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Rédaction du Bulletin

Susan Waddy

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Cover: *Loxechinus albus* juveniles in suspended cage culture in Chile
Photo courtesy of Christopher M. Pearce

Introduction

Chris Pearce



In many parts of the world, populations of sea urchins are declining.^(1,2) However, imports of sea-urchin products by Japan have been on a general increase for the last ten years or more (Figure 1), although overall value is on a slight decline (Figure 2). It is unlikely that future market demand for sea urchins will diminish and, as a result, it is predicted that aquaculture will be required to fill this potential gap between supply and demand. Over the past ten to fifteen years, commercial interest in rearing echinoids has increased in a number of countries, including Australia, Canada, Chile, China, New Zealand, Norway, Scotland, and the USA. Concomitantly, the amount of research on sea-urchin aquaculture has increased dramatically in the last decade and a half (Figure 3). The papers in this issue of the Bulletin of the Aquaculture Association of Canada (AAC) are a result of my request to the authors to summarize the state of research and commercial interest in sea-urchin aquaculture in particular countries interested in developing an urchin-culture industry. I would like to take this opportunity to thank all of the authors for their contributions (and patience with me), Leah Sauchyn for data analysis and figure production, and Susan Waddy (AAC Bulletin editor) for all her help in putting this issue together.

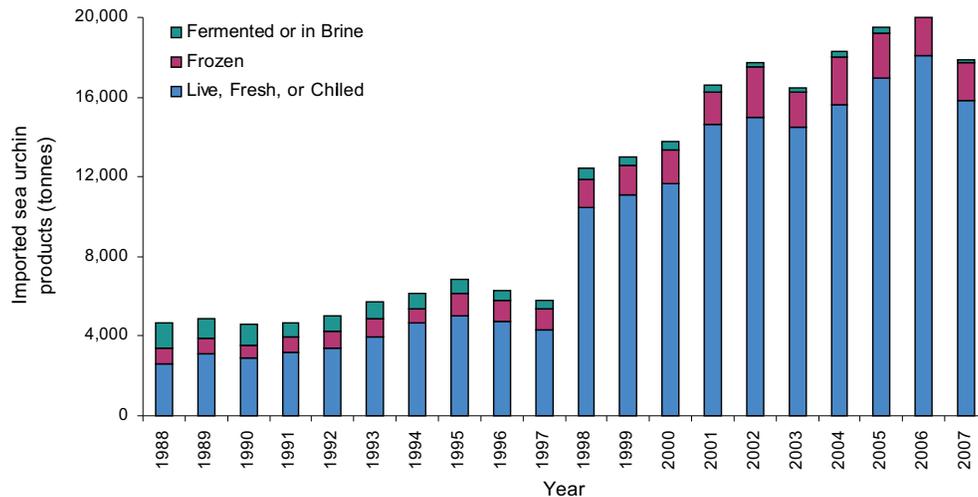


Figure 1
Tonnage of various sea-urchin products imported to Japan by year since 1988. Source: FAO Fisheries and Aquaculture Department, Fishery Commodities and Trade database (<http://www.fao.org/fishery/statistics/global-commodities-production/en>). Data published in: FAO Yearbook of Fishery Statistics, volumes 43 – 105 (1976 – 2007). Weights measured in national units and converted to tonnes (includes net weight of commodity, excluding weight of container and any liquid added).

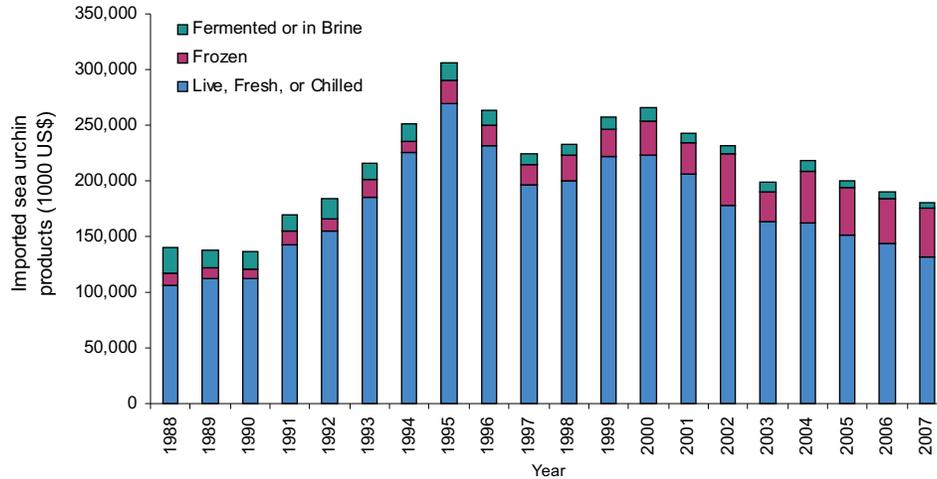


Figure 2
Value of various sea-urchin products imported to Japan by year since 1988. Source: FAO Fisheries and Aquaculture Department, Fishery Commodities and Trade database (<http://www.fao.org/fishery/statistics/global-commodities-production/en>). Data published in: FAO Yearbook of Fishery Statistics, volumes 43 – 105 (1976 – 2007). Values expressed in national currency units and converted to thousand US\$ by applying average annual exchange rates from the International Monetary Funds. Values are c.i.f. (cost, insurance, freight).

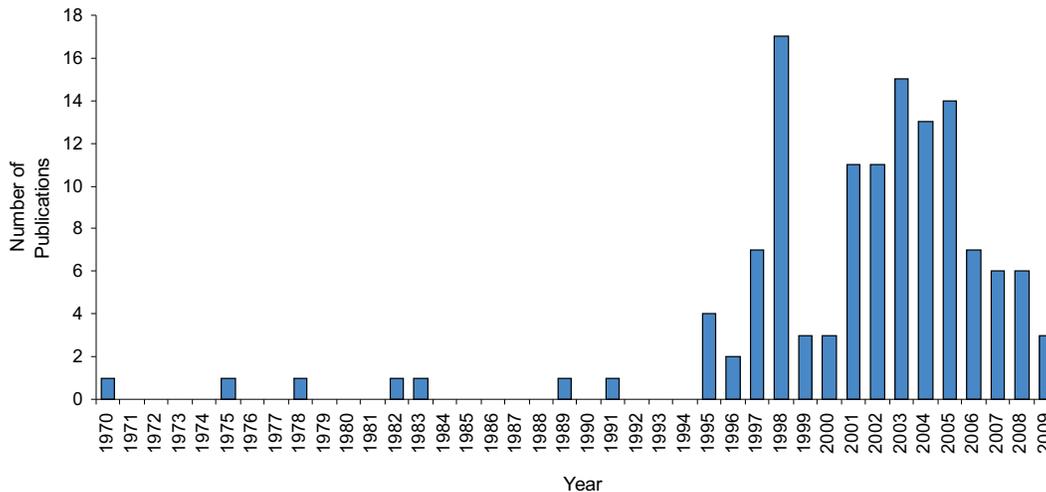


Figure 3
Number of publications on sea-urchin aquaculture by year since 1970. Literature search was conducted with Scopus using search parameters “urchin” AND “aquaculture” and looking for these terms in Article Title, Abstract, and Keywords. The abstract of each article was read to ensure that it was about sea-urchin aquaculture.

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Yukio Agatsuma

Recent Advances in Sea-Urchin Aquaculture in Japan

Yukio Agatsuma, Yuichi Sakai, and Ken-ichiro Tajima

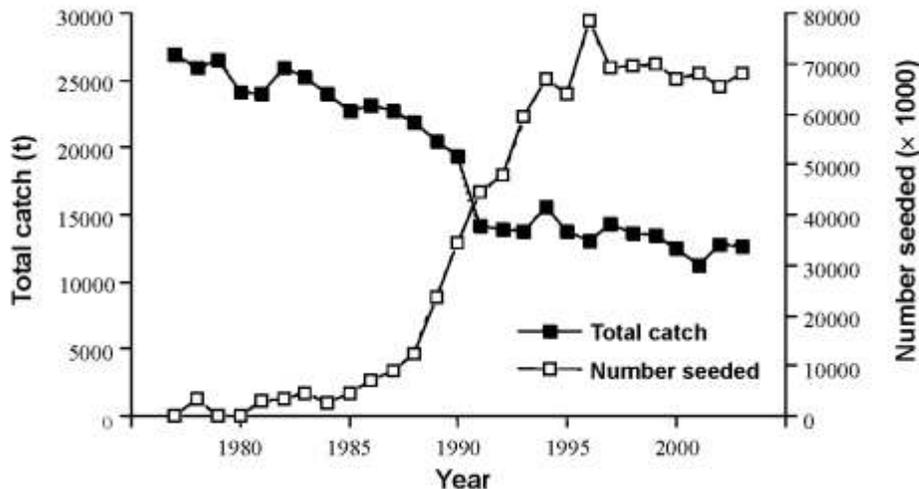
In Japan, the sea-urchin fishery is enhanced by seeding hatchery-raised juveniles into the wild. On national and prefectural scales, the effectiveness of the seeding program is being determined from the proportion of wild and cultured sea urchins in the harvest. Characteristics of the annual growth bands that form in grained and charred genital plates, or marking urchins with alizarin complexone (ALC), can be used to identify seeded urchins. In addition, under recent warming conditions, barren grounds are expanding and sea-urchin growth and gonad development are likely to be useful indicators for evaluating subtidal algal vegetation. Such indicators would contribute to the scientific basis for managing fisheries for wild and seeded sea urchins.

Introduction

In Japan, hatchery-raised juveniles are being used to enhance sea-urchin fisheries. The numbers of sea urchins seeded into the wild increased sharply in the late 1980s and has been relatively stable since 1997. In 2003, 68 million juveniles were released (Figure 1). Total fishery landings declined from the mid-1970s until 1991, and since then have fluctuated between 11,000 and 15,000 tonnes (Figure 1). It seems that the increase in the number of seeded urchins has had no effect on landings.

The two species *Strongylocentrotus intermedius* and *S. nudus* account for 70% of the total sea-urchin land-

Figure 1
Number of sea urchins seeded and total catch (tonnes) by year for all sea-urchin species and prefectures. [Data from the Japan Fisheries Agency, Japan Sea Farming Association, and Annual Statistical Report of Fisheries and Aquaculture Production]



ings in Japan.⁽¹⁾ Fisheries for these species are concentrated in Hokkaido and along the Pacific Ocean in Tohoku. In 2003, 59 million hatchery-raised juveniles of *S. intermedius* and *S. nudus*—accounting for 87% of total juvenile productivity in Japan—were seeded into the wild in Hokkaido. The number of seeded *S. intermedius* increased steadily to 60 million in 1996, then fluctuated between 53 million and 57 million (Figure 2). In contrast, catches of *S. intermedius* in Hokkaido, as indexed by roe weight, declined until 1992, then stabilized and even increased slightly until 1998 in parallel with the increase in seeding until 1996. The number of urchins seeded declined slightly in 2001 and then increased again until 2003 (Figure 2). The effectiveness of seeding on either a national or prefectural scale is still not clear. In addition, warmer seawater temperatures in recent years have tended to cause the barren grounds to expand to upper subtidal areas, in concert with the reduction in the marine forest. Actually, seeding at some localities along the Pacific coast in southern Tohoku has ceased.

In the present paper, we summarize recent advances in the hatchery production of *S. intermedius* and *S. nudus* (reviewed by Sakai et al.⁽²⁾) and provide a few examples of aquaculture in Hokkaido. We also argue for the development of technology to clarify the effectiveness of sea-urchin seeding on a prefectural and national scale and to evaluate algal vegetation which is closely associated with the growth and gonad production of wild and seeded sea urchins.

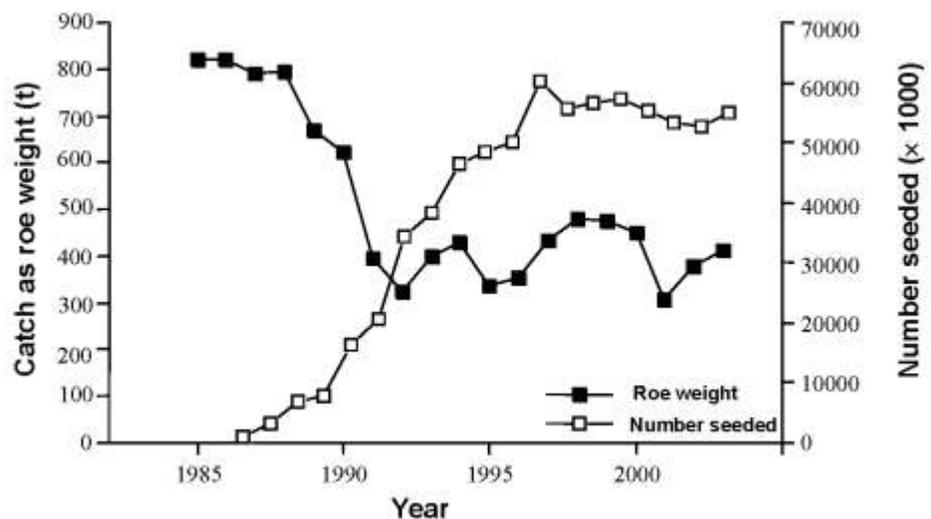
Hatchery

Broodstock

Reproductive cycles of *S. intermedius* differ among areas around Hokkaido.⁽³⁾ Seeded urchins have the same reproductive cycle as their parental broodstock. During the fishing season, gonad development of sea urchins seeded to areas different from the habitat of the broodstock can be inferior to that of the wild sea urchins, or gonad quality can deteriorate due to effusion of the gametes.⁽³⁾ Hence, hatchery-raised *S. intermedius* are now being released to the same, or adjacent, areas

Figure 2
Number of sea urchins *Strongylocentrotus intermedius* seeded and landings (roe weight in tonnes) by year from Hokkaido.

[Data from Japan Fisheries Agency, Japan Sea Farming Association, and Hokkaido Fishery Annual Statistics]



from which the broodstock originated. This also helps to avoid genetic disturbances. Furthermore, to maintain genetic diversity, no offspring are fertilized from seeded parents and fertilizations between parents are not repeated.⁽²⁾

Larvae and early juveniles

The amount of *Chaetoceros gracilis* fed to the larvae of *S. intermedius* and *S. nudus* is based on the food intake of each developmental stage.⁽²⁾ The 8-armed plutei, with fully developed rudiments, settle and metamorphose on corrugated PVC plates covered with *Ulvela lens*. Juveniles grow from a diameter of 0.3 to 5.0 mm in about 4 months. When they reach a size of 3 to 4 mm, *Laminaria* spp. and *Ulva pertusa* are also offered to them.⁽²⁾ Most juveniles that reach 5-mm diameter are seeded into the wild or are cultured intermediately until release.

Juvenile Grow-out and Gonad Enhancement

The recognition that fisheries may be limited in their ability to meet the demand for sea urchins has increased interest in aquaculture. Although urchin culture in Japan is still not widespread, studies have been conducted on roe enhancement and improvement of roe texture, firmness, taste, and colour (e.g. de Jong-Westman et al.⁽⁴⁾).

