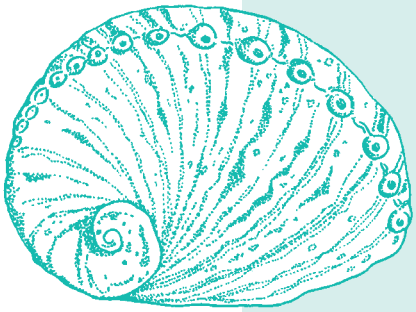
FISHERIES RESEARCH REPORT

No. 128, 2001

Aquaculture and related biological attributes of abalone species in Australia – a review.

Kylie A. Freeman



***Haliotis laevigata* – Greenlip Abalone**

***Haliotis conicopora* – Brownlip Abalone**

***Haliotis rubra* – Blacklip Abalone**

***Haliotis roei* – Roe's Abalone**

***Haliotis asinina* – Donkey ear Abalone**

***Haliotis scalaris* – Staircase Abalone/Ridged Abalone**

FISHERIES
WESTERN AUSTRALIA

Western Australia Marine Research Laboratories
Department of Fisheries
PO Box 20, North Beach, WA 6020

Fisheries Research Report
Titles in the fisheries research series contain technical and scientific information that represents an important contribution to existing knowledge, but which may not be suitable for publication in national or international scientific journals.

Fisheries Research Reports may be cited as full publications. The correct citation appears with the abstract for each report.

Numbers 1-80 in this series were issued as Reports. Numbers 81-82 were issued as Fisheries Reports, and from number 83 the series has been issued under the current title.

Enquiries
Department of Fisheries
3rd floor SGIO Atrium
168-170 St George's Terrace
PERTH WA 6000
Telephone (08) 9482 7333
Facsimile (08) 9482 7389
Website: http://www.fish.wa.gov.au/res

Published by
Department of Fisheries
Perth, Western Australia
June 2001
ISSN: 1035 - 4549
ISBN: 0 7309 8456 7

FISHERIES
WESTERN AUSTRALIA

An electronic copy of this report will be available at the above website where parts may be shown in colour where this is thought to improve clarity.

Fisheries research in Western Australia
The Fisheries Research Division of the Department of Fisheries is based at the Western Australian Marine Research Laboratories, P.O. Box 20, North Beach (Perth), Western Australia, 6020. The Marine Research Laboratories serve as the centre for fisheries research in the State of Western Australia.

Research programs conducted by the Fisheries Research Division and laboratories investigate basic fish biology, stock identity and levels, population dynamics, environmental factors, and other factors related to commercial fisheries, recreational fisheries and aquaculture. The Fisheries Research Division also maintains the State data base of catch and effort fisheries statistics.

The primary function of the Fisheries Research Division is to provide scientific advice to government in the formulation of management policies for developing and sustaining Western Australian fisheries.

TABLE OF CONTENTS

ABSTRACT

China and Taiwan are the major producers of cultured abalone; with annual production estimated at 3,500 and 3,000 tonnes respectively. The world production of cultured abalone sold in 1999 was 7,775 tonnes. Australian farm production was still relatively low (89 tonne in 1999) but numerous abalone farms have been proposed and many have been constructed. On a national scale, Tasmania and South Australia are the major states involved in temperate abalone culture; however, new projects have commenced in Victoria and considerable interest exists in New South Wales. Pilot scale trials with tropical abalone aquaculture using the Donkey-ear abalone (*Haliotis asinina*) have been undertaken in Queensland and Western Australia. The culture of abalone in Western Australia is still in its preliminary stages with only one hatchery operating in Albany and a major farm under construction and partly stocked at Bremmer Bay, near Albany.

A commercial fishery for abalone exists in Western Australia, consisting of Roe's (*H. roei*), Brownlip (*H. conicopora*) and Greenlip (*H. laevigata*) abalone. The current total catch of these abalone species (1998/99) is estimated to be approximately 341 mt (live weight). The Australian and world catches are 5,538 mt (1999) and 10,150 mt (1999) respectively.

The major world markets for abalone are China and Taiwan, which consume around 80% of the world catch. Markets also exist in Japan, Europe and Korea. While mainland China is the largest consumer nation for the canned product, Japan is the largest consumer nation for live, fresh and frozen abalone. Overall, Japan, Taiwan and Hong Kong represent the major markets for Australian abalone.

Biological attributes and farming technology, where information is available, are outlined for six abalone species of interest for aquaculture within Australia. These are Greenlip, Roe's, Blacklip (*H. rubra*), Brownlip, Donkey ear, and Staircase (*H. scalaris*) abalone.

Hatchery production of abalone larvae and spat is well developed with spawning, hatching and larval rearing, and nursery procedures proving quite successful.

Artificial feeds for Australian abalone are of high quality but are still being optimized. In Australia, nutritional research, higher product volumes and market place competition have lowered artificial diets to about $AUS 3.00-3.90 per kg. In their natural habitat, adult abalone generally feed on drift algae or graze on attached algae.

Growth is affected by many factors such as source of stock, density, type and amount of feed, water flow and quality, handling techniques, temperature, and the type of culture system. Several tank systems (both land-based and sea-based) have been designed and tested within Australia in trials organized by the Fisheries Research and Development Corporation (FRDC) and carried out by abalone farmers in South Australia and Tasmania.

Current and future research could be aimed at possible diseases of the Western Australian abalone species, broodstock conditioning, cryopreservation of sperm and eggs, control of bacteria in hatcheries, genetic issues (hybrid and/or triploid abalone, selective breeding) and species-specific information. To date, the majority of research conducted within Australia has been carried out on the Greenlip abalone, particularly in land-based systems.

