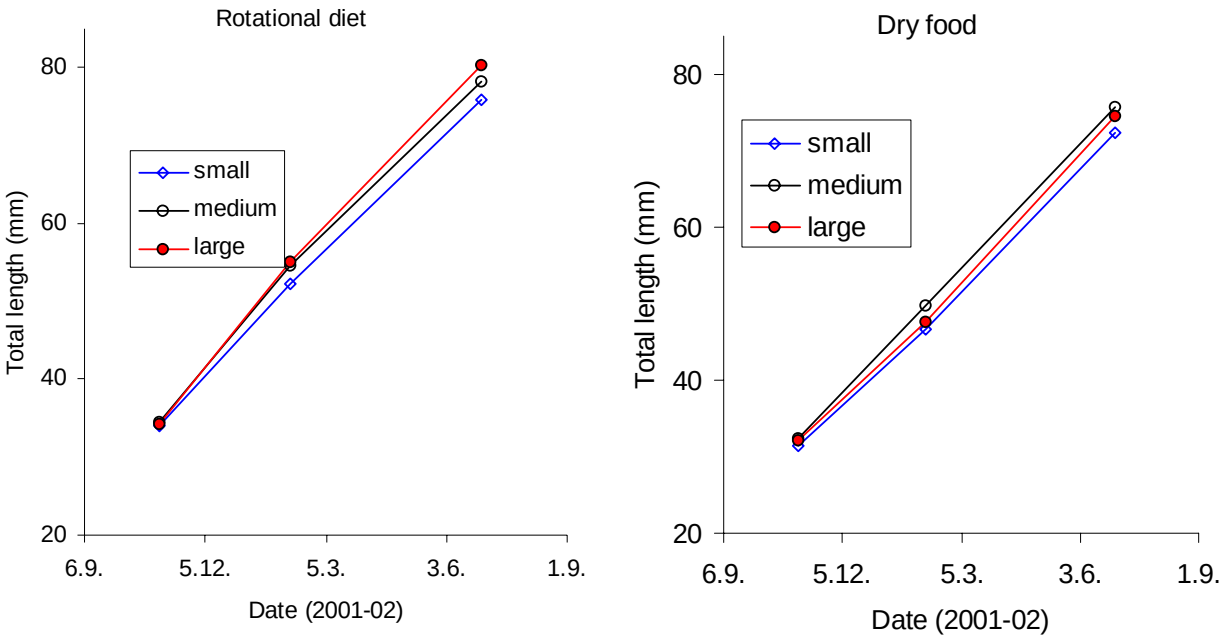


Figure 6.7. Mean total length (mm) of two diet groups reared in the three different compartment sizes at three monitoring points.

An equation for necessary minimum space for unlimited growth, $A=(aTL)^2$, was given by Richards (1981), where he found the area factor, a, to lie between 1 and 2 for European lobster. Aiken & Waddy (1978) and van Olst *et al*. (1980) found area factors between 2.7 and 3.4 for American lobster (recalculated from $A=55CL^2$ to $A=78CL^2$), and severe growth limitation at a=1.6. This gives a relative difference of 11 times larger area from the smallest to the largest value (a=1 to a=3.4). In our study the smallest compartment area at the end of the study was comparable to an area factor of a=0.85 for the smallest compartment and the largest of a=1.23 (TL=80mm). We found no indications of deviation from the linear length increment that should indicate area limited growth. The first sign if area limited growth is reduced length increment at moult (Richards 1981). These results indicate that the European lobster is less area dependent than the American lobster, but further studies should be conducted, and especially for larger lobsters.

Family variation

There were significant effects of family background on size after three months ($F(5.2\ 850)=6.8422$, $p<0.0001$). Especially family 4 were outstanding. There were no significant interaction effects between family and substrate or feed (Figure 6.8).

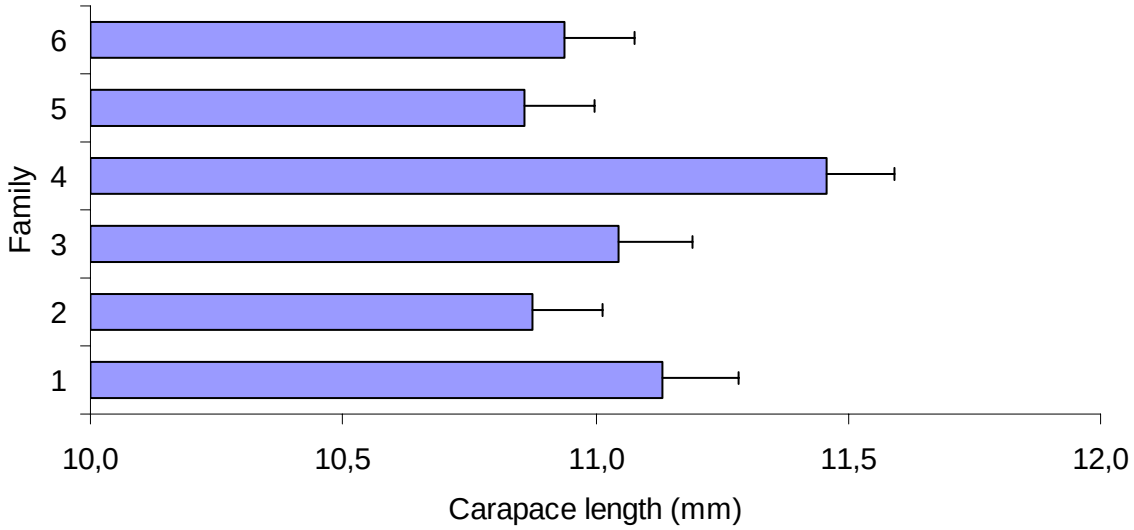


Figure 6.8. Mean carapace length (mm) with 95% conf. int. of the different lobster families (all survivors pooled).

Survival

The outstanding Family 4 had also the highest survival, but there were in general small differences between families (Figure 6.9). There were significant differences in survival between the different diet groups, where especially the "krill" group had high mortality, which we believed was related to nutritional deficiencies in the feed (stale oxidised krill). Most of the mortality in the other groups occurred the first weeks of the experiment and was related to technical problems with the confinements (small openings between the walls and floor where the lobsters interacted and got injured), and was not related to diet. Without these problems the survival had probably been more than 90%.