One of the few examples of the culture of hatchery-raised *S. intermedius* is being undertaken in western Tsugaru Strait, Hokkaido. Juveniles (12-mm diameter) are cultured in cages that are 80 cm x 80 cm x 30 cm deep with 5-mm mesh. The cages are suspended in the sea in March or April with 1,000 urchins per cage. Fresh cultured kelp is added to the cages once or twice a month, except during the winter when salted or boiled kelp is used. The number of specimens held in each cage is reduced as the urchins grow. Urchins reach the legal fishing size in Hokkaido (4-cm diameter) 14 months after the initiation of the culture. The urchins are harvested in March or September when the price is high. Survival rates to harvest exceed 90%. Mass mortality occasionally occurs during high water temperature in the summer, and this problem is not yet solved.

In the Sea of Japan, Hokkaido, *S. nudus* with undeveloped gonads are taken from barren grounds and intensively cultured for a short period of time to enlarge their gonads. They are then transferred to fishing ports, small inlets, or excavated rocky grounds with calm waters, and are stocked at a density of ca. 40 individuals m⁻².

Off the coast of the Sea of Japan in Hokkaido, the kelp *Laminaria japonica* is cultured as food for hatchery-raised *S. intermedius* until they are seeded. Growth of kelp is slow in the winter (until March). It is well known that foods with high protein content strongly promote gonad production.⁽⁵⁾ Fish flesh is one of the foods that promotes gonad development,^(6,7) but it causes the gonad to have a bitter taste due to the increase in valine⁽⁶⁾ and results in a white gonad.⁽⁷⁾ These features decrease the quality and market price of the gonad, which has led to changes in the approach used to enhance roe. During the winter, low-priced fish flesh (river-run salmon, Pacific saury, and arabesque greenling) are fed to sea urchins to enlarge their gonads. In the spring, the diet is changed to kelp, konbu, and wakame, which improves gonad quality.⁽⁷⁾ An abundance of cultured kelps are available from spring to summer, so the urchins are harvested twice a year—in the spring and summer. Grazing activity of the urchins is critical for the maintenance of enlarged gonads. Hence, moderate exchanges of water from the open sea to the cultured grounds is required to avoid the decline in water temperature in the winter that can result from low air temperatures.

Wild Stock Enhancement

Stock enhancement plays a major role in the management of sea-urchin fisheries in many Japanese prefectures, and in Hokkaido in particular.^(1,8) Enhancement efforts involve: 1) releasing cultured juveniles to augment the number of animals available for harvest; 2) providing additional habitat to increase the carrying capacity of inshore waters for sea urchins; and 3) improving the size and quality of the roe.⁽⁹⁾

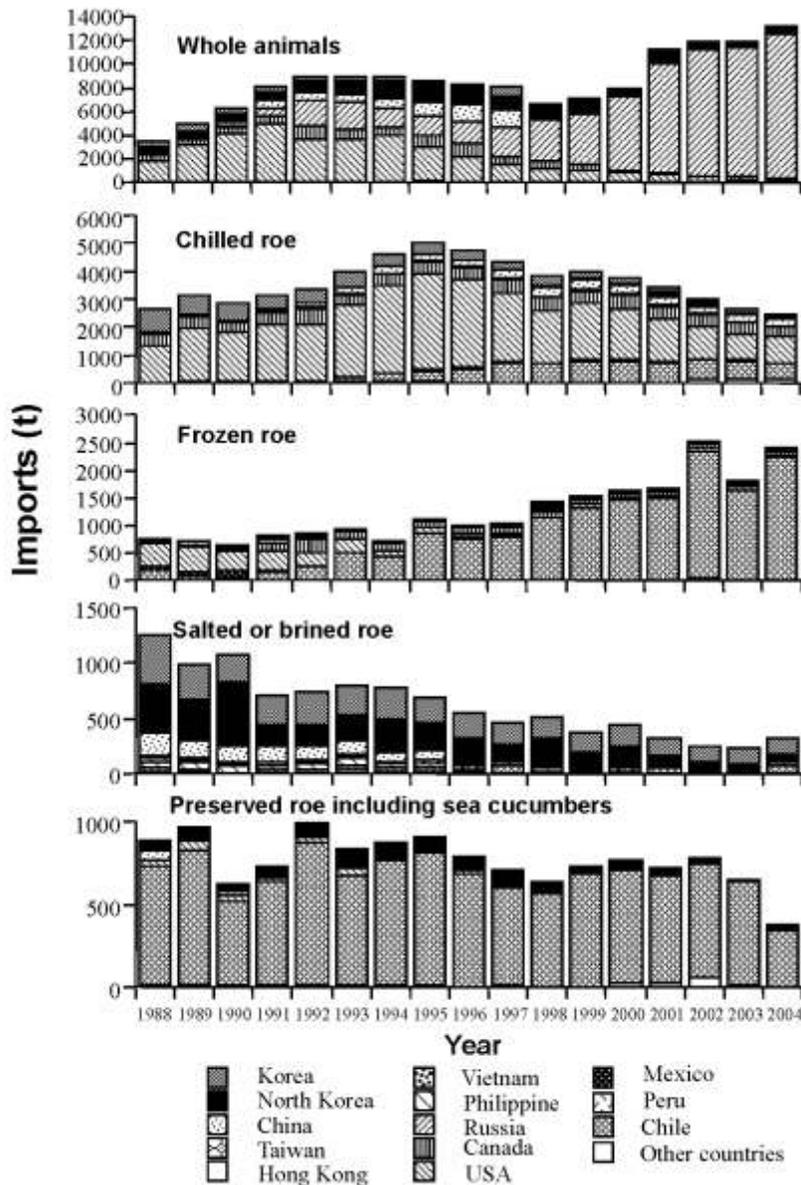


Figure 3
Quantity of sea urchins imported as whole animals, chilled roe, salted or brined roe, and preserved roe (including sea cucumbers) by year from major countries.
[Data from the Japan Tariff Association]

The effectiveness of seeding juveniles depends on the growth rate, gonad size, and survival of the sea urchins until harvest, as well as the cost of seed. To clarify the effectiveness of seeding on both a prefectural and national scale, it is necessary to distinguish between seeded and native sea urchins. Characteristics of the annual bands formed in grained and charred genital plates,⁽¹⁰⁻¹²⁾ and marking with the red fluorescent dye alizarin complexone (ALC),⁽¹²⁾ are effective for identifying seeded *S. intermedius*. Using these methods, some studies have demonstrated the positive effect of seeding on a local scale in Hokkaido.^(1,10)

Growth and gonad production of *Strongylocentrotus* spp. are greatly affected by the type and abundance of algae (e.g. Agatsuma⁽¹³⁾). A reduction in the marine forest results in a decrease in gonad size and an increase in the incidence of *S. nudus* with brown-coloured gonads.⁽¹⁴⁾ In northern Japan, subtidal vegetation affects a sere in the course of algal succession, altering the temporal expansion and reduction of marine forests or coralline flats.⁽¹⁵⁾ Hence, the present sere can be evaluated by classifying the algal vegetation as five life forms characterized by thallus size and longevity.⁽¹⁶⁾ Growth and gonad production of *S. nudus* and *Hemicentrotus pulcherrimus* can be ranked, in order, by the algal sere, climax, seral, and pioneer stages. In northern Japan, results suggest that growth and gonad production are affected by algal sere and species of small perennial algae in the seral stage with or without feeding-deterrent chemicals.^(13,17) Thus, urchins are likely to be useful as indicators for evaluating subtidal vegetation. Such indicators would enable the changes in species composition of algae and sere to be evaluated under recent warming conditions and would contribute to providing the scientific basis of managing fisheries for wild and seeded sea urchins. In the pioneer or seral stages, progression to climax marine forests is achieved by introduction of concrete blocks⁽¹⁸⁾ or removal of competitive algae by grazing pressure from seeded hatchery-raised juveniles.⁽¹⁰⁾

Future Studies

The Japanese market consumes more than 80% of the world production of sea urchins.⁽¹⁹⁻²¹⁾ Imports of whole animals from Russia and frozen roe from Chile have increased dramatically, while imports of chilled, salted, or brined roe have decreased (Figure 3). The increase in imports has lowered the Japanese market price of sea urchins, particularly for *S. intermedius* and *S. nudus*. Hence, growers have been forced to improve hatchery techniques to reduce production costs. The possibility of larval and juvenile rearing at high densities has been studied. Determination of the maximum stocking density, which will not negatively affect larval and juvenile growth and survival, will lower the cost of seed due to savings in labour costs and energy.

The effectiveness of seeding on national and prefectural scales can be evaluated from examining harvested sea urchins. In combination with data on fishing effort, it is likely possible to evaluate the size of wild and seeded urchin populations, and develop a rational approach to fisheries management.

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Recent Advances in Sea-Urchin Aquaculture in New Zealand and Australia

M. F. Barker

Evechinus chloroticus is the only sea urchin species commercially harvested in the north and south islands of New Zealand (NZ). In Australia, *Heliocidaris erythrogramma* and *Centrostephanus rodgersii* are fished in Tasmania and New South Wales respectively.

E. chloroticus survives well in shallow tanks of well-aerated running seawater maintained at densities of 1 urchin per 1.5 L of tank volume or in cages suspended in water with some tidal flow. Temperature range should be between 8° and 20°C depending on latitude. Urchins will survive well if fed several different kelp, especially *Macrocystis pyrifera* (southern NZ) or *Ecklonia radiata* (northern NZ). Adult and sub-adult urchins will also eat a range of commercial pellet (Wenger) or agar-bound artificial feeds and develop large gonads and viable gametes.

Larvae can be successfully reared in experimental quantities in small (3- to 5-L) beakers or pickle jars, or in commercial quantities in large 500-L fibreglass tanks. Larval densities in both systems should be 1 to 3 mL⁻¹ and larvae must be kept suspended using paddles or by bubbling air through the culture. When fed *Dunaliella primolecta*, *D. tertiolecta* or *Rhodomonas lens* at concentrations of 5,000 to 10,000 cells mL⁻¹ settlement and metamorphosis occurred 18 to 24 days after fertilization. Echinopluteus stage larvae will settle on a range of natural and artificial substrata with a 1° film. Settlement and metamorphosis is, however, most rapid on coralline algae. For settlement and grow-out of large numbers of juveniles we use a large V tank. Juvenile urchins initially graze the natural diatom film that forms on the tank walls, but at a diameter of 7 to 8 mm we introduce the macroalgae *Macrocystis pyrifera* for subsequent growth.

Gonads of *E. chloroticus* fed prepared feeds were white or cream colored and larger than the yellow or orange gonads from urchins fed algal diets. Enhancing artificial feeds with carotenoid pigments resulted in little change in colour. Sensory analysis by a taste panel of gonads of urchins fed prepared feeds show marked seasonal differences in taste, and testes were sweeter and preferred to ovaries of urchins fed the same diet. *E. chloroticus* held in sea cages and fed both artificial feeds and kelp developed larger gonads than wild urchins.

NIWA has tested feeds prepared from gelled fish skins and kelp diets in a range of experiments using both land-based and sea cages. They found little difference in gonad sizes between holding systems or with density of urchins or depth of cages, although gonad indices were higher in urchins from wave disturbed cages.

Experiments in South Australia show some potential for roe enhancement in *Heliocidaris erythrogramma*.

Introduction

Only one species of sea urchin, *Evechinus chloroticus* (Valenciennes), is commercially harvested in New Zealand and only in the last 3 to 4 years has the fishery expanded to catches of hundreds of tonnes. The biology and ecology of this species was recently reviewed.⁽¹⁾ Studies have been done on roe enhancement, but only limited work has been done on the culture and development of larvae and juveniles.

In Australia, two species have been commercially harvested: *Heliocidaris erythrogramma* in Tasmania and New South Wales, and *Centrostephanus rodgersii* in New South Wales.⁽²⁾ The only aquaculture research on these species has been on the post-harvest enhancement of *H. erythrogramma* roe.⁽³⁾

Hatchery

Broodstock

Evechinus chloroticus (known in New Zealand as kina) survive well in tank systems when they are provided with an adequate water supply, are reasonably well fed, and are not kept in over-crowded conditions. New Zealand spans a wide latitudinal gradient with summer water temperatures in shallow water ranging from 18° to 23°C, and temperatures can be even higher in land-based tanks. To keep urchins in good condition at temperatures above 20°C, flow rates need to be increased and densities of urchins lowered, especially for larger animals.

a. Rearing systems

At our laboratory, we keep 130 to 150, 70- to 80-mm diameter kina in good condition in shallow 215-L tanks (2.2 m x 1.4 m x 0.7 m deep) at a density of approximately 1 urchin per 1.5 L of tank volume. Fresh filtered seawater is provided from a single outlet at a rate of 10 L min.⁻¹ Spraying water into the tank from multiple jets is a better arrangement, however, as it allows for higher oxygenation of the water. The water exits from a single standpipe protected with plastic mesh to prevent urchins or food material from clogging the outlet. The advantage of shallow tanks is that urchins can be easily fed and checked, and uneaten food and dead or moribund animals removed. An alternative holding system is to place animals in cages suspended in the sea from a wharf or buoy system. Providing the cage is in an area with adequate water currents, this is a very convenient way of holding large numbers of animals without utilising tank resources. The disadvantage of using cages is that access for feeding or cleaning is more difficult and marine fouling can reduce water flow in fine-mesh cages. Coarser mesh can be used, providing feed, especially if in pellet form, stays in the cage. Urchins collected from some field sites have a tendency to move up the sides of tanks so that a portion of the test is exposed to air. While this can occur as a result of animals at lower levels in the tank forcing smaller and higher individuals out of the water, some urchins will climb out of the water even when tank densities are low. When this occurs it is necessary to fit tanks with heavy or tight-fitting lids.

b. Physical requirements

A prime requirement for almost all sea urchins is good quality sea water. *E.*

chloroticus requires well-oxygenated flowing seawater within a temperature range of 8° to 20°C. Urchins in northern New Zealand will tolerate water temperatures as high as 23° to 24°C, but they show signs of severe stress or morbidity if temperatures rise above this level. Similarly, urchins will tolerate water temperatures of less than 8°C, but movement and feeding rates decline markedly.

c. Feed

Providing algae are available, and operators have access to them (harvesting is tightly controlled by conservation and fisheries regulations in New Zealand), they are the ideal food because they are the natural feed of sea urchins. In the south of the country, the laminarian bladder kelp *Macrocystis pyrifera* is used as feed and is occasionally supplemented with the green alga *Ulva lactuca*. In more northern areas, the laminarian *Ecklonia radiata* is often the dominant laminarian and is also one of the more common dietary items of wild urchins. Algae will support growth of both smaller and larger urchins, and urchins fed algae develop gonads with high-quality gametes. Adults will consume a variety of artificial diets and develop large gonads and produce viable gametes. Little research has been done on the development of artificial feeds for the growth of adult or juvenile *E. chloroticus*. Neither is it known how gamete quality differs between urchins fed artificial and natural diets.