INTRODUCTION

Abalone are distributed along much of the world's coastline. They are found from the intertidal to depths of approximately 80-90 m, from tropical to cold waters (Hone and Fleming, 1998). Most of the Australian species of interest for aquaculture are found in the southern waters, ranging from the coast of New South Wales, around Tasmania and to as far north as Shark Bay, WA (Figure 1). They are mostly found on substrata of granite and limestone (Joll, 1996); however, newly settled abalone prefer to live on encrusting coralline algae (Hone *et al*., 1997).

The major producers of cultured abalone are China (3,500 mt annually) and Taiwan (3000 mt annually) (Gordon, 2000). Also, there are small industries in California, New Zealand, France, South Korea, Japan and Australia. In fact, Australia is now in a position to become a major contributor to the world aquaculture production of abalone following very significant investment proposed in warm temperature abalone farms (Maguire and Hone, 1997) with much of it having been realised. Furthermore, Donkey-ear abalone culture techniques have been developed in Thailand, the Philippines and Australia.

Figure 1. Represents the geographic distributions of abalone species of aquaculture interest in Australia.

South Australia and Tasmania are the principal states within Australia that have investment in abalone culture. There are 17 land-based farms in South Australia and 3 land-based farms in Tasmania, with production in 1999 estimated at 72 tonne and 10 tonne, respectively (Gordon, 2000). Additional farms have been built particularly in Victoria. The abalone cultured in Tasmania and South Australia are Greenlip (*Haliotis laevigata*) (Figure 2), Blacklip (*Haliotis rubra*), and a hybrid of these two species. Also, South Australian farmers have trialed Roe's abalone (Figure 2). Currently there is one commercial

Figure 2 'Foot view'. Greenlip Haliotis laevigata *(left), Roes* Haliotis roei *(centre), and Brownlip* Haliotis conicopora *(right)*

'Shell view'. Greenlip (left), Roes (centre), and Brownlip (right)

hatchery operating in Western Australia, which is at present concentrating on Greenlip, Roe's (*Haliotis roei*) and Brownlip (*Haliotis conicopora*) abalone (Figure 2). Also a major farm is under construction and partly stocked at Bremmer Bay, near Albany.

Development in Western Australia of land-based and sea-based growout sites is limited by appropriate investment partners, native title issues and concerns over potential impacts on seagrass beds. The

Figure 3. *Staircase abalone* Haliotis scalaris

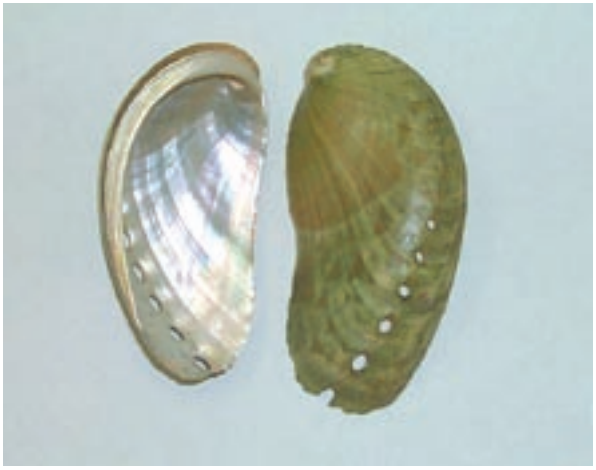


Figure 4. *Donkey-ear abalone* Haliotis asinina

staircase abalone (*Haliotis scalaris*) has recently been identified as a potential species for culture, since it occurs along the west coast and may be easier to spawn than Roe's abalone (Figure 3). Additionally, the Donkey-ear abalone (*Haliotis asinina*) is being evaluated for culture in the tropical areas of northern Queensland and Western Australia (Figure 4).

Aquaculture development planning in several states has identified abalone as a high priority based on current investment and industry potential. This is especially true for Western Australia, particularly along the southern coast.

Relationship between *Haliotis rubra* and *Haliotis conicopora*

Several studies have indicated that *Haliotis conicopora*, Brownlip abalone, is a separate species from the Blacklip abalone (*Haliotis rubra*) (Figure 5). However, others have suggested that the relationship between Blacklip and Brownlip is unclear, and they may be conspecific (Wells and Mulvay, 1992). Furthermore, Brown and Murray (1992) considered *H. conicopora* to be genetically identical to *H. rubra* and therefore conspecific. In this review, information for Brownlip abalone is supplied whenever possible, however, when information is not available for this species, the data for Blacklip abalone should be used as a guide for Brownlip abalone.

Figure 5. *Blacklip abalone* Haliotis rubra

1.0 COMMERCIAL FISHERIES

There are eleven abalone species occurring in Western Australia, but only three are commercially fished, namely Roe's, Greenlip and Brownlip abalone. The Western Australian fishery, as of April 1st 1999, was divided into eight overlapping areas;

Area 1 along the southern coast from the South Australia border to Point Culver,

Area 2 Point Culver to Shoal Cape,

Area 3 Shoal Cape to the Busselton jetty

Area 4 Busselton jetty to Northern Territory/Western Australian border,

Area 5 Shoal Cape to Cape Leeuwin,

Area 6 Cape Leeuwin to Cape Bouvard,

Area 7 Cape Bouvard to Moore River,

Area 8 Moore River to Northern Territory/Western Australian border.

Western Australian's commercial abalone fishery has remained stable over the past 6 years; however, its value has increased in monetary terms. In 1991/92 the fishery was valued at $A7 million, but had increased to $A10.7 million by 1997/98 and was estimated to be 341 tonnes (live weight) for 1998/99 (Fisheries Western Australia, 2000). The Australian and world catches are 5,538 mt (1999) and 10,150 mt (1999) respectively (Gordon, 2000). Supply versus demand on a worldwide scale shows that a 5,000 tonne shortfall in supply exists even without allowing for further fisheries collapses.