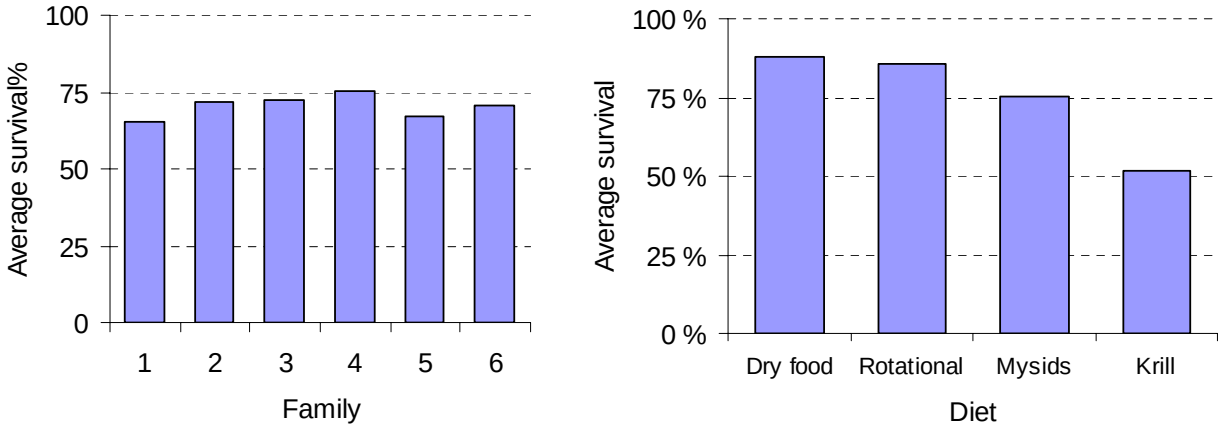


Figure 6.9. Mean survival (%) of the six families (left) and the four diet groups after three months.

7 Communal rearing of IV-VIII stage lobsters

7.1 Introduction

In this experiment the effects of sand substrate on survival and growth were studied. Communal rearing may be an alternative for rearing of lobsters from the IV to the VII-IX stage, and especially for lobsters made for sea-ranching or local stock enhancement. This method can be used in small-scale hatcheries where cheap natural substrate, shelters, and food can be used, and the local fishermen do the labour as a spare time activity. However, the communal method requires more brood-stock due to higher mortality in the benthic stage. Earlier experiments at Kvitsøy had shown that an average of 55 lobsters per m^2, with an average carapace length of 17 mm (45 mm TL) could be produced in four months in communal tanks with semi-natural substrate of shell sand and empty shells (Jørstad *et al*. 2001a). However, the method also gave very variable size distribution, and high ratio of claw loss. These results were better than published from other studies with communal tanks. The main difference in the Jørstad *et al*. (2001a) study was the use of shell sand substrate in addition to the shelters. In this experiment we wanted to test if there was any "sand effect" of the shell sand on survival in communal tanks with empty shells used as shelters.

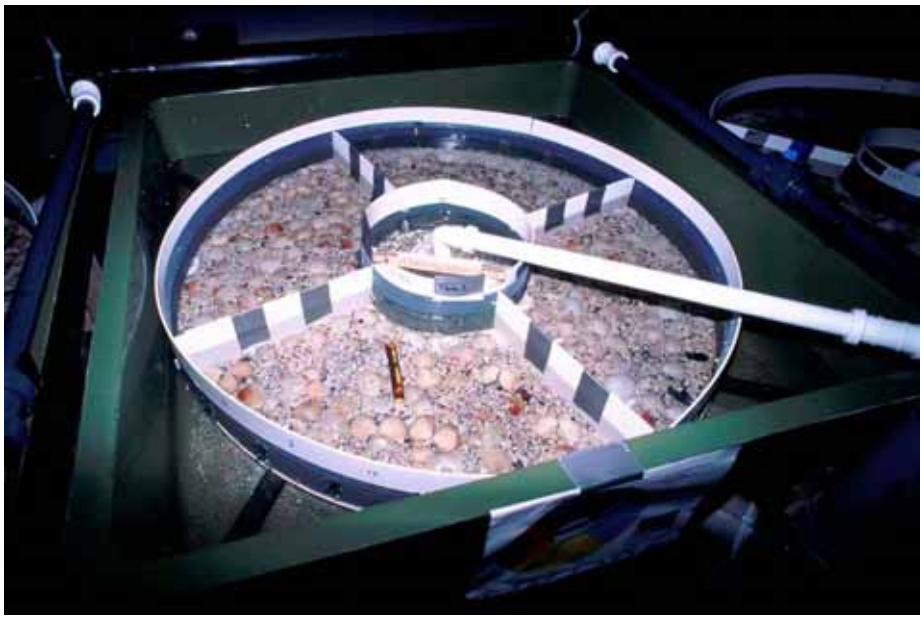


Figure 7.1. Tank and arrangement for communal rearing of lobster juveniles.

7.2 Materials and methods

Six "rearing wheels" were divided in 4 compartments (Figure 7.1). In three of the wheels a 2 cm thick layer of fine shell sand and a lot of empty scallop and cockle shells were added. In the three others only the same amount of empty shells were added. To each compartment, 40 IV-stage lobster larvae from one family were added. All tanks were fed frozen mysids once a day in excess. Temperature was maintained at stable 18 – 20ºC.

7.3 Results and discussion

The survival in the communal tanks with shell sand was 2 – 3 times higher than in the communal tanks without sand (9 – 13% vs. 27 – 29%; Table 7.1), but much lover than in the single compartments (51 – 88%). The juveniles were on average smaller and of more variable size than in the tanks with single compartments. The lobster in the communal tanks also had more claw loss, indicating more fighting. More of the small lobsters had survived in the tanks with sand. This experiment showed clearly that there was a large effect of the sand. Survival could probably be increased by increasing the amount of sand and numbers and quality of the shelters, and probably also the way of feeding (frequency and ration).

Table 7.1. Experimental conditions, number survived until 1 November, mean size, and average numbers of claws.

Tank	*# families*	*# per fam.*	*# lobsters*	*Sand*	*Shelter*	*Feed*	*# 1.Nov.*	*TL(mm)*	*#claws*
L4	4	40	160	+	+	A	47	27	1,5
L6	4	40	160	+	+	A	46	26	1,2
L8	4	40	160	+	+	A	44	26	1,5
L5	4	40	160	-	+	A	19	28	1,1
L7	4	40	160	-	+	A	21	28	1,3
L9	4	40	160	-	+	A	14	28	1,5

8 Growth rate and estimation of production time

8.1 Introduction

In this experiment, the goal was to reveal the growth rate of large juvenile lobsters and to estimate the production time for portioned sized lobsters in our system. A crucial factor in the intensive lobster production is the production time from larvae to marketable product (e.g. 300 g). The only literature data found on full grow-out of European lobster in heated water were given by Wickins & Beard (1991). They kept a group of individual containers and fed them natural feed for 30 months. They found a linear growth rate of 0.0874 mm/day up to stage XXII (67mm CL). After that they got growth reduction, probably due to small container sizes.

8.2 Materials and methods

To estimate production time in our system and to get experience with the feeding and handling of larger lobster juveniles, an experiment with six tanks with 28 juvenile lobsters (2-40g) in each was initiated. These were lobster juveniles produced in 1999 and 2000 that had been reared at ambient sea temperatures most of the time and had slow growth rates during winter. The lobsters were transferred to the horizontal wheels with 28 compartments on 28 August 2001. During the first three months the tanks were equipped with various combinations of shell sand substrate, black plastic foil roof, and a piece of PVC-pipe as shelter (Table 8.1).