Larvae

a. Rearing systems

A main requirement of rearing larvae of any planktotrophic invertebrate is keeping both the larvae and their algal feed in suspension. This can be achieved in different ways. When rearing larvae in small volumes (3 to 5 L) for experimental purposes we use 4- or 5-L Pyrex beakers as the rearing chambers, although a much cheaper option is to use 3- or 4-L pickle jars. These can often be obtained from the restaurant trade, but require extensive rinsing before use. To keep the larvae suspended we have tried a range of devices, and are now using a system originally designed by Richard Strathmann that is comprised of a rack with a series

of horizontal wires from which PVC paddles hang, one per container (Figure 1). The paddles are moved sideways with a second frame suspended by wires below the top rack, also with horizontal wires. This lower frame is moved 5 to 10 cm sideways with a small cam mounted on an electric motor revolving at 10 revolutions min⁻¹. The water in culture vessels should be changed at least every two days. A convenient way to do this is to pour the culture through a filter immersed in seawater

Figure 1
Larval suspension apparatus.
Plastic paddles hang from a plastic frame and are pushed by the underlying plastic frame. The inset shows the cam that pulls the underlying frame.



held at the same temperature as the culture. It is important to ensure that larvae are not poured directly against the filter, i.e. they should be poured into the water which then flows out through the bottom. A simple but effective filter system can be made by gluing Nytex® (100-µm mesh size) to the bottom of a 10- to 20-cm length of plexiglass or PVC pipe and gluing a short (1 to 2 cm) section below the filter.

For larger mass cultures we use 500-L rounded-bottom tanks (Figure 2). The basic culture method is the same as that used for the smaller beaker systems. However, instead of paddles, an aquarium airstone is placed on the bottom of the tank to provide good airflow and sufficient water circulation. It is often too time consuming to change the water every second day; however we complete a partial water change by allowing filtered (0.28 µm) water to flow into the tank which has a ‘banjo’ filter attached to a standpipe outlet to prevent larvae from being flushed away. The flow needs to be slow, ~ 20 to 40 L hour⁻¹, to prevent larvae becoming stranded against the filter. For complete water changes—every 3 to 5 days, depending on the condition of the larvae—a scaled-up version of the PVC pipe filter described above can be used. Water should be siphoned from the tank at a flow rate of approximately 100 L hour⁻¹. This prevents larvae becoming damaged against the filter, which will need to be washed into a clean tank every 15 to 20 minutes.

b. Physical requirements

Larvae are more sensitive than adults to water quality. The build-up of metabolic wastes, as a consequence of high concentrations of larvae in relatively small volumes of water, is a long-standing problem in larval culture. Larvae also require stable water temperatures. *Evechinus chloroticus* will develop in temperatures of 10° to 20°C. However, at temperatures below 12°C development is prolonged, and at temperatures above 18°C bacterial populations can develop rapidly, requiring more frequent water changes. We have found 15° to 16°C is the ideal temperature for larval development. Water quality will vary with the site, but water should be taken from the open coast wherever possible and filtered to at least 1 µm (although ideally to 0.2 µm). Cartridge filters provide a convenient way to filter large volumes of water relatively quickly.

Larvae can be reared at concentrations of up to 4 to 6 mL⁻¹ from early embryos to the 4-armed pluteus stage. However, we progressively dilute cultures as larvae mature: concentrations of 2 to 3 mL⁻¹ at the 6-armed stage, no more than 2 mL⁻¹ at the 8-armed stage, and ideally 1 mL⁻¹ as they approach the echinopluteus stage (see Table 1).



Figure 2
500-L fiberglass tank used for the mass culture of *Evechinus chloroticus* larvae. A ‘banjo’ filter that prevents the loss of larvae during water exchange is attached to the standpipe outlet.

Table 1. Chronology of development of *Evechinus chloroticus* at 15°C

Stage of Development	Time
Fertilization	0
Late blastula/early gastrula	24 h
Prism—skeletal rods present, gut complete	48 h
4-armed feeding pluteus	4-5 d
6-armed pluteus	9-10 d
8-armed pluteus, epaulettes forming	12 d
8-armed pluteus, epaulettes complete	14 d
Early echinopluteus, pedicellaria forming	19 d
Mature echinopluteus, tube feet present	21 d
Settlement when pipetted onto <i>Corallina</i>	24-28 d

As larvae become competent to settle, they need to be provided with a suitable substratum. Although the echinopluteus will settle and metamorphose on a range of substrata—in fact almost any hard substrate with a well-developed primary film will eventually induce metamorphosis—larvae settle most rapidly on encrusting coralline algae.⁽⁴⁾ For experimental cultures, small rocks with encrusting coralline algae can be placed directly into culture beakers. For mass culture, competent larvae are better transferred into tanks provided with a well-developed primary film or settled with a diatom film. If tanks are allowed to stand with running seawater and some illumination, such a film will develop naturally over several days.

c. Feed

Evechinus chloroticus larvae will develop through to settlement in 25 to 30 days using either *Dunaliella primolecta* or *D. tertiolecta* at concentrations from 5,000 to 10,000 cells mL⁻¹. However, the most rapid development to settlement (18 days) is achieved by feeding larvae with *Rhodomonas lens* at concentrations of 8,000 cells mL⁻¹. It is possible that a diet of mixed algal species might provide a better range of fatty acids and would prove to be superior to unialgal diets, but experiments to develop a better diet have not yet been conducted.

Early juveniles

a. Rearing systems and physical requirements

At the completion of metamorphosis, *E. chloroticus* juveniles are 0.38 mm in diameter. Juveniles will grow in almost any size or shape of tank, provided there is an exchange of seawater and a suitable algal food. We have found that an ideal tank for rearing juvenile urchins is one similar to the V tanks used by the abalone industry in New Zealand to rear juvenile abalone. These tanks can be made of fiberglass or PVC plastic. The design used at our laboratory is shown in Figure 3 and comprises a white PVC tank (2.44 m x 0.9 m x 0.45 m high) fitted to a wooden stand. The V shape ensures that particulate waste, which can smother juveniles and also creates potential BOD (biological oxygen demand), falls to the bottom of the V so that it can be periodically siphoned out with little effort. Water is trickled into the tank at one end and exits from a top-mounted outlet. Vertical PVC partitions increase the surface area on which juvenile urchins can graze. We introduce ready-to-settle echinopluteus larvae into this tank and allow them to settle directly on the tank walls. The water can be either turned off for 24 to 48 hours while metamorphosis occurs, or a Nytex[®] screen can be used to prevent larval loss.

b. Feeds

Juveniles graze directly on a diatom film that develops naturally on the walls of tanks provided with running sea water and natural or artificial lighting. Light intensity is quite critical; if light levels are too high, it will often encourage diatoms and other epiphytic algae to grow faster than larvae can graze them down and the juveniles can smother.

Figure 3
V-tank used for settlement of echinopluteus larvae and growth of metamorphosed juveniles.



Juvenile Grow-out

Land-based rearing systems

Juveniles grow to 7- to 8-mm diameter in the above V-tank system, feeding entirely on the diatom film. At this size, urchins will start to feed on macroalgae. If lamina of *Macrocystis pyrifera* are introduced to the tank, juvenile urchins will move onto these and can be gradually weaned off grazing diatoms. It is likely that *Ecklonia radiata* would also be a suitable diet for small urchins, but I have not tried this species. Growth rates increase once juveniles are feeding directly on laminarian algae.

Gonad Enhancement

Land-based rearing systems

Because of the variable gonad colour (cream to brown) and an apparent bitter taste⁽⁵⁾ *E. chloroticus* roe has proved difficult to sell in southeast Asian markets. Improvements in roe quality are essential if the New Zealand fishing industry wishes to supply these markets. Attempts to enhance the colour and taste of roe have produced quite variable results. A study was conducted in which *E. chloroticus* were fed either extruded pellets, agar-bound prepared feed, or natural algal food to three sizes of urchins (30 to 40 mm, 50 to 60 mm, and 70 to 80 mm diameter) held in individual containers during the austral autumn, winter, and spring.⁽⁶⁾ Gonad indices were higher in urchins fed prepared feeds than algae; however there were seasonal differences in which of the four prepared feeds produced the largest gonads. Prepared feeds tended to produce white or cream coloured gonads unsuitable for sale, whereas urchins fed algae generally formed yellow/orange gonads. This study concluded that although prepared feeds can enhance gonad production in *E. chloroticus*, the diets that were trialed did not produce the desirable yellow/orange gonad colour or good somatic growth.

Attempts to improve colour by enhancing levels of carotenoid pigments in diets⁽⁷⁾ also produced variable results with little overall improvement in colour. Current research at Otago University is refining soy protein based diets enhanced with mussel (*Mytilus galloprovincialis*) tissue and dried kelp with some encouraging improvements in colour. This research programme also includes detailed proximate analysis of roe and sensory analysis of odour, colour, and taste. The results of experiments so far completed show significant seasonal differences in the effect of different supplementary amino acids on taste. Ovaries had an intense sulphur odour, bitter taste, and a sulphur, herbaceous or metallic flavour. They also had an intense metallic and bitter aftertaste, that was long-lasting. Testes were generally sweeter and more acceptable to the taste panel.

The National Institute for Water and Atmospheric Research (NIWA) has also been involved in a series of sea-urchin roe enhancement trials over the past 2 years using both artificial diets and natural algal feeds. A water-stable artificial diet, similar in composition to that developed by the Norwegian Institute of Fisheries and Aquaculture (fish skins gelled with the enzyme transglutaminase) was fed to groups of kina held in plastic baskets in land-based tanks.⁽⁸⁾ These diets increased the quantity and consistency of roe colour in a period of 10 weeks.

Sea-based rearing systems

Kina held in sea cages in a pilot commercial-scale experiment were fed a range

of both artificial diets and seaweeds.⁽⁹⁾ Artificial diets produced the greatest increase in gonad indices from 8% wet weight at the start of the experiment to 23.15, 18.83, and 20.81%, respectively, in three sequential experiments conducted through the year. These increases were significantly higher than for all other diet treatments and for gonads collected from urchins in field populations over the same time periods. Urchins fed *M. pyrifera* produced gonad indices (18.16, 12.96, and 18.29%) significantly higher than for other algal treatments and field populations, although not quite as high as those obtained using artificial diets. The best roe colours were produced by urchins fed algae, especially *M. pyrifera* and a switched artificial/*M. pyrifera* diet.

NIWA has also conducted experiments comparing sea-cages vs. land-based systems for holding wild-caught urchins on two commercial mussel farms in the Marlborough Sounds at the top of the South Island. Over a 10-week enhancement period there were no significant differences in roe quantity (GI) or quality (colour) between the two systems.⁽¹⁰⁾ The effects of depth and stock density were also examined and the results showed no significant differences between urchins held at depths of 3 or 6 m, or between urchins held at low and high density.⁽¹⁰⁾ The effects of wave and feeding disturbance were measured by holding urchins in sea-cages suspended from a surface line (wave disturbed) or from a subsurface line buoyed from a bottom line (not wave disturbed) and fed and cleaned *in situ* underwater (no feed disturbance) or removed from the water for feeding and cleaning (feed disturbed).⁽¹¹⁾ Increased water movement in the wave-disturbed cages resulted in a higher gonad index (GI) compared to urchins in cages that were sub-surface buoyed. Feeding disturbance had no effect on the GI values or colour quality of the urchin gonads, regardless of the disturbance treatment.⁽¹¹⁾

Wild Stock Enhancement

There are no published accounts of experiments where urchins have been moved from areas known to have poor gonad production to areas where gonad growth is better.

Some short-term experiments have been completed where pebbles encrusted with coralline alga on which recently-settled juveniles (0.38-mm diameter) were transplanted into caged and uncaged sites at two depths in Doubtful Sound and Otago Harbour (Barker, unpublished). Survival was consistently higher after 2 days than 21 days treatment, in caged compared to uncaged treatments, and in shallower (12 m) compared to deeper sites (16 m). These experiments need to be repeated over a longer time period and with a range of juvenile sizes at different sites before any firm conclusions can be drawn. However they have shown that re-seeding of laboratory cultured urchins is technically possible.

Heliocidaris erythrogramma

Four laboratory trials and one sea-cage trial were run in South Australia to determine the effect of environmental and nutritional factors on roe enhancement in the purple sea urchin *Heliocidaris erythrogramma*.⁽²⁾

The most appropriate size of sea urchins for roe enhancement was found to be approximately 72-mm test diameter. *H. erythrogramma* of 80-mm diameter produced larger roe than animals of intermediate size and smaller (mean size: 55.5 mm). Although much of the roe of this size group was fine-textured, it was light in colour and little was of high quality.

The results of trials using either an imported Wenger diet (Wenger Manufactur-

ing, Inc., Sabetha, KS), or locally manufactured equivalent, in both land-based systems and in sea-cages, suggest that between 70 and 90 days are necessary to produce adequate roe yield (10% of wet body weight). In laboratory trials conducted over the spring and early summer using the Wenger diet, “the final mean roe yield for medium-sized sea urchins was 12.28% (initial yield: 4.01%) after 84 days, with 74% of the sea urchins producing yields over 10%. In the field trial, 80 days were sufficient to achieve a mean yield of 11.2% (initial yield: 2.63%), with 63% of sea urchins producing yields of over 10%. Both trials were run during spring/early summer with the result that a moderate percentage of sea urchins showed mature roe, prone to leakage, which in a commercial setting would reduce the value of the product. Thus it is recommended that sea-cage roe enhancement should be conducted during the cooler months while gonads are still premature (i.e. April to September), which may lengthen the time taken to achieve commercially useful roe yields, but should optimise the roe quality”.⁽²⁾ It is suggested that sea-cage culture rather than land-based systems would be more commercially viable.

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Nils Hagen

Recent Advances in Sea-Urchin Aquaculture in Norway

Nils T. Hagen and Sten I. Siikavuopio

Sea-urchin aquaculture (echiniculture) in Norway is being developed along two separate paths with some overlap. Bodø University College (HBO) is pursuing a strategy of full domestication, with the explicit goal of bringing the entire production cycle of the sea urchin under a controlled industrial regime, whereas the Norwegian Institute of Fisheries and Aquaculture Research (NIFA) is developing techniques for gonad enhancement of wild urchins using formulated feed. Both institutions focus their R&D efforts on the green sea urchin, *Strongylocentrotus droebachiensis*. The closely related species *S. pallidus* is also being investigated at HBO, as it appears to be largely resistant to infection by the parasitic nematode *Echinomermella matsi*.⁽¹⁾ Nematode infection is easy to prevent in land-based echiniculture facilities using hatchery-reared juveniles, but all sea-based urchin aquaculture in northern Norway is susceptible to infection by *E. matsi*. *S. pallidus* is, therefore, targeted as an integral part of an ongoing effort to develop a disease-resistant sea-urchin variety suitable for both land-based and sea-based echiniculture.⁽²⁾

Hatchery

The only sea-urchin hatchery in Norway is located in Bodø. HBO's main emphasis is the development of methods for continuous mass production of larvae and juveniles of *Strongylocentrotus droebachiensis*. Experimental quantities of *S. pallidus* and hybrids of the two species are also being produced. The hatchery is supplied with running seawater from a depth of 250 m, where salinity and temperature remains stable at 35‰ and 7°C throughout the year.

Broodstock

Broodstock are maintained in plastic shopping baskets in a simple rearing system consisting of racks of standard salmon hatching trays. Both wild and cultivated broodstock are fed on fresh kelp, *Laminaria hyperborea* and *L. digitata*. Gametogenesis of captive broodstock is not synchronized.⁽³⁾ Although gamete quantity and quality vary, it has nevertheless proved feasible to initiate spawning and start new larval cultures on a weekly basis throughout the year.