2.0 MARKET FACTORS

2.1. Marketing Information

In the early 1990s, both demand and price increased for premium abalone products. This resulted in an economic environment in which abalone culture became attractive as a financial investment. Currently, cultured abalone are shipped to several international markets and the abalone aquaculture industry is becoming known as a reliable year-round source of high quality abalone products. The major consumers of abalone are Japan and China (including Southeast Asia), which together purchase around 80% of the world catch. There are also well established markets in Europe and Korea. Mainland China is the major consumer of abalone mostly as canned product. In contrast, the largest world consumer of live, fresh and frozen abalone is Japan. Profitable markets for live abalone exist in Hong Kong, Taiwan, Singapore, Thailand, and other Asian metropolitan centres. In addition, there is a traditional market in California for tenderized abalone steaks (Oakes and Ponte, 1996).

In 1997, Hong Kong was regarded as one of the world's largest importers of abalone in the world with total imports reaching over 2.3 million kg worth US$135 million (Hong Kong Census and Statistics Dept. in Kiley, 1998). In comparison to 1996 figures, these values represent an increase of 15.4% in quantity and 36.4% in value. Moreover, in the first quarter of 1998 abalone imports into Hong Kong decreased by 10-20% in price and 33% in volume (compared to same quarter in 1997), reflecting the general Asian economic downturn. The Hong Kong market is mostly supplied by Australia, New Zealand, South Africa, Taiwan and Japan (Kiley, 1998).

2.1.1. Southern Australian abalone

Japan, Taiwan and Hong Kong represent the major markets for Australian abalone, accounting for 48%, 24% and 16% respectively of the total volume of Australian abalone exports in 1995-96. In 1997 Hong Kong was regarded as one of the largest importers of abalone in the world with total imports over 2.3 million kg (US$135 million) (Kiley, 1998). Australia is the world's largest exporter of fresh, frozen and canned abalone supplying about 81% of fresh and frozen abalone and 67% of canned abalone traded internationally (Brown *et al*., 1997).

Traditionally, abalone has been exported from Australia as either canned or fresh (dead fresh meat only), and depending on the market, canned prices can exceed the fresh prices. Currently most farmed product is sold canned as this requires less effort when exporting (pers. comm. Shane McLinden, 2000). However, the premium market for abalone has been regarded as the live (whole fresh abalone) market. Greenlip abalone often fetch the highest price of the four main commercially traded species (Greenlip, Brownlip, Blacklip and Roe's). However, Greenlip abalone are prone to stress when shipped and consequently this can result in a reduction of the price for the live product. Approximately 250 mt of abalone are exported to Southeast Asia, Japan and China per year from South Australia. The majority of this product is wild-caught abalone; however, it is predicted that the percentage of cultured abalone will increase with the development of more commercial farms (Kiley, 1998).

2.1.2. Donkey-ear abalone

In the Asian markets, tropical abalone are being sought to fill an increasing demand for small ('cocktail') abalone. There is potential that the Donkey-ear abalone will be a valuable export earner for Australia. It is expected to complement, rather than compete with the larger temperate species. Currently, Donkey-ear abalone are collected throughout Southeast Asia for Asian, European and Australian markets, with over 500 mt each year being harvested from the Philippines. Aquaculture production of Donkey-ear abalone is practically non-existent, and research efforts to establish a culture industry exist only in Thailand, Australia and the Philippines (Williams and Degnan, 1998).

2.2. Product Attributes

There are a few characteristics that determine an abalone's quality, value and market place (Oakes and Ponte, 1996). These include:

1. Foot colour – abalone species with lighter pigmentation of the foot generally fetch the highest price in the market. The darker ones require more preparation before selling.

2. Texture – traditional abalone recipes use the meat in the following three textured forms:
   a) tenderized by cooking, canning or pounding
   b) raw meat with a crisp texture
   c) dried abalone

3. Size – The size of an individual will command a different price depending on the particular market. The preferred size (shell on) per animal is:
   a) North America – 600-800 g
   b) Japan – 300 g
   c) Southeast Asia – 60-85 g

2.2.1. Nutritional facts

Apart from water, the edible portion of abalone is largely protein and carbohydrate (glycogen) (G Maguire, pers. comm., 2001). The nutritional profile of the lipid (fat) content provided in Table 1 is based on Blacklip abalone (per 100 g of raw product).

Total fat (oil)	0.8 g
Saturated fat	31% of total fat
Monounsaturated fat	22% of total fat
Polyunsaturated	47% of total fat
Omega-3, EPA	48mg
Omega-3, DHA	2 mg
Omega-6, AA	100 mg

Table 1 Nutrition facts (per 100 g of raw products, unless stated) based on Blacklip abalone (adapted from Yearsley et al., 2000)

3.0 TECHNOLOGY

3.1. Broodstock

3.1.1. Availability in the wild

A successful hatchery depends on access to good quality broodstock. The three sources of abalone broodstock include:

a) Wild-caught
b) Wild-caught and farm-conditioned
c) Second or later generation farmed abalone

South Australian hatcheries currently use mostly wild-caught individuals; however, conditioned wild abalone are used on some farms. In future years, use of second generation farmed broodstock is likely to become more common than collecting wild broodstock. Currently, most Tasmanian and Victorian farms obtain wild broodstock by selecting animals from those sent to processing factories. However, some farmers use their own divers to collect broodstock but special administrative procedures permitting access to wild stocks must be in place as commercial access to the wild-stock fishery is usually restricted to licensed fishers within tightly managed, lucrative fisheries (Grove-Jones, 1996a). Some abalone farmers in Tasmania, Victoria and South Australia are currently using some of their farmed abalone as broodstock (S. Parsons, pers. comm., 2001). Wild broodstock are also being conditioned outside of normal breading season, at several locations in Australia including Albany.