The lobsters were measured and weighed after three months (1 November 2001). After the first measurement the sand, shelter and roofs were removed and the lobsters were kept in empty containers, and the largest lobsters were transferred to larger containers when necessary. They were than measured after five (5 February 2002) and ten (29 June 2002) months from start. Some samples of the largest lobsters were taken in the last period for test by a sensory panel at the Culinary Institute in Stavanger influencing on the growth results. Until February 2002 the lobsters were fed a mixture of fresh shrimps (*Pandalus borealis*) and frozen krill (*Thysanoessa* sp.) once a day in excess. During the last period they were fed dry marine fish feed (Danafeed 4 mm pellets).

8.3 Results and discussion

In the first period we found no significant effects of the treatments (Table 8.1), but the mean growth rate for all groups were slightly better than observed by Wickins & Beard (1991). In the following period the mean growth rate decreased from 0.29 mm/day in the first period to 0.21 mm and 0.23 mm/day in the second first and third period, respectively (Figure 8.1).

Only the lobsters that were alive at the last measurement were used in the growth calculations. The reduced growth rate in the second period was partly due to problems with the water heaters, which caused a period with reduced and unstable temperature. After February 2002 (the last period) all groups were fed dry marine fish food, but, importantly, this did not lead to a decrease in growth rate compared to the second period. However, it soon became evident that the lack of pigments in the food led to a light blue pigmentation of the lobsters after only 1 – 2 moults.

Table 8.1. Experimental design and average growth rates after three months in the various tanks and weighted mean for all tanks

Tank	Roof	Shell sand	Shelter	28 Aug			01 Nov					
				#	W(g)	CL (mm)	#	W(g)	CL (mm)	DCL (mm/d)	DV(g)	SGR
1	+	+	-	28	7.4	22	22	14.5	27	0.082	7.1	1.03
2	+	+	-	28	7.6	24	24	16.5	30	0.094	8.9	1.19
3	-	+	+	28	11.0	25	26	21.5	31	0.098	10.5	1.03
4	-	-	+	28	9.7	24	25	16.3	29	0.077	6.6	0.80
5	+	-	-	28	11.4	25	28	20.9	32	0.097	9.5	0.93
6	+	+	+	28	11.9	26	20	22.0	32	0.091	10.1	0.95
Mean				**28**	**10.3**	**25**	**24**	**18.6**	**31**	**0.091**	**9.1**	**0.98**

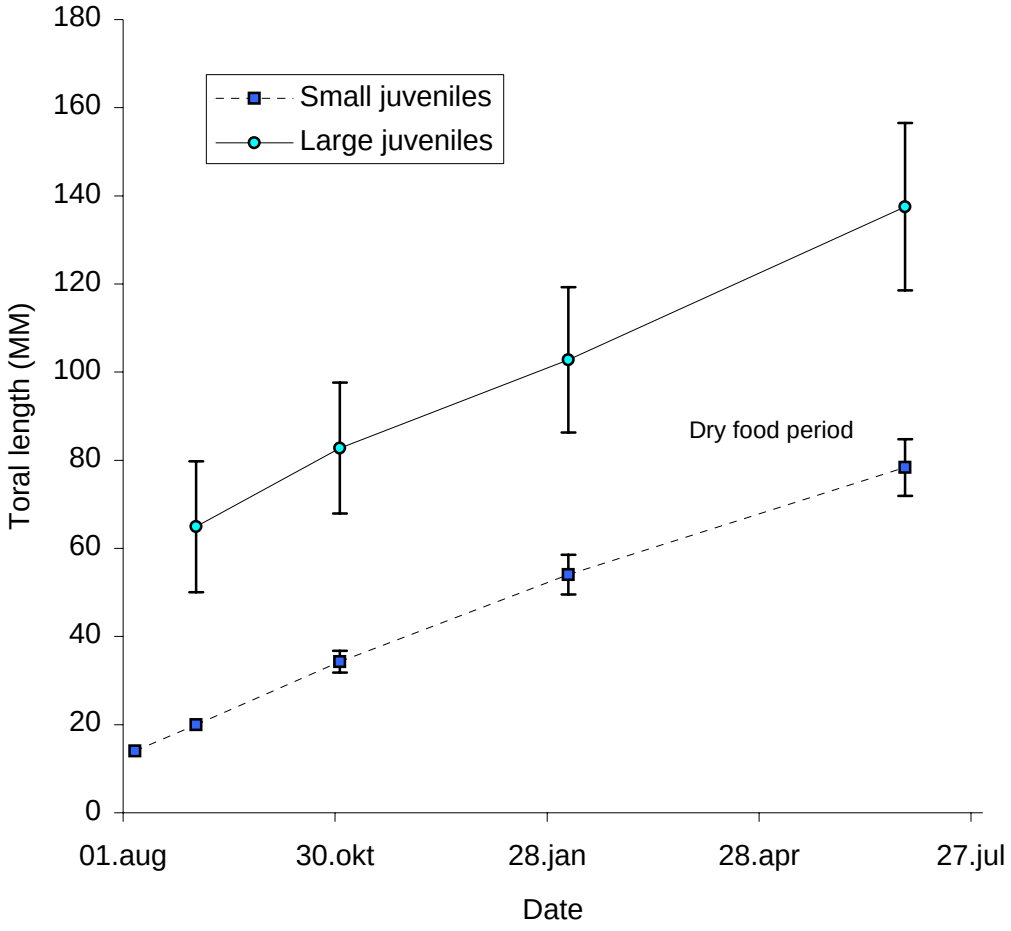


Figure 8.1. Growth of large and small juveniles from August 2001 to late June 2002. The error bars show one standard deviation.

The three tanks of small lobsters fed a mixed diet until February 2002, were also followed to late June 2002, and were fed dry food diet in the last period. As for the large juveniles technical problems led to a period with low and unstable temperatures in the second period, and a decrease in growth rate and some mortality during moulting were observed in all groups. The mean growth rate of the mixed feed groups fell from 98% to 75% (from 0.29 to 0.20 mm/day TL) of the Wickins & Beard (1991) average, while the dry feed groups fell from 85% to 65%.

In the third period when all groups were fed dry marine fish feed, the growth rates of the mixed feed groups fell further to 65% (0.18 mm/day TL) of W&B average, while the two groups earlier fed dry feed and lobster larvae (one day a week) increased slightly to 67%. These growth rates were slower than found in the large juvenile, which indicated that the small juveniles were more vulnerable to food quality than large juveniles. However, the container sizes could also reduce the growth rates in these groups (se chapter 8). Furthermore, the groups of small juveniles turned light blue to transparent white after a few moults when fed only dry feed and also seemed to be less vital than before.

The conclusion from these experiments was that it is possible to obtain the same growth rates as Wickins & Beard (1991) in our system when the lobsters were given enough good quality food and a stable temperature close to 20°C. However, the lobsters were vulnerable both to feed quality and temperature variations.