Spawning is routinely induced by intracoelomic injection of isotonic KCl solution,^(4,5) as electric stimulation is not recommended.⁽⁶⁾ Males and females are kept separately to prevent uncontrolled female spawning. Individual identification of sea urchins is feasible by intracoelomic insertion of electronic transponder tags,⁽⁷⁾ but the cost of tags precludes routine tagging of the entire broodstock population.

Larvae

Larvae are reared in 160-L tanks with a cone-shaped bottom, and a gentle flow of filtered seawater (Figure 1). Water drains through a central standpipe with a double banjo filter, and the water level is controlled by an external overflow pipe. Larvae are kept in suspension by gentle aeration or with mechanical agitation by a submerged plastic propeller. Larvae are fed once or twice per day cultivated microalgae including *Chaetoceros gracilis*, *Dunaliella tertiolecta*, and *Hymenomonas elongata*. The amount of food is routinely adjusted after microscopic inspection of the shape, pigmentation, and stomach content of larvae (Figure 2). The rearing temperature is kept below 10°C, and time to metamorphosis is approximately 30 days.



Figure 1
Larval rearing tanks at the sea-urchin hatchery in Bodø, Norway.

Early juveniles

Early juvenile rearing in Bodø is based on the Japanese system⁽⁸⁾ where competent larvae are induced to settle on corrugated plastic plates covered with cultivated benthic diatoms that provide the initial food for postlarvae and early juveniles (Figure 3). The growth of diatoms on the settlement plates is controlled by the amount of artificial light from fluorescent light tubes positioned directly above the rearing tanks. Detachment of early juveniles from the plates is facilitated by KCl-induced paralysis.⁽⁹⁾

Early juveniles may require inter-

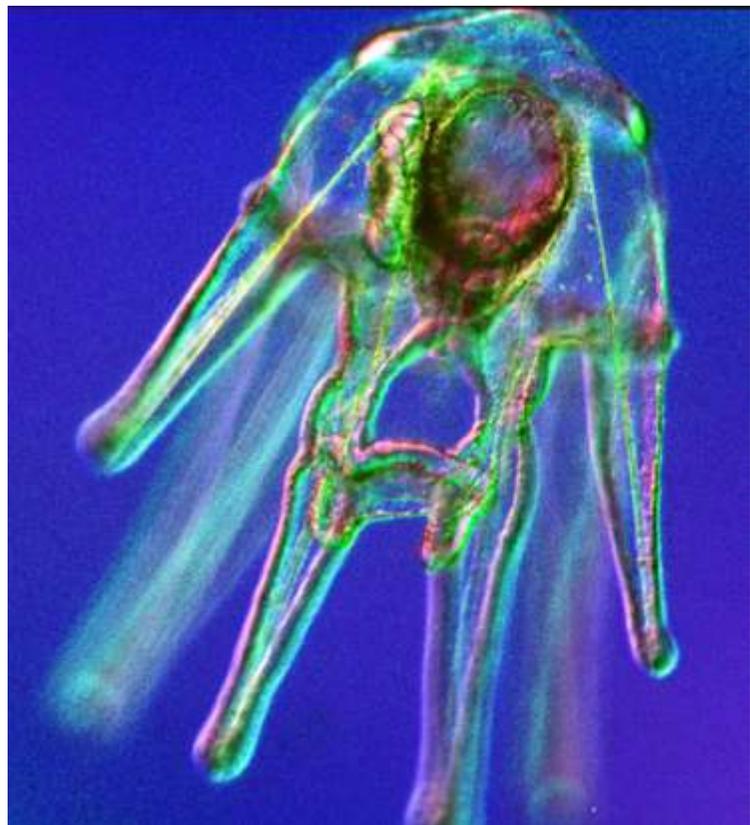


Figure 2
Sea-urchin larva with early juvenile rudiment on the left side of the stomach.

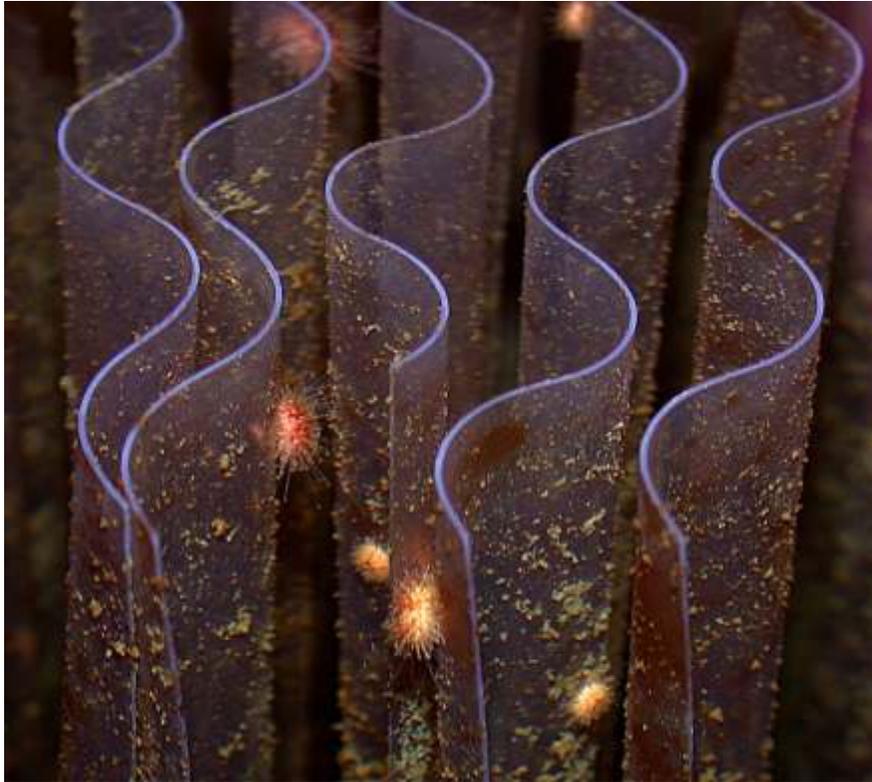


Figure 3
Early sea-urchin juveniles on corrugated settlement plates.

mediate culture and additional feeding with locally available foliose seaweed, such as *Ulva lactuca* or *Palmaria palmata*, before they are ready for transfer to grow-out.

Juvenile Grow-out

Grow-out trials are currently conducted in a variety of experimental containers, as a commercial-scale juvenile grow-out system for sea urchins is not yet available. Both land- and sea-based systems face the dual challenges of maximizing production capacity and minimizing maintenance effort. Juveniles fed fresh kelp may reach harvestable size in approximately 2 to 3 years of grow-out

cultivation,⁽¹⁰⁾ and recent trials with a new dry food from NIFA (Figure 4) suggest that the grow-out time may be reduced to less than 2 years.

The gonad index of cultivated sea urchins may be greater than 25%, or approximately twice the average gonad size of urchins

harvested from natural populations.⁽¹¹⁾ Ongoing experiments at HBO are aimed at improving the composition and pigment content of formulated feeds, in an attempt to match the superior colour, consistency, and flavour of gonads from urchins fed fresh kelp.⁽¹²⁾



Figure 4
Experimental production of dry feed pellets for sea urchins.

Gonad Enhancement

Although NIFA had previously developed a moist, formulated feed for sea-urchin gonad enhancement,⁽¹³⁾ they have recently amalgamated with the Norwegian Herring Oil and Meal Industry Research Institute, and are now focusing their research on the development of an improved commercial dry feed suitable for both grow-out and gonad enhancement. Feed composition influences both the ‘bitter taste’ and the ‘sweet taste’ of sea-urchin gonads. The undesirable bitter taste is associated with increased levels of the amino acid valine, while the desirable sweet taste is associated with increased levels of the amino acids alanine and glycine.⁽¹⁴⁾

Sea urchins in gonad enhancement trials are prone to increased mortality during the first four weeks after harvest. Controlled experiments have demonstrated that such post-harvest mortality is caused by lack of salt water immersion and rough handling during harvest and transport. Rough handling may also cause non-lethal injuries which lead to reduced gonad growth due to a combination of reduced appetite and lower feed conversion efficiency.⁽¹⁵⁾

Gonad enhancement in experimental land-based rearing systems has been carried out successfully at sea-urchin densities up to 6 kg⁻².⁽¹⁶⁾ Increased mortality and reduced gonad growth at higher stocking density may be due to the fact that adult *S. droebachiensis* has a relatively low tolerance of nitrite⁽¹⁷⁾ and ammonia,⁽¹⁸⁾ because they have a low oxygen requirement (< 0.15 mg min⁻¹ kg⁻¹ at temperatures < 14°C).⁽¹⁹⁾

A prototype of a new commercial system for sea-based cultivation of sea urchins is currently being tested in northern Norway (see www.seanest.no). A feed-lot based management scheme for harvesting natural urchin populations is also being evaluated (www.sjomatkllynge.no).

Processing

Attempts to operate processing plants for sea urchins in Norway have failed, possibly due to the variable quality and unpredictable supply of sea urchins from natural populations. As a result, wild sea urchins from Norway are now exported whole for processing abroad. This practice greatly increases the risk of accidentally introducing the parasitic nematode *Echinomermella matsi* into new areas. This epizootic parasite was discovered only 30 years ago,⁽²⁰⁾ and is still not reported outside northern Norway.

Prospects

Sea urchins are short-listed among the candidate species worthy of inclusion in national efforts to diversify the aquaculture industry.⁽²¹⁾ Recent developments in dry-food manufacturing and hatchery production may prompt greater national involvement in the strategic development of echiniculture in Norway. A successful echiniculture industry would also benefit sea-urchin harvesters by providing needed access to domestic processing and marketing channels.

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Recent Advances in Sea-Urchin Aquaculture and Enhancement in Scotland and Ireland

Maeve S. Kelly and John Chamberlain

The sea-urchin culture strategies adopted by researchers in Scotland have a very different focus than those of researchers and a commercial producer in Ireland. Currently targeting *Paracentrotus lividus*, researchers from the Scottish Association of Marine Science (SAMS) are focusing on producing *P. lividus* in integrated aquaculture systems, culturing the sea urchin alongside both Atlantic salmon and the blue mussel. In Ireland, Dunmanus Seafood continues to pioneer Europe's first commercial production of sea urchins. Hatchery-reared juveniles are grown to market size mainly by ranching and are then seeded to rock pools or sub-tidal areas. At the University College Cork, research is focusing on a novel land-based rearing unit—the UP system—and on producing new binders for moist diets, which increase their shelf-life and stability in sea water.



Maeve Kelly

Introduction

Scotland is slightly unusual amongst nations with active research into sea-urchin cultivation in that, despite having three edible urchin species, there has not been a major fishery in recent times. The large and common *Echinus esculentus* has been fished in the past from Cornwall, England, but for its test—as a curio—rather than for its gonad. With the exception of some small landings in the Shetland Isles, the poor-tasting and variable gonad content of this species, and its poor survivorship in transit, have prevented major fishing efforts. *Psammechinus miliaris* is also abundant, but the gonad generally has a low biomass for much of the year, and is perceived by the marketplace as being too small to warrant commercial extraction. However, in a farmed environment, the gonad content can reach acceptable quantities.⁽¹⁾ *Paracentrotus lividus* is at the northernmost limit of its range in Scotland, with only a few, scant populations recorded. This species, however, was the subject of a considerable fishing effort in southern Ireland throughout the late 1970s and early 1980s. At its peak in 1976, more than 350 tonnes were extracted,⁽²⁾ but the fishery rapidly declined in the early 1980s. Since 1993 only minimal quantities (~ 2 tonnes per annum (p.a)) have been fished and the population shows no sign of recovery.⁽³⁾ As a consequence, research activity in Scotland (SAMS) has explored the potential of all three species,^(1,4) whilst research effort in Ireland focuses exclusively on *P. lividus*.

Europe's first commercial sea-urchin operation is found in southern Ireland: Dunmanus Seafoods, established as a sea-urchin hatchery in 1995, produces *P. lividus* juveniles, which are primarily on-grown by ranching. The majority of the

resulting produce is sold via shellfish buyers to the UK restaurant market, although the domestic Irish market is expanding. Current prices are 15 Euro kg⁻¹ for a market size urchin of 60 to 70 g. A smaller proportion of their produce goes to the French market or for biomedical research.

Hatchery

Broodstock

All three species of sea urchins have an annual reproductive cycle and can be induced to spawn in early (*P. miliaris*)⁽⁵⁾ and mid (*P. lividus* and *E. esculentus*)^(6,7) summer, with some local variation. Broodstock are collected from local wild populations. The commercial producer in Ireland, Dunmanus, is able to discriminate between intertidal and subtidal populations in terms of their quality as broodstock; whilst the latter have a larger gonad and are more fecund, the intertidal urchins perform more robustly in the hatchery. Dunmanus has also initiated a breeding program, retaining a selection of the fastest growing individuals to serve as broodstock for subsequent seasons.

Broodstock are typically held in flow-through seawater tanks and conditioned on natural diets: *Saccharina latissima* for *P. miliaris* and *Laminaria digitata* for *P. lividus*. The effect of broodstock diets on fecundity, egg quality, and subsequent larval performance has still to be fully evaluated in these species.

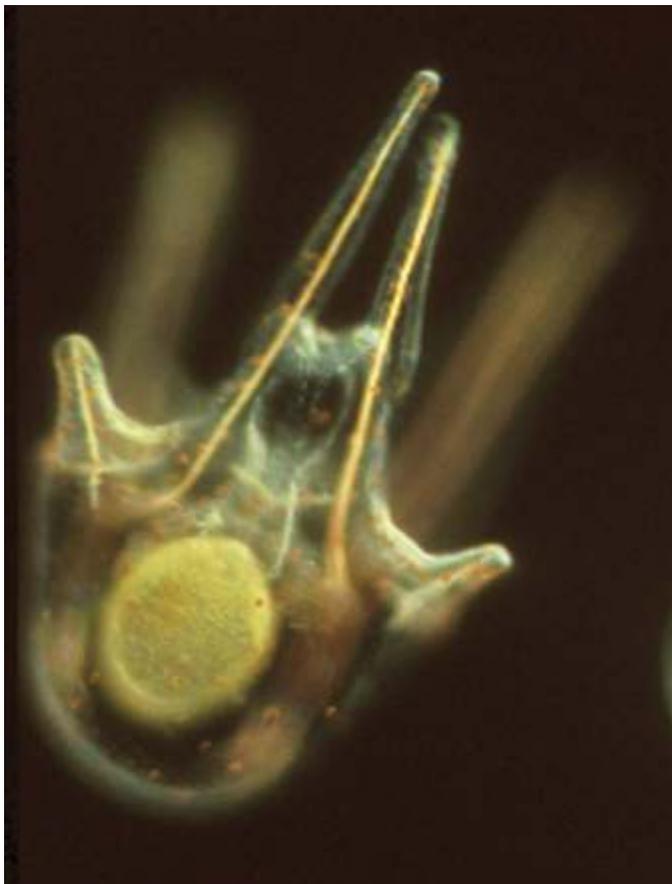
Gravid adults are induced to spawn by injection of 1.0 M KCl into the haemocoel via the peristomal membrane. Gravid individuals spawn within 40 min and the gametes are then mixed to achieve fertilization. Hatching to release swimming blastocysts occurs in 24 to 48 hours, depending on species and temperature.