Mature males and females can easily be recognized by the differences in gonad colour [males = creamy white, females = usually green] (Bardach *et al.*, 1972). Shepherd and Laws (1974) found that the gonad colour of female Blacklip abalone changes quite regularly depending on the stage of maturation. Spent or developing ovaries are coloured a grey-blue or brown. A change from grey-green to olive green is evident as they approach maturity. In Donkey-ear abalone, mature ovaries are a rich green colour (R. Counihan, pers. comm., 1999).

3.1.2. Size and age at maturity

Estimates are provided in Table 2. While animals may reach sexual maturity at these sizes, substantial spawning may not occur until subsequent years (Shepherd and Laws, 1974).

Species	Size at maturity	Location	Age at maturity	Reference
Greenlip	90-100 mm	SA	3 years	Shepherd & Laws, 1974
	80-90 mm	SA	2 years	Joll, 1996
	90 mm	–	3-4 years	Benzie, 1996
Brownlip	130 mm	WA	–	Wells & Mulvay, 1992
	90-110 mm	SA	–	Joll, 1996
Blacklip	70-110 mm	SA or WA	3 years	Shepherd & Laws, 1974
Roe's	55-60 mm	SA	–	Shepherd & Laws, 1974
	40-50 mm	WA	1 year	Wells & Keesing, 1986; Wells & Bryce, 1987; Joll, 1996
	40 mm	WA	+1 years	Keesing & Wells, 1989
Staircase	45-70 mm	–	–	Shepherd & Laws, 1974
	65-80 mm	–	–	Shepherd *et al*., 1985
Donkey-ear	40.6 mm (Wild) = male and females	QLD	–	R. Counihan, pers. comm.,1999
	30.5 mm = males	QLD		R. Counihan, pers. comm.,1999
	35.9 mm = females (Captivity)	QLD		
	35 mm (Captivity)		–	Castanos, 1997
	60 mm (Captivity)	Philippines	1 year	Capinpin *et al*., 1999
	70-100 mm	–	–	Lee, 1998

Table 2 Size and age at maturity of six species of abalone (for wild stock unless stated).

3.1.3. Captive maturation (conditioning) and tolerance to captivity

3.1.3.1. Blacklip abalone

O'Sullivan (1994) reported that a Tasmanian farm had success in conditioning Blacklip abalone out of season by using summer water temperatures. Savva *et al*. (2000) found that temperatures of 15.0-16.0ºC was successful in conditioning *H. rubra*. In addition, the breeding performance of *H. rubra* was most successful when fed a commercial formulated diet, however, adding dried *Phyllospora comosa* to the diet did not improve the reproductive performance of *H. rubra*.

3.1.3.2. Greenlip abalone

There has been success in conditioning Greenlip broodstock out of season (over winter months) by holding them at 18°C for 3-4 months while feeding to excess (Grove-Jones, 1996a). In other research into broodstock conditioning of Greenlip abalone, the mean temperature during conditioning was 16.0°C and the number of elapsed degree days was recorded as 1,750 (Lleonart, 1992). At degree days of 1,750 the abalone were only just coming into condition. Note that degree days is usually estimated relative to a biological zero temperature, for example, the maximum low temperature at which larval development is prevented. In the study by Lleonart (1992) an actual zero °C reference was used not a biological zero. Recent collaborative research by Fisheries WA with industry has yielded excellent winter spawnings (see Freeman *et al*., 2000a for design).

3.1.3.3. Roe's abalone

Fisheries Western Australia has had some success in conditioning wild Roe's abalone by holding them at ambient temperature and staff feeding to excess for 6 and 12 months.

3.1.3.4. Donkey ear abalone

Conditioning of broodstock has been achieved in captivity. This indicates some potential of Donkey-ear abalone as an aquaculture species (Castanos, 1997).

3.1.4. Genetic issues/translocation challenges

Genetic studies have revealed that dispersal of larvae is highly restricted, perhaps less than 1 km. It is thought that even some neighboring populations of abalone should be regarded as separate gene pools (Brown and Murray, 1992). However, Hancock (2000), found that across 10 sites in southern Western Australia (over a 3,000 km range) there were relatively high levels of gene flow among *H. roei* populations but that there is clearly discernible differentiation between populations separated by as little as 13 km.

Brown (1991b) suggested that larvae with the ability to disperse over large areas may determine the genetic capabilities of that population. He found within abalone populations that non-random mating between individuals can cause genetic structuring. It was suggested that "such mating patterns can result in spatial differentiation of 'local' populations and can be reflected in the geographic distribution of genetic variation". The genetic structure among local populations can also be altered by mutation, natural selection and genetic drift. Until longer term sampling of specific populations is undertaken, it will not be possible to determine whether observed differences between adjacent populations reflect effective participation by small numbers of broodstock (volatility in genetic profile as larvae settle from other locations), or permanent genetic separation of populations.

Benzie (1996) considered that high levels of genetic diversity could be maintained as current spawning and hatchery technology is sufficiently developed for abalone. If appropriate broodstock management procedures are used, gene frequencies can be maintained approximating those in the wild stocks.

Based on the relatively small differences in allozyme frequencies between relatively distant populations of Roe's abalone (Hancock, 2000), Fisheries Western Australia abandoned a policy of discrete genetic zones, for this species, that would have required farmers in a particular zone to rely on broodstock from that zone. However, there is evidence of separation of Greenlip populations in Western Australia (N. Elliot, pers. comm., 2001).

3.1.4.1. Ensuring genetic diversity

Currently in South Australia about 12-18 females and 6-9 male Greenlip abalone are stimulated to spawn in a commercial hatchery run. This number of broodstock yields around 30-50 million eggs depending mainly on the size of the abalone and the number that spawn. The quantity of sperm is usually in excess. This number of males is appropriate for ensuring that genetic diversity is maintained, especially as several batches per year are produced with different broodstock at each hatchery. However, it must be noted that not all of the males will spawn. Additionally, sperm from several males guards against the possibility of one defective male fertilizing the whole batch (Grove-Jones, 1996a). Smith and Conroy (1992) recommended, in a study on *H. iris* in New Zealand, that no less than 10-13 males and 25-50 females should be used for a single spawning batch in order to retain 95% of the wild variation in hatchery seed.