The relationship between carapace length for the reared juveniles was calculated to $W=0.0003*CL^{3.1522}$, which was very similar to the same relationship calculated from larger wild lobster caught in the sea (Figure 8.2).

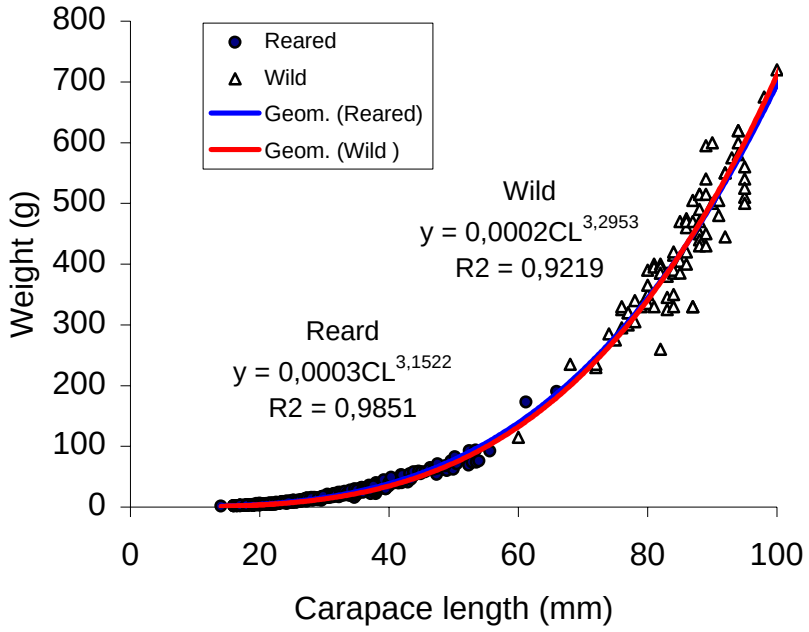


Figure 8.2. Relationship beteween carapace length (mm) and live weight of reared juveniles and wild lobster caught at Kvitsøy.

The time needed to produce a 300g lobster (approximately 75 mm CL) is dependent on growth rate. In Figure 8.3 four different linear growth rates are plotted and time to 75 mm CL is indicated by the vertical dotted lines. The sizes at age data from our experiments are also indicated. The start age of the large juveniles was set to the day that the 0.09 mm/day line reached the mean start size of the large juveniles. The larger juveniles follow quite well the 0.09 line, so with an improved dry food, stable temperature and water quality, and probably also improved feeding frequency, a mean production time from IV stage to 300g of less than 800 days should not be unrealistic. Richards (1981) also showed that darkness or continuous low light level increased the growth rates and probably reduced the stress level. Moreover,

selection of family groups (see previous chapter) with fast growth under intensive farming conditions should further reduce the production time.

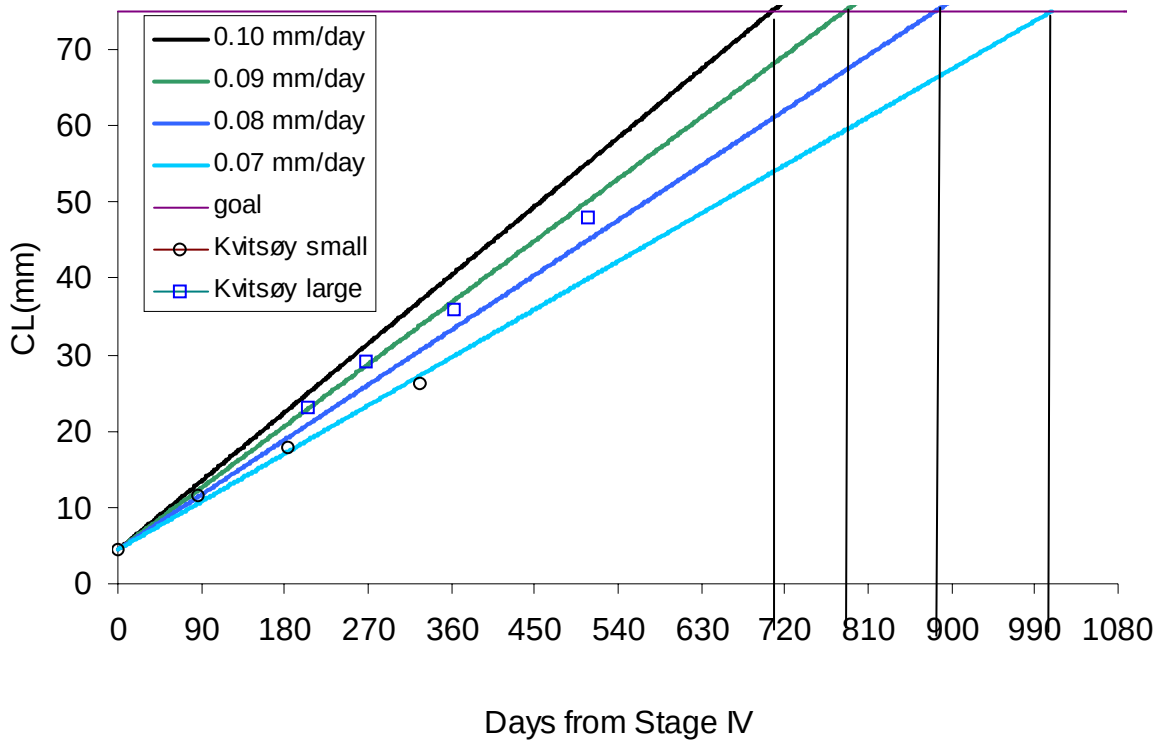


Figure 8.3 Production time (days from stage IV) until portion size (75 mm CL) at four different growth rates. Growth data from the Kvitsøy experiments are indicated.

9 Astaxanthine contents vs. natural pigmentation

9.1 Introduction

After five months with feeding with marine fish feed, without astaxanthine, the lobsters had become light blue/white/transparent in colour. None of the available commercial dry marine fish feeds in the market has both high protein content and the needed levels of astaxanthine to ensure natural pigmentation of lobster. The production of lobster juveniles has so far been limited to R&D purposes, and natural feeds (Artemia, Krill, Mysids, frozen fish, etc) have fulfilled the required quantity and quality. Further feed development must consider both the nutritional value and the physical aspects of a dry diet. A fully automated farming concept requires a formulated feed that can be portioned in exact amounts to each lobster in each cage in order to avoid excessive feeding and feed wastes. It is also important that the feed is resistant to the farming environment (20°C and 33‰) without dissolving too fast. According to Wickens & Lee (2002), no one has ever reared lobsters from metamorphosis to commercial size in 2 – 3 years solely, or even largely, on a compounded diet. The lack of an adequate and cost-effective formulated diet is one of the major bottlenecks in lobster culture today. Thus, a minor investigation was initiated where the main goal was to quantify the minimum level of astaxanthine needed in a formulated feed to ensure natural pigmentation in the European lobster.