Larval rearing systems, physical requirements, and feeds

Sea-urchin larvae in the research facilities at SAMS and the commercial hatchery at Dunmanus are maintained in static cultures in aerated, ambient filtered seawater at densities ranging from 1 to 4 mL⁻¹. Larval culture is based on methods developed for *P. lividus* by P. Leighton⁽⁸⁾ at the Shellfish Research Laboratory in Galway, Ireland, and modified for *P. miliaris* and *E. esculentus*.^(9,10) Larvae of all species are now routinely brought to the point of metamorphosis in 14 to 21 days—depending on the species and characteristics of the individual larval batches—without substantial losses. Production of juveniles at SAMS is in the order of 10,000 juveniles p.a., whereas Dunmanus produced 3 million juveniles in 2006.

The larvae are most commonly fed the

Sea urchin larva



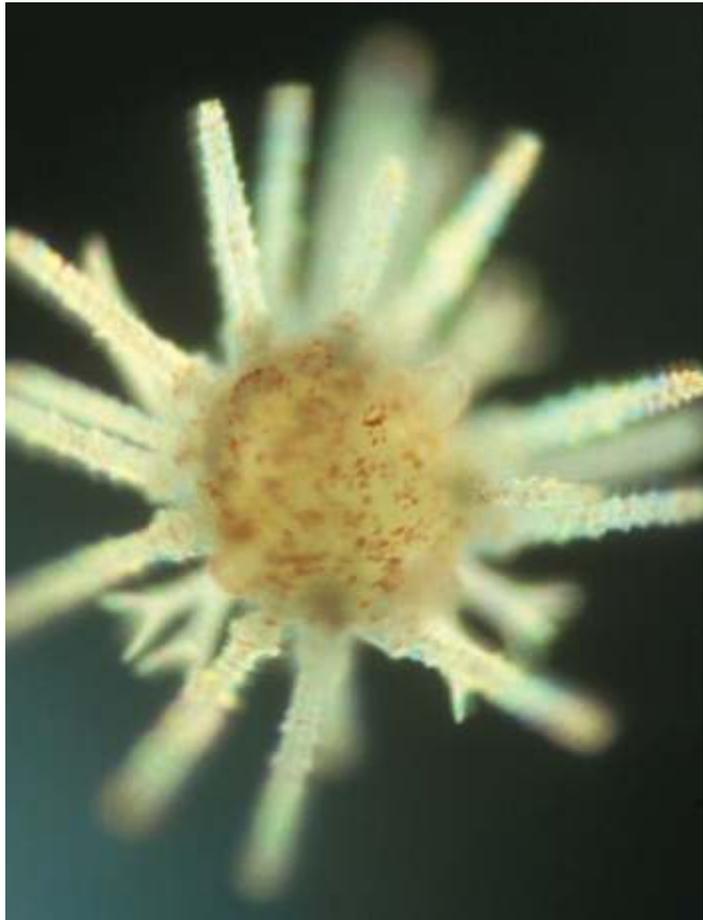
microalgae *Dunaliella tertiolecta*, *Phaeodactylum tricornutum* (SAMS) and *Pleurocystis carteri* or *P. tricornutum* (Dunmanus). Feeding is initiated once the larval stomach is formed and feeding rates are increased with the acquisition of each pair of larval arms. Most recently at SAMS, *P. lividus* and *P. miliaris* larvae have been successfully raised to settlement using the microencapsulated shrimp diets Lansy™ and Frippak™ as supplied by INVE Aquaculture.^(11,12) This is a significant advance because it provides hatchery operatives with an alternative to the labour-intensive practice of microalgal culture. It also offers a safety net should algal culture fail during a larval production cycle. While larvae of both species accepted the artificial diets, *P. miliaris* larvae adapted more readily to the feed than did *P. lividus*. However, these diets were designed for shrimp and could clearly be modified to better meet the sea-urchin larva's nutritional needs.

Early juvenile rearing systems, physical requirements, and feeds

When considered competent to settle, larvae are transferred to settlement tanks, containing settlement panels coated in a suitable biofilm. At SAMS, the settlement tanks are outdoor raceways (3 m x 0.5 m x 0.7 m high, with a water depth of 0.5 m) subjected to natural light and provided with aeration. Sea water is provided from a sub-sand intake and is then pumped to a header tank where aeration and a degree of settlement occurs before being gravity-fed to the raceways. The settlement panels are PVC wave plates which have been maintained in sea water and allowed to coat with a natural biofilm. The amount of growth on the plates can be controlled by shading, if needed. In this low maintenance system, larvae are added to the settlement tanks and left untouched for several months. Once juveniles of approximately 3- to 4-mm diameter are easily visible on the plates and tank walls, soft pieces of *S. latissima* are added to supplement their diet. The juveniles are collected by brushing the plates and walls, and from the macroalgae, as required. After 3 to 4 months, one raceway yields approximately 4,000 juveniles > 5 mm and innumerable smaller specimens, which are not collected for on-growing.

Dunmanus operates a more intensive system. The settlement tanks are indoors and prior to larval settlement the plates are seeded with a selection of locally isolated benthic diatoms. The bloom on the settlement plates is subsequently managed by adding more of the diatom culture to the tanks to meet the demand of the feeding juveniles. In the past, the settlement tanks have been subject to colonization by copepods which out-compete the urchins for food. This problem has been solved with additional filtration on the seawater inlet. The juveniles are fed soft macroalgae (*Alaria esculenta* and

Post-metamorphic juvenile



Palmaria palmata) from when they are 1-month old and/or 1-mm test diameter. The largest juvenile urchins tend to attach to the seaweed first and they are then removed from the settlement tanks and placed in cone-shaped rearing tanks (450-L volume, 4.5 m² surface area). The remainder are brushed off the plates and tank walls once they are large enough to handle. The cone tanks are cleaned regularly by siphoning. From the age of 5 to 6 months, the juveniles are periodically graded by size to prevent cannibalism. For urchins of < 10-mm diameter, the stocking density is 10,000 per cone tank; for urchins 10 to 20 mm, 4,500 per tank; and for urchins over > 25 mm the density is reduced to 1,500 per tank. Throughout the on-growing period, sea urchins are fed a mixture of macroalgae, predominantly *L. digitata*, *P. palmata*, *S. latissima*, and *A. esculenta*.

Juvenile Grow-out

Land-based rearing systems

Researchers at the Aquaculture Development Centre, University College Cork, have recently designed and patented a novel land-based rearing system for juvenile and adult sea urchins.⁽¹³⁾ Known as the UP system, the urchins are held in cages within a tank, which facilitates the presentation of fresh food. Stocking yields of 80 to 120 kg m⁻² of tank floor space can be achieved. A pilot UP system is currently undergoing trials in a commercial setting at Dunmanus.

Sea-based rearing systems

Previous research at SAMS showed that *P. miliaris* thrived when suspended in and around cages of Atlantic salmon.⁽¹⁾ The salmon cages provided shelter from the elements in sites that would otherwise be far too exposed for sea urchins. In addition, the sea urchins were able to trap and utilize any uneaten fish feed, and could be maintained in culture with salmon for long periods (> 1 year) without requiring any additional feed. This research has recently been repeated with

Wild *Psammechinus miliaris*



P. lividus, which also survived and performed well in the salmon cage environment.⁽¹⁴⁾ This integrated approach offers the advantages to the embryonic sea-urchin cultivation industry of shared sites, reduced need for capital investment in infrastructure, and a low-cost (no feed) rearing environment. For the salmon farmers, it offers the opportunity to recycle part of the feed that would otherwise be lost to the environment and potentially provides a second income stream. The salmon farming company Loch Duart Ltd.

(www.lochduart.com) is now undertaking feasibility trials with a view to scaling up their sea-urchin cultivation efforts from a research to a commercial scale.

A similar concept was the motivation for exploring the possibilities of co-cultivation of sea urchins and mussels. Many sea-urchin species will readily prey on mussels and in an experiment on the west coast of Scotland, small under-sized or crushed mussels and other grading table waste were fed to juvenile *P. lividus*. The juvenile urchins were maintained in pearl nets suspended from the same long-lines as the mussel cultures. The sea urchins fed mussels had a high survival rate, but relatively slow growth rates (approximately 1.25 mm month⁻¹) compared to those in the same suspended cultures fed a mixture of macroalgae (approximately 2.0 mm month⁻¹).⁽¹⁴⁾ This suggests that *P. lividus* is perhaps more herbivorous by nature than some other urchin species or has a more 'sedentary' character and is slow to target and feed on live prey items. Similar differences have been observed in other species; for example *Strongylocentrotus pallidus* has stronger predatory tendencies for mussels than *S. droebachiensis*.⁽¹⁵⁾ The experiment is being repeated using *P. miliaris*, which is recognised for its omnivorous nature.⁽¹⁶⁾ Both integrated aquaculture experiments (*P. lividus* with salmon and with mussels) were conducted as part of the SPIINES 2 project 'Sea Urchin Production in Integrated Systems, their Nutrition and Roe Enhancement' funded by the European Commission CRAFT scheme, contract number COOP-CT-2004- 512627.

Dunmanus primarily raises juvenile urchins to market size by ranching. Once the juveniles reach a test diameter of 25 mm, they are seeded to intertidal pools and subtidal areas. The proportion not on-grown by Dunmanus are sold to local growers who either release them to rock pools or on-grow the urchins in suspended culture hung from de-commissioned trawling vessels. The intertidal pools are flushed every tide and the diet is supplemented with additional macroalgae, mainly *L. digitata*. The juveniles in well-tended pools reach market size (50 to 55 mm) in 2 years, at which time they are generally sold back to Dunmanus for shipment to market. Urchins in pools that are less well tended can take 3 to 4 years to reach market size. There is recent interest from mussel farmers in obtaining juvenile urchins for on-growing as the industry seeks to diversify to avoid some of the restrictions on harvesting periods resulting from harmful algal blooms.

Feeds

Researchers at the Aquaculture Development Centre have recently developed novel binders for sea-urchin and other macroalgivore feeds.⁽¹³⁾ The binder, which is based on natural products, gives moist preparations increased shelf-life and stability in sea water. Further experiments are planned to test the palatability of the diets made with these binders and also to experiment with a range of ingredients to enhance the nutritional profile of the feeds.

Gonad Enhancement

Sea- and land-based rearing systems

The sea- and land-based integrated aquaculture and ranching systems described above are all used for gonad conditioning of adult sea urchins as well as the grow-out phase. Researchers at SAMS and UCC are experimenting with formulated feeds and although Dunmanus exclusively uses natural diets of macroalgae at all stages of the life cycle at present, they are actively involved in diet research,



Paracentrotus lividus roe

as providing the required daily amount (25 to 35 kg) of fresh seaweed is time consuming and becoming increasingly impractical.

Feeds

Paracentrotus lividus exclusively fed a macroalgal (*L. digitata*) diet generally produce a gonad of a desirable colour, which for this species is a deep orange-red. Feeding only kelp, however, can produce a gonad of limited biomass, so a diet that enhances gonad biomass without detriment to colour or flavour would be an advantage in conditioning ranched or kelp-fed urchins. It would also be useful as a finishing diet for sea urchins grown in integrated systems. As part of the SPIINES

2 project, researchers from SAMS; the University of Liverpool; Bodø Regional University, Norway; and the Institute of Limnological and Oceanographical Research, Israel, have been experimenting with different diet formulations for *P. lividus* and *S. droebachiensis*. Initial experiments have focussed on how natural pigments (β -carotene in the form of spray-dried *D. salina* ALGRO™) added to the diet, developed by a Canadian research team,⁽¹⁷⁾ affect gonad colour. While feeding diets with high levels of ALGRO™ did increase the amount of carotenoid in the gonad, the improvement in gonad colour was not universal and further research trials are planned which will also test some diets recently formulated in the USA.⁽¹⁸⁾ A recent study of the seasonal pigment profile of wild male and female *P. lividus* gonad (conducted as part of the SPIINES 2 project) has shown that, although both all-*trans* and 9-*cis* forms of β -echinenone are found in the gonad, the levels of the 9-*cis* form typically are 10-fold greater, making it the predominant carotenoid in the gonad of this species. The detection of large levels of 9-*cis*-echinenone in wild *P. lividus* was unexpected due to the absence of 9-*cis* forms of carotenoid in the natural diet. Amounts of lutein and isozeaxanthin are consistently higher in female than in male gonads.⁽¹⁹⁾

Wild Stock Enhancement

There have been several attempts at enhancement of wild sea-urchin stocks in Ireland. In 2004, Bord Iascaigh Mara—the Irish Sea Fisheries Board—experimented with the release of 100,000 juveniles at four sites. The experiment is on-going, but the urchins have successfully colonized at least one of the four sites, but it is too soon to estimate if there will be any further recruitment to these populations as a result. General observations on the wild populations suggest that natural recruitment is very low, with the ratio of adult to recent recruits (< 1-year-old) on average being in the order of 10:1.

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Hui Liu

Recent Advances in Sea-Urchin Aquaculture and Enhancement in China

Hui Liu, Jian Xin Zhu, and Maeve S. Kelly

Sea urchins have been cultured in China since the 1980s and several species are involved. Intensive experiments and research have resulted in the development of relatively complete methods for the hatchery, juvenile, nursery, and grow-out phases of culture. The scale of sea-urchin cultivation is likely to expand in order to meet market demand.

Introduction

The earliest publication on Chinese sea-urchin taxonomy and biology was in the 1950s.⁽¹⁾ There are about 100 sea-urchin species (Echinodermata, Echinoidea) in the China seas,⁽²⁾ of which about 14 are commercially important (Table 1). *Strongylocentrotus nudus* and *Anthocardis crassispina* are presently being cul-

Table 1
Commercially important aboriginal sea urchins in China⁽³⁾

Latin name	Chinese name	Distribution
<i>Anthocardis crassispina</i> (A. Agassiz) *	紫海胆	Southern China, incl. Zhejiang, Fujian, Guangdong and Hainan
<i>Astriclypeus manni</i> (Verrill)	曼氏孔楯海胆	
<i>Diadema setosum</i> (Leske)	刺冠海胆	South China Sea
<i>Echinocardium cordatum</i> (Pennant)	心形海胆	
<i>Echinometra mathaei</i> (Blainville)	梅氏长海胆	
<i>Glyptocidaris crenularis</i> (A. Agassiz) *	海刺猬或大连黄海胆	Northern China, Liaoning and northern Shandong
<i>Hemicentrotus pulcherrimus</i> (A. Agassiz) *	马粪海胆	All along Chinese coastline
<i>Schizaster lacunosus</i> (Linnaeus)	凹裂里海胆	East China Sea
<i>Stomopneustes variolaris</i> (Lamarck)	口罈海胆	South China Sea
<i>Strongylocentrotus nudus</i> (A. Agassiz) *	光棘球海胆	Northern China, Liaoning and northern Shandong
<i>Temnopleurus hardwickii</i> (Gray)	哈氏刻肋海胆	Northern China, Bohai and Yellow Seas
<i>Temnopleurus toreumaticus</i> (Leske)	细雕刻肋海胆	All along Chinese coastline
<i>Toxopneustes pileolus</i> (Lamarck)	喇叭毒棘海胆	
<i>Tripneustes gratilla</i> (Linnaeus) *	白棘三列海胆	South China Sea

*Major cultivated species

tured, as is *Strongylocentrotus intermedius* (which is the most highly-valued sea-urchin in Japan and has been introduced to China).