3.1.5. Reproductive synchronicity

The sexes are separate in abalone (Bardach *et al*., 1972; Brown, 1991a; Landau, 1992) and fertilization is external (Brown, 1991a; Joll, 1996). Occasionally, however, hermaphroditic animals are found (Pillay, 1993). Landau (1992), suggested that abalone in a single population usually spawn at the same time, probably as a result of a synchronizing factor.

Fallu (1994) observed that sexually mature individuals aggregate where possible before spawning, presumably to increase external fertilization success. McShane (1992) considered that aggregation is advantageous to broadcast spawners to promote synchrony of spawning and enhance fertilization. Aggregations of Greenlip abalone are most commonly up to 20-25 individuals (Shepherd and Partington, 1995) with the size of an aggregation being dependent on habitat type, density and movement (Shepherd, 1973).

Shepherd and Laws (1974) found that spawning in Blacklip abalone was poorly synchronized. Similarly, Heasman (pers. comm., 2000) found that in two intensive NSW studies in the southern and central areas, spawning was relatively rare from recently collected wild broodstock. Hatchery operators emphasize the need for access to a range of reefs to reliably obtain spawning stock. Spawning wild Donkey-ear abalone is cyclical with a very high level of synchrony (i.e. males and females spawn on the same night and within 90 minutes of each other). However, hatchery reared Donkey-ear abalone are generally asynchronous spawners (R. Counihan, pers. comm., 1999).

3.2. Spawning and Egg Quality

Hahn (1989) reported that quite often males spawn slightly earlier and require less stimulus to induce spawning than females. There have been several studies outlining different spawning periods for Blacklip abalone, and the factors regulating spawning. However, Hone *et al*. (1997) found that wild abalone show two patterns.

a) abalone will serially spawn during the reproductive season when weather conditions are constant and mild.
b) abalone near condition will spawn if high stress conditions occur (i.e. when weather conditions are extreme).

3.2.1. Gonad Maturation

Most studies of Australian abalone have indicated relatively extended periods for high incidence of advanced gonadal development (Table 3).

Abalone Species	Spawning season & location	Reference
Greenlip	October-March (SA)	Shepherd and Laws, 1974
	October-December (WA)	Wells and Mulvay, 1992
Blacklip	October-January & March-June (SA)	Shepherd & Laws, 1974
	Generally Spring and Summer along the entire southern coast of Australia	Brown, 1991a
Roe's	Throughout the year (SA)	Shepherd & Laws, 1974
	Observed as February-March in King George Sound, Albany (WA)	S. Parsons, pers. comm., 2000
	Peaks in July-August & continues at a lower level until the end of the year (WA).	Wells & Bryce, 1987; Wells & Keesing, 1986, 1989
Staircase	February-May (SA)	Shepherd *et al.*, 1985
Donkey-ear	Year-round with monthly peak in October (Thailand)	Castanos, 1997
	October-April (Central Qld)	R. Counihan, pers. comm., 2000
Brownlip	April-June (WA)	R. Lambert, pers. comm., 2001

Table 3 Periods of high incidence of advanced gonad development in different locations for five species of abalone.

There are a number of environmental factors that are known to influence the spawning cycles of abalone, which include temperature, photoperiod and food abundance (Shepherd *et al.*, 1985). Fleming (2000c), reports that temperature is the prime trigger for gonadal development for most species of abalone, provided nutrition is adequate. A project has been designed for conditioning of Greenlip and Blacklip abalone by temperature manipulation and will be carried out in Tasmania. The main aims are to determining the biological zero point and the relationship between temperature and gonad development, identify the temperatures required to condition abalone over a set period of time, and to develop protocols for the commercial control of spawning in abalone by temperature manipulation (Ritar, 2000).

3.2.2. Spawning stimuli

Castanos (1997) described a study in the Philippines on the Donkey-ear abalone that observed spontaneous spawning several days before or during the new moon and full moon. Natural spawning occurred regularly every two weeks following a lunar cycle and gametes were released from about 10 p.m. to 3 a.m. There was no need to induce the abalone to spawn since it happened naturally at 28°-30°C and 30-32 ppt. However, it is believed that the release of gametes from one abalone can induce another to spawn. Additionally, Capinpin (1995) found that the techniques frequently used successfully with warm temperate species i.e., desiccation, heat shock, ultraviolet-irradiated seawater and hydrogen peroxide, singly or in combination, failed to induce mature Donkey-ear abalone to spawn viable numbers of eggs or spermatozoa. In central Queensland it has been observed that spawning times for Donkey-ear abalone correlate with the time of the evening high tides. Therefore, since spawning is not only frequent, but predictable, inducement of spawning is not needed for Donkey-ear abalone (R. Counihan, pers. comm., 1999).

3.2.3. Manual stripping

This is used routinely with oysters but is not effective with some other bivalves (Kent *et al.*, 1998).

In abalone, manual stripping is only applied to males as a method for stimulating spawning of females. The testis is removed and a section is mascerated into seawater to make a liquid. This liquid is then distributed near the anterior edge of the shell with a syringe in an attempt to induce the female to spawn (Hone *et al.*, 1997).

3.2.4. Fecundity and frequency of egg production

Most abalone species generally only have one annual maturation period (Shepherd and Laws, 1974). However, Shepherd *et al*. (1992) found that not all eggs are necessarily released in a single spawning and that an individual may be able to release eggs over an extended period. Blacklip abalone have been observed to have multiple spawnings within one spawning season (Brown, 1991a). Castanos (1997) reported that wild caught Donkey ear abalone broodstock spawn more frequently and produce more eggs than hatchery-bred broodstock. He noted that the hatchery-bred abalone had short intervals between successive spawnings of 13-15 days. Abalone are relatively fecund and there is an exponential relationship between size (shell length) and fecundity for Greenlip, Brownlip (Wells and Mulvay, 1992) and Roe's abalone (Wells and Keesing, 1989) (Table 4).