9.2 Materials and methods

Reared juvenile lobsters, in the size range 50 – 150 mm total length, were fed two different sizes of dry pellets (2 mm and 5 mm) with three different astaxanthine levels (50, 100 and 200 mg/kg dry weight).

Table 9.1. Composition and energy content of the diet (% of wet weight)

Nutritional content	**%**
Protein	54.7
Lipid	15.6
Carbohydrates	13.6
Ash	9.5
Water	6.8
Energy (MJ/kg)	21.6

The diet consisted of protein, fat, and carbohydrates (energy 21.5 MJ/kg) and was mainly made of high quality fish meal (Table 9.1). Minerals and vitamins accounting for less than 1% were mixed in the feed after standard procedures for fish feed extruding. Due to a relatively low amount of fat in the formula, this was injected in the mix before extrusion instead of giving the pellet a coating of a hydrophobic surface. In the experiment (20°C; 33‰), this led to premature decomposition of the feed and leaching of nutrients into the water.

9.3 Results and discussion

Before the start of this trial, all lobsters had been fed with ordinary cod feed (DanaFeed) for more than one year. As a result, most lobsters had pale pigmentation due to a lack of pigment in this feed. It was therefore easy to observe the changes that occurred in colour and thickness of the shell after introducing the new lobster feed. Already after the first two moults (6 – 8 weeks) there were significant and homogenous changes in pigmentation, where all lobsters included in the feed trial turned from white to light blue, and finally to dark blue (Figures 9.1). There were no differences in pigmentation between lobsters given the three levels of astaxanthine, and 50 mg astaxantine/kg seems to be sufficient to ensure strong pigmentation.

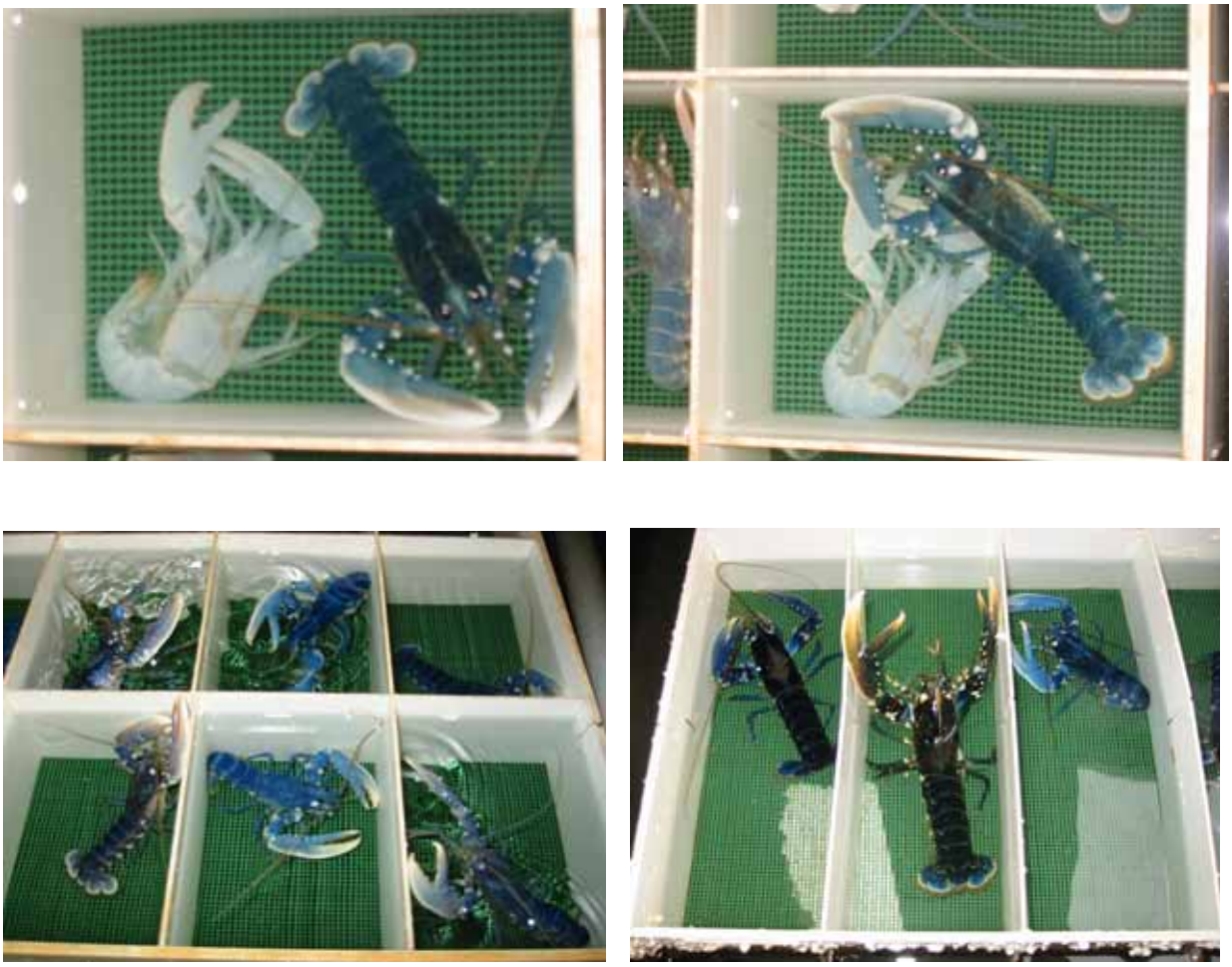


Figure 9.1. The feed added astaxanthin initiated a significant change in shell colouration after moulting.

The feed was also used for newly hatched larvae, and they maintained their natural pigmentation in addition to achieving high growth rates and survival. Moreover, the feed generated less wastes and maintenance to avoid clogging in the incubator was reduced significantly. Thus the feed seemed highly suitable for production of larvae during the pelagic stages, and it was proven that it is therefore possible to farm lobsters from hatching to plate size solely on a formulated diet.

Although only visual observations were done, comparisons of the different lobster feeds showed that the lobsters fed the new feed seemed to be more vital and opportunistic in their behaviour.

Astaxanthine is an important part of various enzymatic processes in the protein skeleton in lobsters, and the primary role in nature is to provide correct pigmentation (camouflage). However, astaxanthin also interacts with various digestive enzymes. Within the various classes of natural pigments, the cartenoids are among the most widespread and structurally diverse pigmenting agent. Thus, it is likely to believe that the astaxanthine content in the new feed functioned as an important attractant which can improve appetite, growth and shell thickness.

The temperature during the experimental period was on average 14°C±2°C. Temperature is the primary regulator of growth, and moulting frequency increases in proportion to temperature within the range of 6-24°C. According to Waddy (1988), the most rapid growth rates occur when lobsters are held at 20-22°C year-round, and that juveniles may grow at a rate of 0.1 mm/day or faster at these temperatures. In the present study the lobsters' specific growth rate were 0.43 – 0.67%/day, which correspond to 0.05 – 0.06 mm/day. Hence, the growth performance in this study was lower than optimal, but as expected within the experimental temperatures. The average feed conversion rate (FCR) varied between 1.0 and 1.14 (*Drengstig et al. 2003b*). Since the fundamental nutrition needs of lobsters were lacking, the feed was composed similar to marine fish feed. The feed gave acceptable growth rates at the ambient temperatures, but should be tested at optimal temperatures for growth.