Roe products are mostly exported to Japan; only a small percentage is consumed domestically. Since sea urchins form a minor portion of the cultivated species in China, there were few production statistics before 2003. This is reflected in the discrepancy between the FAO report that total sea-urchin production in China in 1995 was 150 tonnes and the Japanese record that 209 tonnes of Chinese urchin products were imported into Japan that same year.⁽⁴⁾ However, aquaculture production of sea urchins has been recorded in the Chinese Fisheries Year Book since 2003, and the total output varied between 6500 and 9500 tonnes from 2004 to 2007.

Hatchery

Broodstock

Strongylocentrotus intermedius naturally spawns in October and the seed grow slowly. They have low survival during the winter because of unfavourable temperatures and a shortage of food. To obtain seed in the spring, broodstock are conditioned in land-based systems either for 3 to 4 months (which results in spawning in April and May)⁽⁵⁾ or for 6 months (which results in spawning in March).⁽⁶⁾

a. Rearing systems and feed

Broodstock are conditioned in land-based tanks with flow-through seawater, and are held either in lantern nets or in the open tanks. They are fed *Laminaria japonica*, *Undaria pinnatifida*, boiled mussel (*Mytilus edulis*) and artificial feed.⁽⁷⁾ Sea urchins provided with a mixed diet of *Laminaria* and artificial feed increased in weight by 306 mg day⁻¹ and achieved a final gonad index (GI = gonad weight/body weight × 100%) of 22.9%.⁽⁵⁾

b. Physical requirements

The theoretical basis for advancing time of spawning is that complete gonad development requires the achievement of the Effective Accumulated Temperature (EAT):

$$\text{EAT} = (\text{daily average temperature} - \text{biological zero temperature}) \times \text{number of days}$$

EAT for *S. intermedius* varies from > 800 to 1850 degree-days.^(5,7) Broodstock are maintained at 18–20°C for about 120 days before being induced to spawn. At this point, their GI has increased from 5% to 21.0–24.6%, indicating the gonads are mature.⁽⁸⁾

Broodstock are maintained in sand-filtered seawater at a salinity of 29–32‰, with a water exchange rate of 100–200% day⁻¹ at rearing densities of 10–20 individuals m⁻² and 800% day⁻¹ at a density of 200 individuals per square meter.^(5,7)

Larvae

KCl injection, followed by artificial fertilization, is the routine method for spawning broodstock in Chinese hatcheries.⁽⁹⁾ Broodstock can also be induced to spawn by exposing them to the air for 2 hours, followed by stimulation with rapid water flow for 0.5 to 3 hours, or by injection of 0.5 M KCl into the coelom.⁽⁷⁾

a. Rearing systems

The earliest experiments on larval culture of *S. nudus* were done in the 1980s

and the first report on harvesting and gonad-processing techniques was published in 1982.^(8,10-13)

Systematic hatchery work on *S. intermedius* was done in the 1990s by Wang and Chang.⁽⁷⁾ Fertilized eggs are hatched at a density of either 10–20 or 20–30 eggs mL⁻¹ at 17–18°C.^(7,16) Swimming larvae are siphoned from the tank and placed in static larval tanks. The optimum larval density is 0.75–1.0 individuals mL⁻¹ during the early stages and 0.3–0.8 individuals mL⁻¹ in the 8-arm stage. Water is exchanged twice every day at a daily rate of 60–140%. Filter drums or mesh cages are used for water exchange, with a gentle out-flow speed of < 4.0 m³ h⁻¹. Larvae are transferred into new tanks every 5 to 10 days.^(7,14,16)

Presently, there are no specially designed sea-urchin hatcheries in China. Larvae are usually cultivated in ordinary scallop or abalone hatcheries.⁽¹⁷⁾ Containers used for hatching fertilized eggs are usually small (about 15 L), while those used for larval culture range in size from several liters to tens of cubic meters. Larger tanks are often used for commercial production.

b. Physical requirements

Water is not usually aerated during egg hatching, although at higher densities, gentle aeration improves survival.⁽¹⁶⁾ Larval cultures are not usually aerated either, but the water is stirred thoroughly every 0.5–1.0 hours.⁽⁷⁾

Duration of egg hatching in *S. intermedius* varies from 11.5 hours at temperatures of 15.8–18.5°C⁽⁷⁾ to 12–16 hours at 18–20°C.⁽⁵⁾ In *S. nudus*, the swimming blastula appears 12 hours after fertilization at 20–24°C.⁽¹⁴⁾

There is not much difference between the length of the larval development period in *S. intermedius* reared at 15–18°C⁽¹⁶⁾ and 18–20°C.⁽⁵⁾ Larvae held at these

Table 2
Development of fertilized eggs and larvae of *S. nudus* and *S. intermedius*^(7,8)

Developmental stage	<i>Strongylocentrotus nudus</i> (22-24°C)		<i>Strongylocentrotus intermedius</i> (15.2-18.5°C)	
	Time after fertilization	Diameter or body length (µm)	Time after fertilization	Diameter or body length (µm)
Fertilized egg	0	130-145	0	
Two-cell stage	45 min		1 h 30 min	
Four-cell stage	75 min		2 h 12 min	
Eight-cell stage	100 min		3 h	
Swimming blastula	9 h	160-190	12 h 10 min	
Gastrula			18 h	125-170
Prism larvae	20 h	190-220	30 h	162-205
Two-arm larvae	36 h	250-450	36 h	210-268
Four-arm larvae	48 h	375-550	50 h	270-480
Six-arm larvae			7-8 d	406-596
Eight-arm larvae	8-11 d	500-800	12-13 d	605-1050
Metamorphosis	15-21 d	300-350	18-21 d	320-410

temperatures metamorphose 18–21 days after fertilization. *S. nudus* larvae held at 20–24°C metamorphose 20 days after fertilization.⁽¹⁴⁾ Extreme temperatures can be lethal to eggs and larvae. Fertilized eggs of *S. nudus* stop developing at temperatures < 5°C or > 26°C, and normal larval growth is achieved only at 15–24°C.⁽¹⁸⁾

Sedimentation and sand-filtration are routinely used to purify water in hatcheries. The use of micro-filtered (5 µm) sea water and uniform temperatures increased larval survival from 32–65% to 87%.⁽⁵⁾ Control of water quality parameters such as pH (7.9 to 8.36), DO (> 5 mg L⁻¹) and COD (< 1 mg L⁻¹) is important for successful hatchery work.⁽¹⁴⁾

Eggs of *S. nudus* survive salinities from 24 to 35‰, but the optimum salinity for both fertilized eggs and larvae is reported to be 27–35‰⁽¹⁹⁾ or 28–32‰.⁽¹⁴⁾

Light intensities used for culture of larval *S. intermedius* have ranged from < 300 lux⁽⁷⁾ to between 500 and 1000 lux.⁽⁵⁾

c. Feed

The best larval diet may vary among species. Feeding starts 24 hours after hatching, when prism larvae form. Microalgae are dispensed into the larval tanks 2 to 4 times per day, and the feeding ration is increased from 5000 to 20 000 cells mL⁻¹ for early stage larvae and 50 000 to 70 000 cells mL⁻¹ for late stage larvae.⁽¹⁶⁾ The highest survival in *S. intermedius* larvae has been achieved with *Chaetoceros gracilis*.⁽⁷⁾ High survival and rapid growth were also obtained when larvae were fed *Chaetoceros muelleri* in combination with other microalgae.⁽²⁰⁾

A study was conducted in which five microalgae (*C. muelleri*, *Dunaliella* sp., *Dicrateria zhanjiangensis*, *Isochrysis galbana*, and *Platymonas* sp.) and two formulated feeds were compared for their support of larval growth and survival in *S. nudus*. The best results occurred in larvae fed *Chaetoceros*; those fed *Dunaliella*, *Dicrateria*, or *Isochrysis* had slower growth and less uniformity in development. However, larvae fed a mixed diet of *Chaetoceros* and *Dicrateria* also had excellent development.^(14,15) Most larvae fed on other diets died before metamorphosis.⁽¹³⁾

Hemicentrotus pulcherrimus larvae, in contrast, developed well on *Isochrysis* and *Nitzschia* sp.,⁽²¹⁾ but *C. gracilis* was also the best diet for this species. *Phaeodactylum tricornerutum* supported normal growth, though not as good as *Chaetoceros*. *Platymonas* was used for later-stage larvae.⁽²²⁾

In *A. crassispira*, the most rapid development occurred in larvae fed *C. muelleri*—with development being completed in only 11 days.⁽²³⁾

Early juveniles

a. Rearing systems

Juveniles are cultivated in two stages because their dietary and environmental requirements change with development.^(16,24) Early-stage juveniles are kept in shallow rectangular abalone tanks (ranging in size from 3 to 10 m long × 1.3 m wide × 0.5 to 0.7 m deep). PVC wave plates (40 cm × 33 cm) fixed into frames (20 plates per frame) are used as substrates. Late stage juveniles are kept in mesh cages in land-based flow-through systems, with 1 or 2 black PVC wave plates (50–80 cm × 30–70 cm) placed on the bottom of each cage. Several holes (2 to 4 cm in diameter) are driven through the plates for urchins to move through. Cages are sized to fit the tanks, ranging from 0.6 to 1.5 m long × 0.5 to 1.5 m wide × 0.3 to 0.4 m deep. The mesh sizes of the cages range from 1.0 to 10 mm, depending on the test diameter (TD) of the urchins.

For early-stage juveniles, PVC wave plates are inoculated with benthic microalgae 10 days⁽⁵⁾ or 20–40 days^(7,14) before settlement. Rudiment larvae are transferred into settlement tanks at a density of 0.2–0.4 individuals cm⁻² of wave plate surface area. Plates are placed horizontally, and are turned over after 1 or 2 days when an optimum number of larvae have settled on the upper surface of the plates. At 10 days post-settlement, metamorphosis rates range from a mean of 13.2%⁽⁷⁾ to 33% (range: 18.4 to 75%).⁽⁶⁾ Water flow is started either 2, 3, or 5 days after settlement begins.⁽⁵⁻⁷⁾ The daily water exchange rate is 100% for the first 2–7 days (before metamorphosis is completed) and 100–500% after 8 days. The wave plates are turned over every 10 days to enhance growth of benthic microalgae. Frequent cleaning of the tanks is necessary to destroy harmful organisms such as copepods. Settlement plates may be soaked in a 3–5 ppm Metrifonate solution for 6–8 hours to destroy the copepods.⁽⁶⁾ Early stage juveniles reach a size of 2 to 3 mm TD in 30–50 days, and are then transferred to mesh cages.⁽⁷⁾ Alternatively, they are maintained on wave plates for 50–60 days⁽⁵⁾ or 71 days,⁽⁶⁾ and are transferred into cages when they reach a size >7 mm TD. For easy removal of the juveniles, plates are soaked in 0.4% KCl solution for 2–3 min.⁽⁶⁾

Juveniles (2–5 mm TD) are held at a density of 10 000–20 000 or 2000–6000 (> 5 mm TD) in each cage (0.5 m × 0.6 m × 0.3 m) with a daily water exchange rate of 100–300%. The average daily growth rate was 30.5–65.8 µm (13.8–18.0°C) to 57.6–165.2 µm for late stage juveniles, and the survival rate was 33.3–90.0%.⁽⁷⁾ After 1–2 months^(5,7) to 152 d,⁽⁶⁾ seed of 5–13 mm TD are transferred onto the seabed for growout. Growth rate of late stage juveniles is strongly influenced by rearing density, feed availability and water temperature.

b. Physical requirements

Continuous aeration is required during the juvenile nursery stage.⁽²⁴⁾ Optimum temperatures for juvenile *S. nudus* are reported to be 16–22°C⁽¹⁸⁾ and 13.8–18.5°C or 12.0–18.0°C for early- or late-stage *S. intermedius* juveniles.⁽⁷⁾ *S. intermedius* juveniles cannot survive temperatures higher than 22°C.⁽⁵⁾

Both species of *Strongylocentrotus* spawn in the autumn, and improving the survival of the juveniles during the winter is important for culture success. To reduce the stress of low winter water temperature, sea urchins are held at 10–16°C in land-based tanks. Alternatively, urchins can be maintained in cages suspended at a depth > 4 m in the sea, where water temperature is uniform throughout the winter.⁽²⁵⁾

Light intensity is controlled in land-based systems to enhance the multiplication of diatoms and suppress the growth of other benthic microalgae on the wave plates.⁽¹⁴⁾ During the early-stage juvenile nursery phase, light intensity of 500 to 3000 lux is recommended.^(5,6)

c. Feeds

Wave plates are fixed into frames before being soaked in 500 ppm NaOH solution for 2 days. The frames are then placed in abalone tanks (10 m × 1 m × 0.6 m) filled with seawater. Seaweeds collected from the intertidal seabed are rubbed and washed in a bucket to collect the benthic microalgae. This ‘microalgae broth’ is filtered through a 150-µm mesh before being dispensed into the tanks. The major species used for the inoculation are *Navicula* sp., *Cocconeis* sp., and *Nitzschia* sp. Frequent water exchange and fertilization is started 2 days after inoculation, and the light intensity is 2000 lux. Before larval settlement, the wave plates are cleaned of fouling organisms by being soaked in 2 to 3 ppm Metrifonate solution

for 10 hours, and thoroughly flushed with seawater.⁽¹⁴⁾

After settlement, nutrients are added to the juvenile tanks at a daily ration of N:P:Si:Fe = 2:0.1:0.1:0.01 ppm to enhance benthic diatom growth. The light intensity is kept < 3000 lux.⁽⁷⁾ When the juveniles reach 3 mm TD one month after settlement, shredded tender seaweeds such as *Enteromenia sinuosa* and formulated feeds are added to supplement the diatoms.⁽¹⁴⁾

During cage-culture, juveniles are fed on *Ulva* sp., *Colpomenia sinuosa*, *Hizikia fusiforme*, and formulated feeds.^(7,24) Urchins greater than 10 mm TD tend to select *Ulva*, *Laminaria*, and *Undaria*^(20,25,26) among other diets. They also eat formulated feed, mussels, sea squirts, etc., when seaweeds are unavailable. Urchins are fed once every 2 to 15 days. The feeding ration is adjusted according to the size of the containers to avoid obstructing water flow.