Abalone species	Fecundity (number of eggs measured in a single spawning)	Reference
Greenlip	2 million eggs	McShane, 1988
Blacklip	2 million eggs	McShane, 1988
	2.2-2.8 million eggs	O'Sullivan, 1994
Brownlip	5 million eggs @ 190 mm	Wells & Mulvay, 1992
Roe's	200,000 eggs @ 40-50 mm	Wells & Bryce, 1987
	1 million eggs @ 60 mm	
	183,000 @ 37.5 mm	Wells & Keesing, 1986; 1989
	8.6 million @ 122 mm	
Donkey-ear	200,000-600,000 0	Singhagraiwan and Doi, 1992
	@ 58-80 mm	

Table 4 Fecundity of four species of abalone.

3.2.5. Gamete quality

Abalone eggs become fully developed near the natural spawning period. This is the best time to spawn when using wild-caught broodstock so there will be high quality abalone gametes for the hatchery (Joll, 1996). Viable fertilized eggs from Greenlip and Blacklip abalone are usually around 250 μm in diameter. In comparison, eggs from Roe's abalone are approximately 220-250 μm (S. Parsons, pers. comm., 1999), while those from the Donkey-ear abalone are about 190 μm (Singhagraiwan and Sasaki, 1991). Good quality eggs are green in colour, sink to the bottom and do not clump together (Hone *et al*., 1997).

The density of sperm added to the abalone eggs is a very important aspect of abalone culture. A high sperm density during fertilization can cause polyspermy with a high proportion of abnormal embryos and trochophores. In contrast, lower percentage fertilisations may result from very low sperm densities. The desired density is 5-10 sperm per egg (Hone *et al*., 1997). High sperm densities (usually >186,200/ml) with Donkey-ear abalone may cause abnormal larval development or embryogenesis. The ideal sperm concentration for Donkey ear abalone is approximately 19,000/ml (R. Counihan, pers. comm., 1999).

3.3. Early Development

Hatched trochophore larvae are approximately 200 μm in size, lecithotrophic (i.e. draw their nutrition from the yolk sac), and positively phototactic (Huner and Brown, 1985).

3.3.1. Critical development issues

3.3.1.1. Duration of larval phase

The planktonic eggs generally hatch within 24 hours. Abalone larvae have the ability to complete larval development on the yolk provided in the egg. This greatly simplifies hatchery culture, as an external food source is not required (Joll, 1996). Organisms with shorter larval periods are easier to rear to the juvenile stage, and are therefore considered better aquaculture candidates at least for this attribute.

The length of the larval stage in abalone is related to the water temperature. Hone *et al*. (1997) state that the length of the larval stage ranges from 4-5 days at 20°C to 9-10 days at 14°C. However, the length of larval development is highly species specific, and will vary between species at the same water temperature (R. Counihan, pers. comm., 1999) (Table 5).

Species	Length [days]	Reference
World-wide	6-11	Bardach *et al*., 1972
WA-species	4-7	Joll, 1996
Greenlip	5	Benzie, 1996
	4-5 @ 20ºC	Hone *et al*., 1997
	9-10 @ 14ºC	
Blacklip	4.5-6	O'Sullivan, 1994
Donkey-ear	2	Capinpin, 1995

Table 5 Length of the larval phase in abalone (Haliotis spp).

Hatching and settlement in Donkey-ear abalone occurs 8 and 48 hours post-fertilization (respectively), which is rapid in comparison to temperate abalone species (Williams and Degnan, 1998). This characteristic is an advantage for the culture of this animal since individuals are most susceptible to bacterial infection during the early stages of development.

3.3.1.2. Metamorphosis (associated with settlement)

During the transition from planktonic veliger to benthic juvenile, survival is very low (approximately 10%). This is not a problem for pilot scale work, however, low survival does pose a problem if production is to meet the ever-increasing demand for abalone. The critical issue in the stage of metamorphosis is habitat requirement. The habitat required by newly settled larvae, and their ability to discriminate between substrata that may be crucial to their survival, is critical and poorly understood (Hahn, 1989).

Hahn (1989) reports that certain larval structures indicate when larval development is complete and the larva is ready to settle. He describes competent larvae to be veligers, which have not lost their ability to swim or crawl and have not yet changed shape. It was also reported that larvae are capable of crawling on the substratum after the first epipodal tentacle forms and settlement is initiated after the snout protrusions form (see Hahn, 1989). Hahn (1989), suggests that before metamorphosis can proceed, the development of sensory organs is extremely important for choosing the proper substratum. Moreover, abalone larvae have the ability to return to a swimming mode after an initial settlement attempt in order to find a more suitable substrate for settlement. However, there are limits to how long the larva can go on 'seeking' better substrata as it will eventually exhaust the yolk supply (Joll, 1996).

Heasman *et al*. (2000), found that settlement on diatom coated settlement plates were poor with values from 0 to 5.5%, however, when crustose coralline algae coated rocks (CCARs) were used as a settlement substrate a higher percentage of settlement occurred (20-40%). Moreover, temperature effects as indicated by early juvenile growth and relative yields of *H. rubra* on both substrates were

consistent. *H. rubra* larvae have the ability to settle on CCARs over a temperature range of 7-26ºC and on diatom plates, 12-26ºC, with peak settlements occurring at 19ºC and 17ºC for diatom plates and CCARs respectively (Heasman *et al*., 2000).