10 Market studies

A significant effort has been done during the project in order to be acquainted with the relevant market potential for European lobster (annual catches, farm-gate prices, export and import prices and quantities) (*Gregersen & Mongstad 2001*). The target markets were identified as the so-called emerging markets in Europe and Asia, but most of the work was concentrated on domestic markets. The base line market information was collected from various international databases, literature, Norwegian fishery statistics prepared by the Norwegian Trade Council and the Norwegian Seafood Export Council.

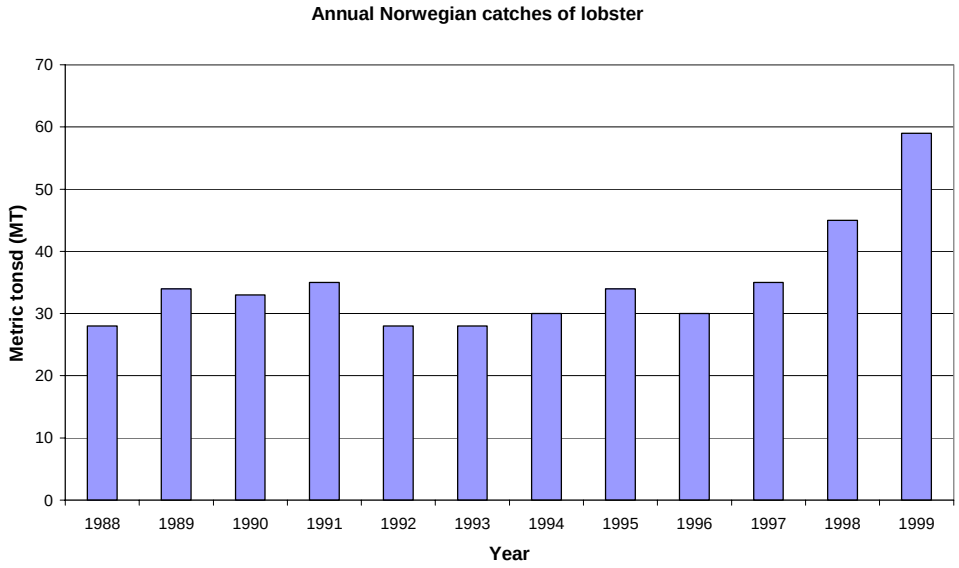


Figure 10.1. Annual recorded landings of wild lobsters in Norway during the period 1988 – 1999.

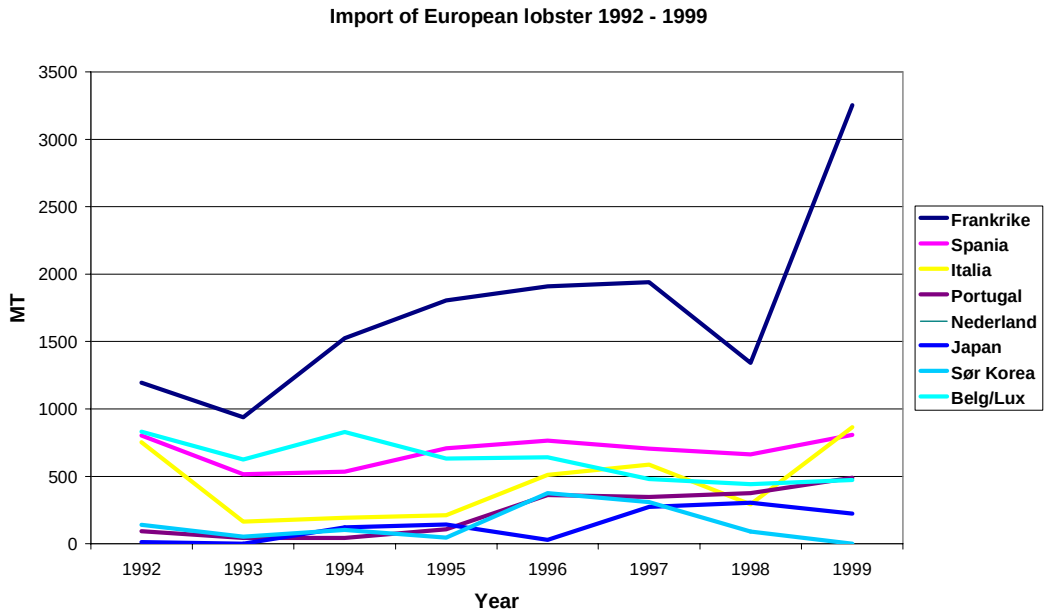


Figure 10.2. Annual import of lobster (both American and European lobster) in various European countries during the period 1992 – 1999.

The price, which Norwegian fishermen have received during the period 1994 – 2000, is given in Figure 10.3. However, since the price is often highly influenced by both seasons and availability, it was important to develop sales strategies for gaining the maximum benefit from the consumers demand for lobster.

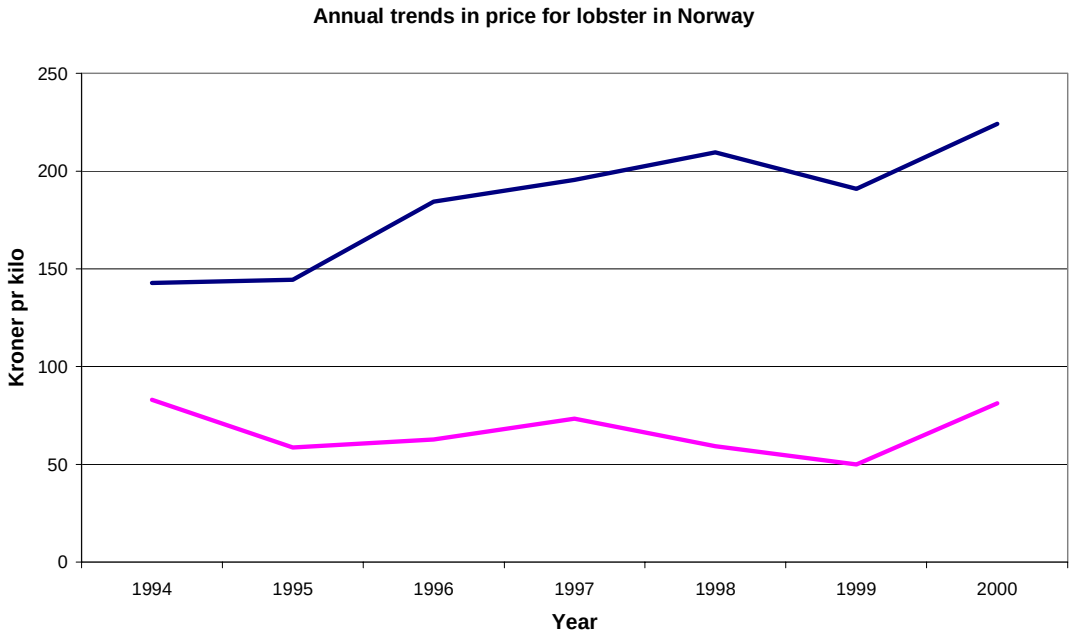


Figure 10.3. Annual average farm-gate price for lobster landed in Norway from 1994 – 2000. Upper line indicates live lobster while the line below indicates frozen products.