Juvenile Grow-out

Land-based rearing systems

Land-based urchin culture allows for better management and control of environmental conditions, and provides flexibility in harvesting time. Escape of animals is also minimized. It takes 12 to 18 months for juvenile *S. intermedius* (1–3 cm TD) to reach market size (> 4.5 cm TD), and productivity is > 15 kg m⁻². Tanks (2.4 m × 0.6 m × 0.3 m) with flow-through seawater are used for juvenile grow-out, and daily water exchange is 1000%. Rearing density is 1000 to 2000 urchins m⁻² for 1.0 cm TD urchins, 500 to 1000 m⁻² for those at 2.0 cm TD, and 150 to 500 m⁻² when the TD is > 3.0 cm.⁽²⁷⁾

The first experiment on land-based echinoculture in China was carried out by Prof ZC Wang and YQ Chang at the Dalian Bay Seafood Company (Dalian) in 1996. Juvenile *S. intermedius* (1.0 cm TD) were held at a density of 3500 m⁻², and the density was reduced to 1400 m⁻² at 3.0 cm TD and to 200 m⁻² at 5.0 cm TD. Relatively higher water exchange rates were required because of the high densities. Juvenile urchins (1.16 cm TD, 0.47 g wet weight) reached 5.98 cm TD and 61.5 g with an average roe index of 18% in 12 months.

The Dalian Pacific Seafood Company (Dalian) uses rectangular plastic boxes in flow-through systems for urchin grow-out. Faecal wastes are sieved out of the boxes through the holes in the bottom, which spares frequent cleaning. This farm now deploys urchins over a 5000 m² cultivation area, with an average productivity of 15 kg m⁻² of market size urchins.

Sea-based rearing systems

a. Longline culture

Longline culture of urchins in China uses an approach adapted from abalone or scallop rearing. Containers hung from longlines have a large bottom area and openings on each side. The most popular container is a multi-layer cage with a zipper fixed along one side.⁽²⁷⁾

b. Benthic cage rearing

Urchins are held in cages with a bottom area of 2–3 m². Wave plates fixed to the bottom provide an attachment surface for the urchins. Rearing density is 1000 m⁻² for urchins at sizes of 1.0–2.0 cm TD and 300–500 m⁻² for later stages. Frequent cleaning and removal of harmful animals in the cages are required.⁽²⁷⁾

c. Bottom seeding

An experiment in Dalian showed that 1.0 cm TD juveniles can reach a size of 4.5 cm TD and 32–38 g within one year, or 6.0–7.0 cm TD and 80 g in 22 months. The survival rate was 40% after 2–3 years of growout. Integrated culture of sea urchin and *Laminaria* or *Undaria* utilizes the complementary metabolism of both species and minimizes the environmental influence of echinoculture.⁽²⁷⁾ Precautions must be taken to avoid predators.

Physical requirements

Optimum temperatures for *S. nudus* juveniles are 10–24°C.⁽¹⁸⁾ After 10 years of acclimatization in the Dalian area, *S. intermedius* is adapting to higher water temperatures. Young urchins (1.0–3.6 cm TD) grow well at 10–25°C, and the best growth is at 19°C. Adults (TD > 3 cm) grow well at 10–22°C, with the best growth at 16°C. The optimum temperature decreases as urchins increase in size from 1.0–5.3 cm TD. Urchin cages should be lowered to a deeper layer when water temperature is too high; otherwise feeding should be suspended.⁽²⁹⁾

Relatively high and steady salinity is needed for good growth and survival of sea urchins⁽²⁷⁾ and fresh water inputs should be avoided. Optimum salinity for adult *S. nudus* is 28–35‰.⁽¹⁹⁾

Rock or gravel substrates provide hiding places for the urchins. Sometimes artificial reefs are constructed in order to protect and accumulate the animals.⁽²⁷⁾

Feeds

The ranking of feeds suitable for *S. intermedius* is *Laminaria*, *Undaria*, *Sargassum horneri*, *Chondrus* sp., and *Ulva*,⁽²⁹⁾ with *Laminaria* being the best diet.⁽³¹⁾ Growth of *A. crassispina* is supported better by *Ulva* and *Laminaria* than by *Gracilaria* and *Sargassum fusiforme*.⁽³⁰⁾

Research on formulated feeds has shown that adult *S. intermedius* has significantly higher digestibility for soybean meal than fish meal, which suggests that soybean meal could be used to replace fish meal.⁽³²⁾

Seaweeds such as *Laminaria*, *Undaria*, or *Ulva* have been fed to urchins in land-based systems at a daily ration of 5% body weight.⁽²⁷⁾ As for bottom seeding, the preferred natural seaweeds on the seabed should be in sufficient supply for the urchins to graze upon. Otherwise, artificial seaweed planting and reef building is needed to enhance seaweed growth.

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Chris Pearce

Recent Advances in Sea-Urchin Aquaculture and Enhancement in Canada

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There are three species of shallow-water echinoids in Canada that could potentially be cultured: *Strongylocentrotus droebachiensis* (green sea urchin), *S. franciscanus* (red sea urchin), and *S. purpuratus* (purple sea urchin). Canadian research has primarily focussed on the former two. This paper reviews the research that has been conducted in Canada on culturing green sea urchins, with an emphasis on recent work. The review highlights some of the findings on hatchery developments, physical and dietary requirements of the various life-history stages, and gonad enhancement efforts to date.

Introduction

In Canada there are three species of sea urchins that hold potential for aquaculture: *Strongylocentrotus droebachiensis* (green sea urchin), *S. franciscanus* (red sea urchin), and *S. purpuratus* (purple sea urchin). Limited research into culturing sea urchins began in Canada in the early 1980s in Newfoundland and Quebec, but it was not until the late 1990s that serious interest in the potential for commercial-scale cultivation developed. This was, in part, fuelled by the decline in wild fisheries in many urchin-fishing nations⁽¹⁻⁴⁾ and the continued high market demand and prices for urchin roe. Interest has primarily focussed on the cultivation of the green sea urchin for a number of reasons: (1) it is endemic to six of the ten provinces in Canada [British Columbia (BC), New Brunswick (NB), Newfoundland and Labrador (NL), Nova Scotia (NS), Prince Edward Island (PE), and Quebec (QC)] and there is already a developed fishery for it in four provinces (BC, NB, NL, and NS); (2) it can grow to market size in less than two years, given the right conditions; (3) it is fairly tolerant of high-density culture environments; (4) it can be grown successfully using prepared diets; (5) it produces high-quality roe; and (6) it already has an established market in Japan. Within Canada, red and purple sea urchins are endemic only to BC, with the latter being found only in relatively exposed areas of the west coast of Vancouver Island and not forming the basis for a commercial fishery. While there has been considerable research and some industrial interest in sea-urchin aquaculture in Canada in the last two decades, there is as yet no commercial-scale urchin aquaculture venture. The present review is focussed on research and work that has been done with *S. droebachiensis*.

Hatchery

Broodstock: rearing systems and physical requirements

There are no particular requirements identified to date for the type, shape, or size of tanks for holding small numbers of broodstock (see Gonad Enhancement sec-

tion, though, for a discussion on systems and requirements for larger numbers of animals in a commercial-enhancement setting). The animals should be supplied with clean seawater at relatively high flow rates and with a high dissolved oxygen concentration. The tanks should be cleaned of uneaten feed and faecal material every two or three days, depending on accumulation rates. The length of the conditioning period will depend on a number of factors, including the gonad state at the beginning of the conditioning period, the time of year, the physical holding conditions (e.g. temperature, salinity, dissolved oxygen), and the type of feed used. Typically, broodstock can be conditioned for spawning within 8–10 weeks.^(5,6)

Broodstock: feeds

While a plethora of studies has examined the effect of feed on gonad yield and quality (see Gonad Enhancement section), far less research has examined the specific effect of feed on broodstock conditioning, or subsequent fertilization and larval development, in any of the three stronglylenticid species of commercial potential in Canada. One of the few studies to examine this topic with green sea urchins showed that parental condition generally had a small effect on larval development, but that larvae produced from adults in rich feeding areas may metamorphose sooner than those from adults in poorer ones.⁽⁷⁾ Broodstock can easily be conditioned with either prepared diets or certain macroalgae. *Strongylocentrotus droebachiensis* will feed on a variety of macroalgal species, but large brown algae such as kelps and rockweeds are generally preferred.^(8–14) Certain species of foliose green or red algae, however, may also be favoured.^(9,11,14–17)

Larvae: rearing systems and physical requirements

Larvae can be reared in containers of any size or shape, ranging in size from small 4-L glass jars^(18–20) to large commercial-scale tanks of 40,000 L [Island Scallops Ltd. (ISL), Qualicum Beach, BC]. They can be reared under static conditions with periodic water replacement or under flow-through conditions. If the former, then there should be some means of gentle agitation (e.g. stir paddles) and/or aeration. For the latter, low flow rates should be used and there should be a filter (e.g. banjo filter) over the drain to prevent larvae escaping the system. The culture water should be filtered to 1 µm or less to remove particulates, and bacteria/viruses may be sterilized with ultra-violet radiation. Larval densities should be adjusted during development; early-stage larvae can be reared at 1000–1500 individuals L⁻¹, but this density should be decreased to 100–800 L⁻¹ as the larvae approach metamorphosis.^(21–22) Depending on food and physical culture conditions, the larval period can last from 4 to 21 weeks.^(18–20,23)

Larvae: feeds

Larvae of *S. droebachiensis* are planktonic and feed on phytoplankton in the water column. Food should be added to the larval cultures when the echinopluteus stage is reached, generally about day 3 or 4 at 12°C.⁽²¹⁾ Larvae can be reared with a number of different cultured microalgal species (e.g. *Chaetoceros gracilis*, *Dunaliella tertiolecta*, *Isochrysis galbana*) or concentrated natural phytoplankton.⁽²⁴⁾ While growth and survival of larval *S. droebachiensis* are undoubtedly dependent on the phytoplankton species (or combination of species) and ration used for larval culturing, little research has been done on the topic. Hart and Scheibling examined survivorship and growth of larval *S. droebachiensis* fed two species of phytoplankton, *C. gracilis* and *D. tertiolecta*. They found no significant difference in growth rate or rudiment development in larvae fed the two different

microalgal species, but did find that survival was significantly greater with *C. gracilis*.⁽¹⁸⁾ Meidel and Scheibling fed *D. tertiolecta* to larval green sea urchins and found that food ration had a strong effect on the rates of development, growth, and metamorphosis, all of which were significantly greater in larvae fed the higher ration.⁽⁷⁾ Further research is warranted to determine which algal species, or combination of species, are best for culturing larval *S. droebachiensis*. This work should extend further to examine larval nutritional requirements, something which has yet to be done with any echinoid species. This particular avenue of research should be made more tractable with the recent discovery that larval echinoids can subsist on prepared feeds.⁽²⁵⁾

Early juveniles: rearing systems and physical requirements

Nursery systems for *S. droebachiensis* are based on Japanese techniques [see Hagen⁽²²⁾ for review]. Settlement surfaces covered with microbial films are introduced into tanks or raceways of competent larvae. These films induce metamorphosis and form the basis of the early-juvenile diet. Recent research with *S. droebachiensis* has examined the effect of various species of benthic microalgae on metamorphic rates and post-settlement growth and survival (CM Pearce, unpublished data), but research in this area is limited. When the young juveniles reach about 30–50 days old, soft foliose macroalgae can be introduced to the diet.⁽²⁶⁾ The juveniles remain on the settlement plates, feeding on benthic microbial films and foliose macroalgae, until they reach a test diameter of about 5–10 mm. At this point they are removed from the plates and transferred to grow-out systems. The nursery stage is typically flow-through, the water not having to be filtered or sterilized.

Early juveniles: feeds

Recently-metamorphosed individuals of stronglylocentrotid urchins subsist on larval energy reserves for about the first 8–12 days following metamorphosis until their mouth and gut become developed.⁽²⁷⁾ At this point, the young urchins switch over to feeding on benthic microbial films. At approximately 30–50 days old, juveniles can start consuming various species of soft, fleshy macroalgae.⁽²⁶⁾

Juvenile Grow-out

Land-based rearing systems

Much of the work on land-based rearing systems in Canada has been done with adult sea urchins for gonad enhancement purposes. Many of the issues involved with developing suitable land-based systems for gonad enhancement also apply for juvenile cultivation as well. See the Gonad Enhancement section for further discussion of this topic.

Ross Island Salmon Ltd. (RISL) (Grand Manan Island, NB) did some small-scale tests in the late 1990s to examine the feasibility of rearing juvenile green urchins in outdoor earthen raceways covered with pond liners. These were flow-through systems that were relatively shallow (<10 cm deep) and not shaded. During the summer months, urchins were exposed to bright sunlight and developed lesions and, as a result, the systems were not developed further. ISL, however, found that large, outdoor earthen ponds (500–750,000 L) with liners were quite effective for rearing juvenile *S. droebachiensis*. These systems, however, were substantially deeper than the raceways used by RISL. ISL also developed a unique recirculation system for rearing juvenile green urchins that consisted of a long racetrack [twin

raceways (L x W x H: 6.4 x 0.9 x 0.9 m) that were double ended to form an oval] with flow driven by an electrically-powered paddlewheel (Figure 1). To remove faecal material, the speed of the paddlewheel was increased to a rate where the wastes were suspended and then they were filtered off by a de-watering system.

Sea-based rearing systems

Again, much of the work with sea-based systems in Canada has been done with adult urchins for gonad enhancement, but many of the same concepts apply for juvenile rearing (see Gonad Enhancement section). RISL experimented with plastic-coated wire mesh cages (Figure 2) suspended below a floating raft in a lobster pound (enclosed areas in the intertidal zone that trap and hold water from the tidal flows, in which lobsters are traditionally held; Figure 3) to rear juvenile green urchins. These systems worked well although mortality events, which may have been linked to extreme temperatures, did occur periodically.

Physical requirements

Juvenile urchins require clean water, high dissolved oxygen, and prompt removal of uneaten feed and faeces. Little research, however, has examined the specific physical requirements of juvenile green sea urchins. Pearce and colleagues exposed small green urchins (initial test diameter: 2.4 mm) to five temperatures (mean \pm SE: 4.7 ± 0.8 , 9.0 ± 1.1 , 12.9 ± 1.1 , 16.0 ± 1.5 , and $19.7 \pm 1.3^\circ\text{C}$) and concluded that the best temperature for growth and survival was in the range of 9 to 13°C .⁽²⁸⁾

Feeds

Daggett and co-workers reared juvenile *S. droebachiensis* (initial test diameter: 4.5–13.7 mm) on a number of different macroalgal species—including *Enteromorpha linza*, *Laminaria saccharina*, *Palmaria palmata*, *Porphyra purpurea*, and *Ulvaria obscura*—and found that growth rate was greatest on *P. purpurea* and *E. linza*.⁽²⁹⁾ This study also reported that growth rate of young urchins fed kelp (*L. saccharina*) that had been collected next to salmonid culture cages was significantly higher than that of urchins fed kelp that was harvested away from the influence of salmonid culture.⁽²⁹⁾ The authors



Figure 1
Race-track tank, with paddlewheel, used by Island Scallops Ltd. (Qualicum Beach, British Columbia) to rear juvenile green sea urchins.