3.3.1.3. Factors affecting settlement, survival and growth

GABA (g-aminobutyric acid), diatoms or pregrazed conditioned plates are most commonly used to induce settlement in hatcheries. The effectiveness of both GABA and diatoms varies among abalone species. The diatom species within the genus *Cocconeis* can be favourable for settlement as it is flat and stable (Roberts *et al*., 1998), however, these species can be slow growing (S. Daume pers. comm., 2001).

Currently hatchery-reared larvae are given specially "conditioned" plates to induce settlement. Conditioned plates are produced by placing plastic sheets into natural seawater and exposing them to natural light to achieve a growth of bacteria and diatoms on the surface for the settlement of abalone larvae. This is thought to simulate their natural settlement environment. In the wild, abalone larvae will settle on surfaces with a biofilm and prefer to settle on reef surfaces coated with encrusting coralline algae (McShane and Smith, 1988). However, this is impractical for hatchery use as coralline algae are generally slow growing and do not survive after drying. In addition, methods have not yet been established for commercial bulk culture of coralline algae (Roberts *et al*., 1998).

Different diatom species can produce variation in post larval growth and survival. During feeding, diatoms that are easily broken down will produce faster growth rates and increase survival than 'unbreakable' species. The nutritional requirements of juvenile abalone change with post larval growth. A change in diatom characteristic (i.e. cell size) can mean a change in food value of a particular diatom strain. Post-larvae can tolerate about a week of severe food limitation, but major mortalities will result after this period (Roberts *et al*., 1998).

A study carried out by Daume *et al*. (1999) revealed that Blacklip abalone larvae prefer to settle on the natural substratum, non-geniculate coralline red algae (*Phymatolithon repandum*), when given a choice between it and several diatom species. In contrast, Greenlip abalone responded to both non-geniculate coralline red algae (*Sporolithon durum*) and all tested diatom films (*Amphora sp*., *Cocconeis scutellum*, *Navicula ramosissima* and *Cylindrotheca closterium*). Films of *Navicula ramosissima* were the only diatoms as effective in inducing settlement of Greenlip abalone larvae as the non-geniculate coralline red algae (*Sporolithon durum*). Overall, settlement of abalone larvae was higher on older diatom films.

A more recent study carried out by Daume *et al*. (2000) on Blacklip abalone showed that larvae preferred to settle on films with mixed diatom species (depending on the species combination), than single species films. Moreover, the greatest settlement was observed when using a mixture of *Navicula* sp. and *Amphora* sp. Adding germlings to settlement plates with an established diatom community induced greater settlement than using only the diatom films. In fact, a 36% increase was observed if germlings from the green encrusting alga *Ulvella lens* were used. Even greater settlement was achieved if these sheets were first pregrazed by juvenile abalone. Krsinich *et al*. (2000), clearly demonstrated that plates covered with *Navicula* sp. or *U. lens* (+ wild algae) acted as positive inducers for larvae settlement. In terms of growth, *Navicula* sp. produced highest growth rates of 64 μm/day between day 21 and day 28 (and greatest shell length of 1439 μm standard error at day 28). On day 35, mean abalone shell lengths for juvenile abalone on diets of *U. lens* + wild algae and *Navicula* sp. were 1760 μm and 1820 μm respectively, which was not significantly different.

Garland *et al*. (1985), found that *H. rubra* grazes the surfaces of crustose coralline algae from Tasmanian waters. It was suggested that this species depends on the cuticle and epithallial contents for nutrition. Moreover, phytoplankton and bacteria form a minor part of the diet. However, the possibility

that bacteria perform metabolic activities in the gut that are highly significant to the host's development should not be excluded.

3.3.1.4. Disease, deformity and parasites

Larval mortalities usually involve the ubiquitous *Vibrio* bacteria. These bacteria occur in all marine waters and are a major risk wherever hatchery culture of marine molluscs is practised. They can be controlled by proper hygienic procedures, however their presence in large quantities indicates that appropriate procedures are not being followed (Elston, 1990).

3.3.1.5. Antibiotics and bacterial problems

Streptomycin is an antibiotic effective against both gram negative and gram positive bacteria. Adding streptomycin to the larval-rearing water helps to suppress bacterial growth that could otherwise cause water quality deterioration. This can result in a mortality reduction of 10-33% in veliger larvae to early juveniles (Hahn, 1989). Other examples of antibiotics in use include rifampicin and penicillin (R. Counihan, pers. comm., 1998). However, prophylactic use of antibiotics is considered undesirable since it will promote antibiotic resistant strains (B. Jones, pers. comm., 1999). Potential exists for using probiotics, that is, adding harmless bacteria to inhibit increases in population of pathogenic bacteria.

3.4. Nutrition and Diet (Early life stages)

3.4.1. Feed size requirements (diatoms)

Suitable diatom species vary in size and should be supplied in correlation to the juveniles mouth size. Therefore, as the mouth increases in size, the diatoms also should increase in size (Cuthbertson, 1978). However, in practice this is not done, as juveniles are generally supplied with a few different species of diatoms that naturally occur in the incoming water supply.

3.4.2. Nutritional limitations

The length of the larval phase is highly dependent on the quantity and quality of the yolk. If this food source is depleted before a suitable substratum is found then the larvae will most likely die (Joll, 1996).

3.4.3. Weaning feeds

Dunstan *et al*. (1998) attempted to develop a formulated feed to supplement, and possibly shorten the period of reliance on, diatoms. Commercially produced crumbles are being used successfully for small juveniles (<5 mm) after detachment from the plates. In practice, juveniles are left on plates until food supplies are exhausted or the plates are needed for another cohort.

3.5. Hatchery/Nursery/Growout Technology

3.5.1. Hatchery technology

Good hatcheries keep records of all spawning runs which can then be used to refine procedures to improve survival and reduce labour time (Hone *et al*., 1997). Hygiene is one of the most important factors that determines the success of a mollusc hatchery, particularly during the non-feeding larval stage for abalone (G. Maguire, pers. comm., 2000).