Due to a significantly higher price in Japan, a special case study was conducted to reveal yearly trends in prices during the last decade (Figure 10.4). Average price on the Japanese market was 225 NOK/kg.

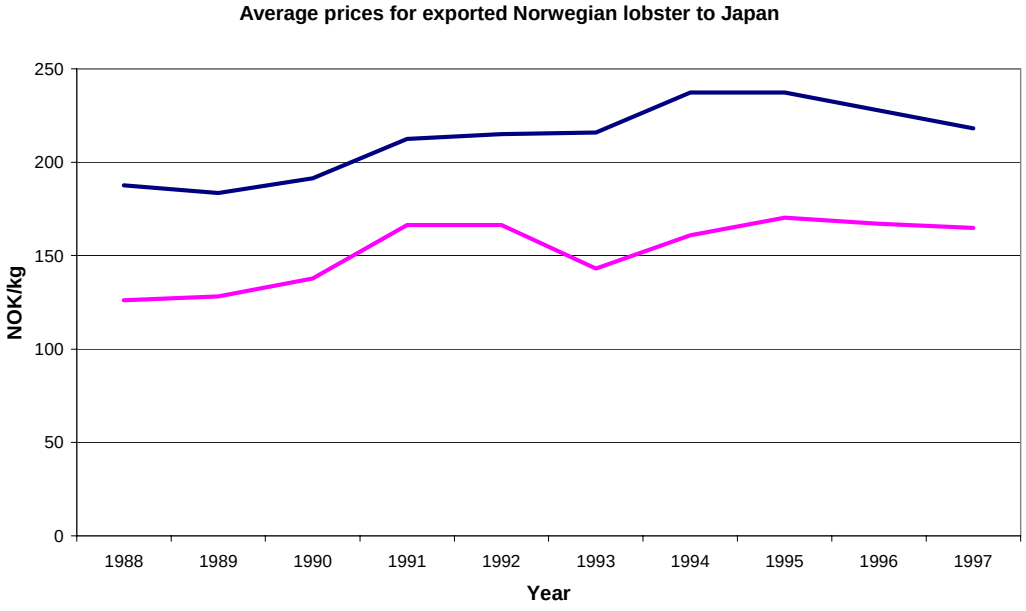


Figure 10.4. Annual average price for exported Norwegian lobster to Japan 1988 – 1997. Upper line indicates live lobster while the line below indicates frozen products.

10.1 Discussion and conclusion

All market research shows that portion-sized lobster has a substantial market potential (*Drengstig et al. 2003c*; KPMG 2003). The farm-gate price for live or fresh lobster to farmers or fishermen in Norway has for the last decade been varying between 180 – 240 NOK/kg (KPMG 2003; Figure 10.3). In 2001, the average price was 195 NOK/kg (KPMG 2003). Moreover, the market demand has been steadily increasing during the last 25 years, and it is expected that the demand will increase further in the future (KPMG 2003). Today, the global consumption of European and American lobster is over 80,000 MT at values exceeding $1.2 billions.

The market studies estimated the national demand in Norway to be over 150 MT annually at the current price level (*Drengstig et al. 2003d*). Moreover, there is a positive attitude to the "new" product regarding both the product's size and weight (21 cm/300 g), especially in the high-end segment (*Anon. 2002*). The majority of consumers to be adequate for the restaurant market and direct sales to private consumers accepted this size. However, most super markets and grocery stores requested a somewhat bigger size (400 – 500g). The future sea-ranching companies in Norway may meet this market demand. Furthermore, there exists a considerably higher global market demand (approximately 40,000 MT annually), with Scandinavia, Europe and Asia being the predominant best markets.

KPMG (2003) estimated and summarised the global market demand for live lobster and lobster products like this:

- Frozen plate-sized lobster: 50,000 MT annually
- Fresh, bigger (> 500 g) lobster: 1,000 MT annually
- Live lobster (≥ 250 – 300 g): 60,000 – 70,000 MT annually

Continues deliveries of lobsters from large-scale factories will meet the yearly demand for lobster in most seafood markets in the world today. It was also documented that continues deliveries will increase the annual average prices in all markets, however, delivery may be made to various markets throughout the year. Some markets (Greece, France, Japan) are in fact willing pay up to € 35 – 40/kg if guaranteed minimum 250 kg live lobsters every Friday (*Drengstig, unpublished data*). In Norway, there are seasonal occasions (Christmas and New Years Eve) where consumers are willing to pay up to 1,000 NOK/kg (€ 120/kg) for lobster, where of the distributor pays 350 – 400 NOK/kg (€ 50/kg) to fishermen.

11 Product quality and culinary results

Two tests have been conducted in order to evaluate the product quality, whereof one was conducted at the Culinary Institute in Stavanger (*Anon 2002*) (Figure 11.1). The tests included evaluation of texture, taste, colour, shell thickness, preparation on able plates, size, weight and food content (gram) in light of the desired amount of meat required in a pre-course. The lobsters were both boiled and fried.

Figure 11.1. Testing of Norwegian Lobster Farm's plate-sized lobster at Culinary Institute in Stavanger in 2002.

The overall conclusions were indeed positive regarding the most important aspects like texture, taste, size, food content and the panel displayed a general positive response to the product. However, the lack of natural colour and a thinner shell were considered to be minor drawbacks. These aspects are now improved by using the specially manufactured lobster feed with astaxanthin for the last 12 months. Therefore, a new test is planned at the Culinary Institute in October 2004. In addition, a larger trial batch will be sold to local restaurants and private consumers during the Christmas holidays. These results will be presented when results from the prototype technology is reported in autumn 2004 (see chapter 12.3).