Figure 2
Plastic-coated wire mesh cages used by Ross Island Salmon Ltd. (Grand Manan Island, New Brunswick) for rearing juvenile green sea urchins at sea.

hypothesized that protein levels in the former may have been higher than that in the latter (although protein was not actually measured) and that these differences in protein content may have led to the differing growth rates between the two kelp treatments. Pearce and colleagues examined growth and survivorship of juvenile green sea urchins (initial test diameter: 12 mm) fed three species of kelp (*L. saccharina*, *Macrocystis integrifolia*, and *Nereocystis luetkeana*) and a prepared feed developed by Drs. John Castell and Shawn Robinson at the St. Andrews Biological Station, NB. They found that urchins grew significantly bigger and heavier when given the prepared diet than when fed any of the three kelp species (which did not differ significantly from one another).⁽³⁰⁾

A significant amount of work has been carried out on prepared feed formulation of diets for juvenile *S. droebachiensis* by Kennedy and colleagues. They examined the effect of protein source (soybean meal and/or fish meal) and protein concentration (20, 30, 40, and 50% dry mass) on growth of two juvenile size cohorts (initial test diameter: 4–8 and 12–20 mm). They found that growth rate and survivorship were not significantly affected by protein source or concentration, suggesting that juvenile green sea urchins do not require high levels of dietary protein for superior growth and that plant protein can substitute for fish protein in the prepared diet.⁽³¹⁾ Further work by Kennedy and colleagues examined the effect of lipid class (n-3 and/or n-6 fatty acids) and lipid concentration (1, 3, 7, and 10%) on the somatic growth of two size cohorts (initial average test diameter: 7.0 and 15.3 mm) of juvenile green urchins. Growth rate was not significantly affected by lipid class, but urchins fed diets with lower lipid levels (3%) had larger average test diameters than those fed diets with higher lipid concentrations (7%).⁽³²⁾ In both these studies, growth on control diets of natural kelp was superior to that on any of the prepared diets, leading Kennedy and colleagues to postulate that there may have been nutritional deficiencies in the prepared feeds. Work by González-Durán *et al.* showed that the lipid content of the test and the somatic tissue closely reflected the diet sea urchins were fed. They showed that the sea urchins were capable of handling a number of different lipid classes and that corn oil may have a role in the production of commercial diets for sea urchins.⁽³³⁾

Kennedy and colleagues also tested potential effects of minerals on sea-urchin growth by feeding juveniles (initial test diameter: 13–15 mm) prepared diets with a modified Bernhart-Tomerelli salt mix at 0, 1.5, 3, 6, and 15% dry mass or a Shur-Gain/Maple Leaf Foods mineral mix at 3 and 6% dry mass. They also tested the effects of added pigment by incorporating 1.25% Algro™ to the prepared diets (*i.e.* 250 mg of beta-carotene per kg of diet). Sea urchins fed diets with beta-carotene added had significantly greater test growth than those fed diets without pigment and mineral

Figure 3
Lobster pound in New Brunswick used for green sea-urchin culture experiments.



concentration in the pigmented diets was directly related to juvenile size at the end of the feeding trial.⁽³⁴⁾ This work prompted Kennedy and colleagues to postulate that diets used in their earlier studies⁽³¹⁻³²⁾ may have been deficient in certain minerals and/or pigments.

Gonad Enhancement

Gonad enhancement of sea urchins is envisioned to occur with wild-harvested animals that have been obtained by licensed harvesters from the marine fisheries located in the coastal communities of Canada. This is seen to be different from a full-cycle grow-out of sea urchins produced from small juveniles (*e.g.* obtained from a hatchery) due to the variation in the initial gonad quality of the individuals, specific fishery regulations involved with their harvest, and the variability of supply due to the direct sale from the fisherman to the buyer without any additional husbandry being applied. Therefore, sea-urchin gonad enhancement research is directly linked with the scale of the local harvest fishery in a particular area.

Land-based rearing systems

One of the major hurdles in any commercial-scale echinoid cultivation system is dealing effectively with the accumulation of faeces and uneaten food. Sea urchins can produce large amounts of faecal material when fed *ad libitum* (up to 3% of their body weight per day) under culture conditions. If these wastes are allowed to accumulate they can start breaking down, releasing hydrogen sulphide and ammonia into the culture system which can negatively affect growth and survival of the urchins. At high urchin densities, it becomes very difficult to remove waste material from between tightly packed sea urchins when their spines are interlocking.

Another issue in cultivating sea urchins is maximizing densities and access to feed. Deep tanks are not particularly effective for rearing urchins since the animals can never enter the water column and much of the tank volume becomes wasted space. In addition, individuals tend to congregate on the vertical walls, making feeding difficult.⁽³⁵⁾ Typically, it is easy to get food to the top few rows of urchins, but substantially more difficult to ensure that individuals further down the walls get equal access to the feed. Adding vertical separators to deep tanks may increase surface area and reduce the footprint required to house a given number of urchins, but these vertical surfaces only exaggerate the problem of uneven food distribution.

Much research has gone into designing appropriate holding systems for juvenile and adult urchins. The most popular designs are those that make use of long, shallow raceways or troughs that can be stacked to maximize biomass per unit area and allow for maintaining even food distribution among individuals.⁽³⁵⁻⁴⁰⁾ Systems with centralized drain channels and sloped walls⁽³⁵⁾ or false mesh bottoms^(36,40) may be particularly suitable as they allow for easy removal of faeces and uneaten food. Land-based systems may utilize flow-through^(35,40) or recirculation^(36,38-39) technology. RISL used stacked, flow-through raceways with false mesh bottoms for gonad enhancement of green sea urchins in the late 1990s (Figure 4).

Sea-based rearing systems

There are two major forms of sea-based systems for gonad enhancement: benthic ranching and mesh cages suspended from rafts or long lines. Work on the former system began in Canada in the late 1980s, when pilot-scale trials in QC examined the potential of corralling for gonad enhancement of adult green urchins. Kelp (*Laminaria* sp.) was fed to the urchins and the study found that gonad yield could



Figure 4
Stacked raceways used by
Ross Island Salmon Ltd.
(Grand Manan Island, New
Brunswick) for juvenile rearing
and gonad enhancement of
green sea urchins.

work by Dr. Derek Keats and colleagues at Memorial University. They used wooden lobster boxes anchored near the surface and fed urchins different macroalgal species (*Alaria esculenta*, *Desmarestia* spp., *Fucus edentatus*, *L. digitata*, and *Saccorhiza dermatodea*). They found that gonad yield of fed urchins could be significantly increased over wild individuals, with *L. digitata* giving the best results.⁽⁴³⁾ In the early 1990s Hooper and co-workers experimented with plastic-coated stainless steel mesh cages (L x W x H: 1.3 x 0.5 x 0.4 m) placed on the sea floor to hold urchins for gonad enhancement. They fed adult urchins a variety of macroalgae (*Agarum cribrosum*, *A. esculenta*, *Ascophyllum nodosum*, *Fucus vesiculosus*, *L. digitata*, and *L. longicuris*) and discovered that the laminarian kelp plants were best for increasing gonad yield and optimizing gonad quality.⁽⁴⁴⁾

In 1995/1996, in the Bay of Fundy (NB), Robinson and Colborne successfully enhanced adult green urchins in plastic-coated wire mesh cages (L x W x H: 1.2 x 0.6 x 0.3 m) suspended from long-lines for a period of 12 weeks with minimal mortality.⁽⁴⁵⁾ Further trials occurred in the Bay of Fundy in 1999 on Grand Manan Island where sea urchins were placed in wire-mesh cages filled with kelp and hung from long-lines. The animals did increase their roe yields, but there were mortality problems associated with storm conditions as the sea urchins suffered damage from the turbulence. There were also trials in the early 2000s when urchins were contained in lobster pounds (Figure 3). The sea urchins were either loosely held or contained in cages, but the resulting survival and roe production were not encouraging and the project was abandoned.

Physical requirements

As with juveniles, adult urchins require clean water, high dissolved-oxygen concentration, and prompt removal of uneaten feed and faeces. Work in NL at the Sea Urchin Research Facility (SURF) examined the effect of stocking density on survival and roe yield. Nash used raceways to rear adult green urchins at three stocking densities: 14, 16, and 18 kg m⁻² (each at a water flow rate of 3.8 L min⁻¹ or one tank exchange every 2 hr). It was found that stocking density did not significantly affect gonad yield, but that 14 kg m⁻² provided the highest rate of survival.⁽⁴⁰⁾

be significantly increased using this form of culture.⁽⁴¹⁾ Further work on corralling urchins and using kelp (*Laminaria digitata*) for gonad enhancement was conducted in the mid 1990s in NL by New Ocean Enterprises Ltd. and Dr. Robert Hooper's team (Bonne Bay Marine Station, Memorial University, NL). They found that sea urchins could be successfully impounded and gonad yields increased over wild stock. Cultured urchins received favourable prices on the Japanese fish market and an economic analysis was done on the corralling operation.⁽⁴²⁾

Work on urchin gonad enhancement in sea cages began in the early 1980s in NL with some pioneering

Feeds

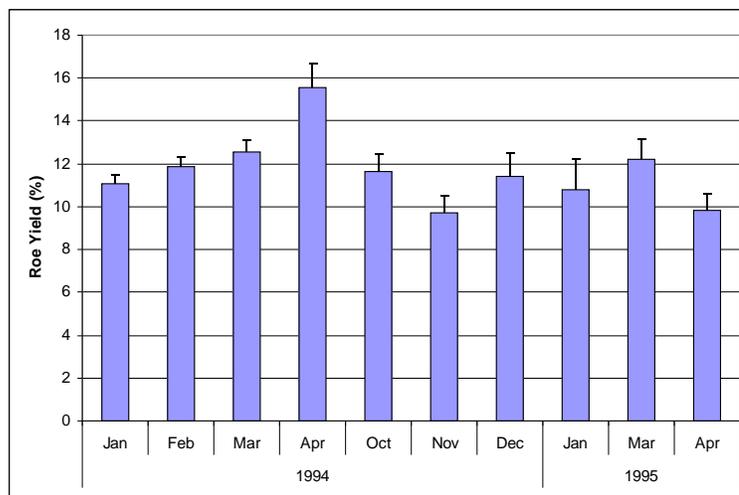
Newfoundland was the first Atlantic province to institute a program on sea-urchin roe enhancement, just as their fishery was being established in 1993. This program was initiated under the direction of Dr. Robert Hooper at the Bonne Bay Marine Station to look at the efficiency of feeding green sea urchins various species of macroalgae, with the support of the Canadian Centre for Fisheries Innovation, Greens Seafoods, and the Marine Institute of Memorial University. This work began with feeding trials in the laboratory on sea urchins held in small tanks. The results showed that sea-urchin gonads could be readily enhanced, but that diet made a large difference in the quality of the gonads that were produced. Sea urchins fed kelps, *L. digitata* or *L. longicuris*, produced the highest gonad yield and best quality roe while those fed other macroalgal species (*A. cribrosum*, *A. esculenta*, *A. nodosum*, and *F. vesiculosus*) produced mediocre or poor gonad yields/quality.⁽⁴⁴⁾ Mortality was minimal in urchins fed *Laminaria*, but higher in individuals fed *Ascophyllum* or *Fucus*.⁽⁴⁴⁾ Further work found that the addition of fish to the diet gave good improvement in gonad yield, but produced unacceptable gonad quality.⁽⁴⁶⁾ Hooper's team also found that, while it was easy to formulate artificial feeds that produced good growth, it was more problematic to get high roe quality with respect to colour, texture, aroma, and flavour. Later work showed that their artificial diets produced roe with much lower omega-3 fatty acid content than urchins fed wild-algal diets.⁽⁴⁷⁾ More recent research has focussed on commercialisation aspects of refining prepared diets, development of grow-out raceways, and transportation systems for the sea urchins from the harvester to the processor.

Early in the development of the Bay of Fundy fishery, several fishermen noticed that, while the average roe yields of harvested sea urchins ranged between 10 and 15% over the fishing season (Figure 5), there were certain areas and times when roe yields could be as high as 30% with excellent colour and overall quality. This inevitably led to questions on whether sea urchins could be harvested and given supplemental feed to increase their roe yield and overall profitability. It was generally known from popular and scientific literature that sea urchins would readily eat kelp and that the resulting roe would be of good quality. The problem in the Bay of Fundy was that kelp is a secondary habitat for lobsters and that any directed harvest of kelp would cause concerns to the powerful lobster-fishery industry.

As a result, the first trials on developing a prepared diet for sea-urchin gonad enhancement in the Bay of Fundy were initiated in 1995 by Green Gold Sea Ranch. This company developed a feed based on ground-up raw waste vegetables mixed with soy meal, minerals, and vitamins and held together with a guar-gum binder. The mixture resembled a stiff porridge, but the urchins ate it well and their gonad growth was enhanced. The colour and quality of the roe was variable, but fermentation problems with the diet made it impractical for large-volume manufacturing and subsequent storage.⁽⁴⁵⁾

As a result, in 1997 and 1998 the next generation sea-urchin enhancement di-

Figure 5
Mean monthly gonad yield of green sea urchins in the Bay of Fundy, New Brunswick in 1994/1995. Error bars are standard error.



ets were formulated from commercially-available dry ingredients supplied by Corey Feed Mills Ltd. in Fredericton, NB and Shur-Gain Feed Mill in Truro, NS. These diets were tested in both laboratory and field (*e.g.* wire cages and lobster pounds) experiments and while more stable for storage, the ingredients were based on fish diets and the resulting roe was of poor quality in colour and taste. In 1999, a sea-urchin specific diet was developed by Castell and Robinson. Unlike earlier attempts, this formulation was an open reference diet and was based on plant carbohydrates, proteins, and lipid sources. A number of different pigment sources in prepared diets were tested for producing suitable gonad colour and beta-carotene (at ~250 mg kg⁻¹ dry weight of feed) was discovered to be an important component in producing the rich yellowish-orange colour in the roe.⁽⁴⁸⁻⁴⁹⁾

Further work on prepared diets and roe enhancement was started in 1998 by Dr. Christopher Pearce with a commercial company RISL on Grand Manan Island, NB. That body of work showed that gelatin was the preferred binder for diets in maintaining the proper stability in seawater for the delivery of the food to the sea urchins.⁽⁵⁰⁾ Protein levels were tested in relation to concentration and source. It was determined that 19% protein levels were suitable for sea-urchin enhancement diets and that plant proteins could be used.⁽⁵¹⁾ Further studies also confirmed that beta-carotene was important for colouration, but that different carbohydrate sources (corn starch, potato starch, tapioca starch, marine plant meals) did not significantly affect gonad yield, colour, texture, firmness, or taste.⁽⁵²⁾ RISL began trials for pilot-scale commercial gonad enhancement in 2003 but mortality, thought to be due to problems with water quality, put the project on hold.

Wild re-seeding

There are currently no wild re-seeding projects underway in Canada, for several reasons. Firstly, the stocks are generally still in reasonable shape in most areas and there is no perceived need to rebuild populations. Secondly, the supply of sea-urchin juveniles from either hatcheries or wild-collection programs does not exist to produce commercial volumes of animals. Thirdly, in most areas there are no sea-bed leases where juveniles could be reliably released to be harvested several years later. Most of the beds are common to the entire fishery of the area and there would have to be 100% compliance on the contributions from the license holders to support such an effort. At the moment, there is not that level of cooperation within the industry and there have been no suggestions to move in that direction.

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Note:

For this review, the authors have used the species names published in the references. The names of some of the algal species referred to in this review have been changed since the papers were published. *Laminaria longicuris* is now known as *Saccharina latissima* and the green seaweeds from the genus *Enteromorpha* are now known as the genus *Ulva*.

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