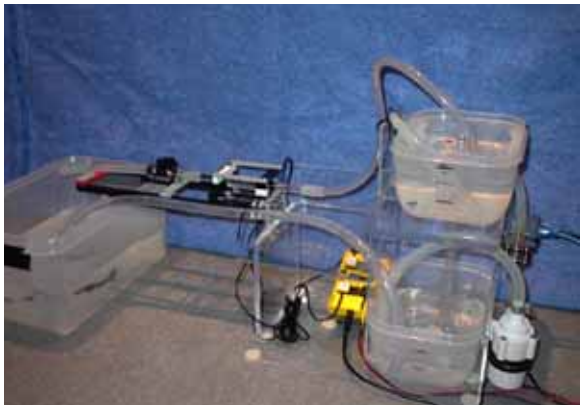
12 Outlook and prospects for the future

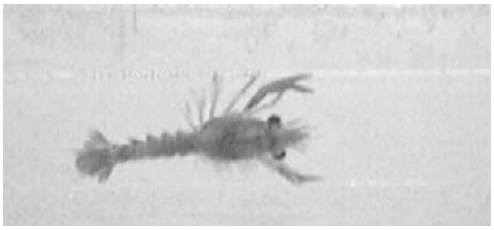
Homarid lobsters are both cannibalistic and highly aggressive. In order to maintain acceptable levels of survival and growth grow-out must be conducted in individual cages, creating a major logistical problem (van Olst *et al*. 1980). A commercial sized lobster farm would stock anywhere between 100,000 and 1,000,000 lobsters at any one time and manual feeding and cleaning the equivalent number of single cells at a regular basis has so far been impossible. Grimsen (1980) estimated that it would require 6 to 7 full time employees to manually feed 120,000 lobsters, a task that would not be economically feasible. Automated cleaning and feeding is therefore needed and technology to do so has recently been developed (*Drengstig et al., 2002a; Drengstig & Drengstig 2003; Drengstig et al., 2003c*).

12.1 Prototype of an automatic production unit

The final farming concept, which has been developed during the trials at Kvitsøy lobster hatchery, is currently under comprehensive testing. Focus is given to water quality, rearing space, FCR, growth performance, survival and technical performance. *Drengstig & Drengstig (2003)* has given a detailed description of all components and investment costs for the new technological farming concept. In addition, Norwegian Lobster Farm AS has developed harvesting robots, robots for automatic transfer of IV-stage juveniles (Figure 12.1) and a software program for image processing of single individuals (Figure 12.2). All robots have been tested on live lobsters and industrialised.

The robot that transfers IV-stage larvae is able to detect whether or not the juveniles have reach the IV stage (Figure 12.1). If not, they are rejected and transferred back into the larvae incubator (described in Figure 4.2). Since this operation in the past has relied on manual labour, a major advance was made.





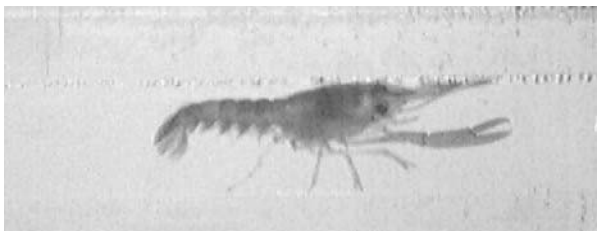


Figure 12.1. Lobster larvae, a prototype of the selection robot and photo image of a III-stage (lower left) and a IV-stage (lower right) larvae.

A software program has been developed for image processing of individual plate sized lobster (Figure 12.2). This program enables full control over moulting frequency, estimates the correct time for harvesting, and monitors growth and mortality.

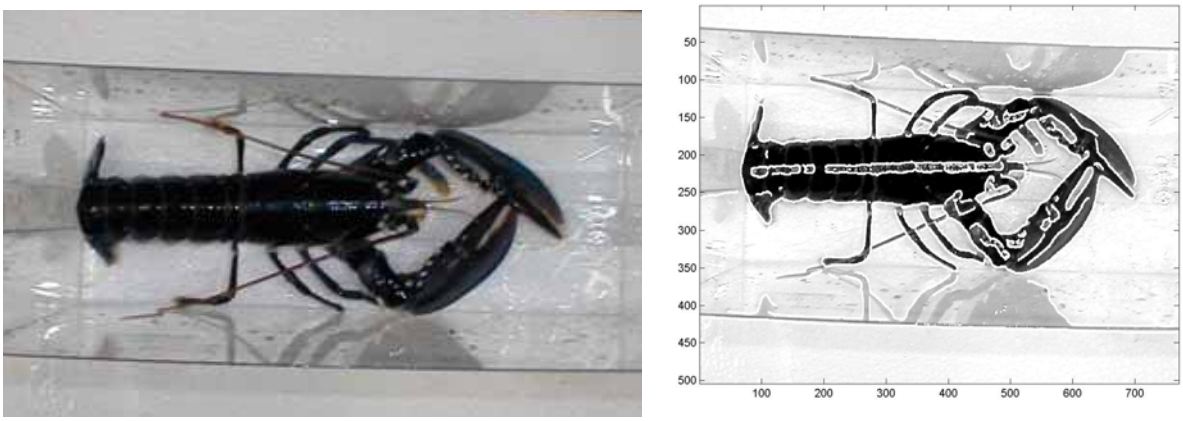


Figure 12.2. Plate-sized lobster and photo

A full scale factory for an annual production of 50,000 (15 metric tons) plate sized lobster and 430,000 juveniles in two different sizes for sea-ranching or on-growing purposes are being planned build in 2004/2005 at a new site at Kvitsøy (Leiasund on the eastern side of the island). The factory requires approximately 500 m^2 of land.

12.2 Investment frame

The total investment for the large-scale factory is MNOK15 including running capital for two years (MNOK 2) and unforeseen costs (MNOK 3). Core investment capital is thus MNOK 10. The payback time is 3.5 years, and the farm achieves a positive cash flow within 12 months. Average results are MNOK 2.5 annually.

12.3 Further research and development

Norwegian Lobster Farm will during the next year focus on the following areas:

1. Building of the prototype of the patented system containing approximately 7,000 juveniles of varying sizes (IV-stage up to 300 g)
2. Evaluate the technical safety of the system during a 12 month production
3. Controlling and documentation of the water quality dynamics and water management in the recirculation system
4. Evaluate the self-cleaning effect, and removal of particulate organic matter
5. Study growth and survival of the various sized lobsters during 12 month production time in the prototype
6. Quantify oxygen consumption rates and excretion rates (NH_3, CO_2) of lobster during all rearing stages
7. Further development and testing of a formulated feed for lobster
8. Compare growth and welfare in the prototype cages with ordinary cages
9. Evaluate the need for rearing space by using different cage sizes and design

10. Conduct a new test of product quality at the Culinary Institute in Stavanger
11. Identify critical factors in the semi-commercial phase, and identify mitigating measures to reduce the risk of investments
12. Fully develop automatic feeding machines, selection robots and photo image software programmes

These plans are currently financed solely by the company, but hopefully Innovation Norway or the Norwegian Research Council acknowledge our proposals for public funding to pay for experimental equipment and research assistance from experienced scientists in this critical phase of business development. In the past, many attempts on commercialising marine species have been strangled by undertaking too high costs in periods of development when income sources are scars. Thus, public funding is necessary as a relief of economic risk factors before companies has a high enough turnover to contribute in further development.

If lobster farming shall be a profitable industry, the necessary research must be carried out in concert with the industrial development. A national research and development program, that involve research on basic lobster biology and ecology, feeding and nutrition, intensive farming technology and tolerance to farming environment, and challenges related to sea ranching and stock enhancement, should therefore be initiated in the near future

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