3.5.1.1. Spawning room

Abalone are induced to spawn in a hatchery room in which light and temperature can be controlled. Ultraviolet light (UV) is mainly used in Australia to stimulate abalone to spawn. It is passed through the seawater immediately before it enters into the broodstock tanks. The UV light breaks down the oxygen molecules to ozone (O_3) (Hone *et al.*, 1997). This is thought to trigger spawning by stimulating the production of PG-endoperoxide in the reproductive system, and therefore increasing the secretion of the hormone prostoglandin (PG), which plays an important role in the spawning mechanism (Uki, 1989). Other methods of spawning broodstock include temperature shock or the use of hydrogen peroxide. Currently most farmers are using a combination of UV light and temperature shock (Hahn, 1989). When purchasing a UV light source the tube should be manufactured from quartz crystal rather than the cheaper plastic or teflon and it should have a power rating of 600 – 800 milliwatt hours per litre (Hone *et al.*, 1997). A timer can also be added.

3.5.1.2. Water supply (spawning)

Water supply to the spawning room is generally filtered to 5 μm nominal (Hone *et al.*, 1997), however, this varies as some farmers filter water down to 0.5 μm nominal for spawning. Flow rates to spawning tanks are approximately 1 liter per minute. Controlling water temperature also plays an important role in spawning success (S. Parsons pers, comm., 2000).

3.5.1.3. Spawning tanks

Generally 5 to 6 rectangular aquaria (glass or plastic) are used with volumes of 15 to 60 litres depending on the size of the broodstock. (Hone *et al.*, 1997). An outlet (19 mm overflow pipe) is added about 25 mm below the top end of each aquaria to direct outflowing water into the drain (Figure 6). Alternatively, the tanks can be set up so that they cascade into the lower tanks. If this method is used, females should occupy the top tanks. The aquaria require no aeration, however it can be added if preferred. All plumbing should be constructed so that it can be pulled apart for cleaning. At the end of each spawning, the set up is dismantled, rinsed, sterilised (with chlorine at a strength of 5 milligrams per litre) and air dried prior to the next spawning (Hone *et al.*, 1997).

Figure 6. One type of spawning aquaria.

3.5.1.4. Hatching tank

There are many different methods used for hatching out abalone eggs. One common method uses the flow-through system as it reduces bacterial build-up in the tanks and maintains oxygen levels around the eggs (Hone *et al.*, 1997) (Figure 7). However, the batch system (manually decanting or siphoning larvae from a hatching tank) is also used (S. Parsons, pers. comm., 2000) (Figure 8). Water to the hatching tank can be filtered to as low as 0.2 μm. Generally eggs are added to the tank as a monolayer. The tanks need to be relatively deep (> 30 cm) to ensure that the trochophores (hatched eggs) can rise to the top of the water column and be clear of bacterial contamination from egg casings and undeveloped eggs. When a large number of trochophores have hatched they can be seen as pale green-white dots just under the surface where they often form shoals. Hatch-out normally takes between 24 hours (at 18ºC) and 36 hours (at 14ºC) to complete (Hone *et al.*, 1997). For the batch method, larvae need to be siphoned out into larval rearing tanks, however, for the flow-through system the larvae flow over a weir that directs the surface water to the outlet, through a tube and into the larval rearing tank.

3.5.1.5. Larval rearing tanks

Currently, there are two methods used to rear larvae; batch (Figure 9) or flow through (Figure 10). Batch method consists of large tanks (approx. 10 000 litres) that are filled with filtered water (1 μm nominal). Larvae are added at a rate of 1– 3 per millilitre. Every two days these tanks are drained and the larvae collected in a wet sieve. They are washed with clean filtered seawater and placed into a new tank that has already been refilled. This means a minimum of two tanks are needed for rotation during this process (Hone *et al.*, 1997). However, it is not uncommon for larval tanks to be drained and cleaned daily (S. Parsons, pers. comm., 2000).

The flow through system consists of a 200 litre tank with a hemispherical bottom and steep sides. However, the size of the tanks for both batch and flow through systems can be varied to suit the farmers own preference (S. Parsons, pers. comm., 2000). Filtered water is supplied through a pipe at the top and filtered air is supplied through the bottom. In addition, a banjo sieve (60 μm) is connected to the outlet pipe to stop larvae from escaping. This is a plastic ring enclosed by taut plankton mesh top and bottom. A density of approximately 20 – 30 larvae per millilitre is used for this method. This allows 4-6 million larvae per 200 litre tank. Every two days the bottom of the tank should be siphoned to remove dead larvae and detritus. This should be done by turning the air off for 5 minutes, siphoning the bottom, then turning the air back on (Hone *et al.*, 1997).

The time from hatch-out to settlement varies depending on temperature, however, at 20ºC it takes 4-5 days and at 14ºC it takes about 9-10 days. During the larval phase the abalone larvae do not require an external feed source (Hone *et al.*, 1997).

Figure 7. Hatching systems using the flow-through method.

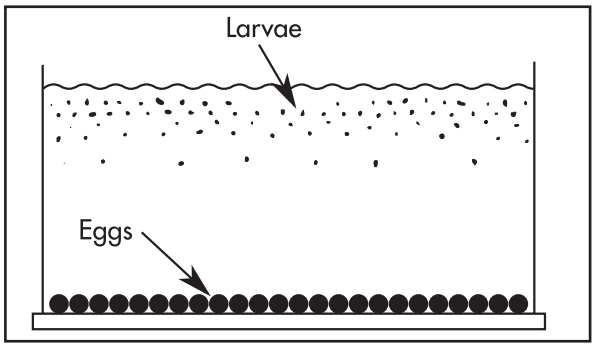


Figure 8. Hatching systems using the batch method (From Hone et al.,1997).

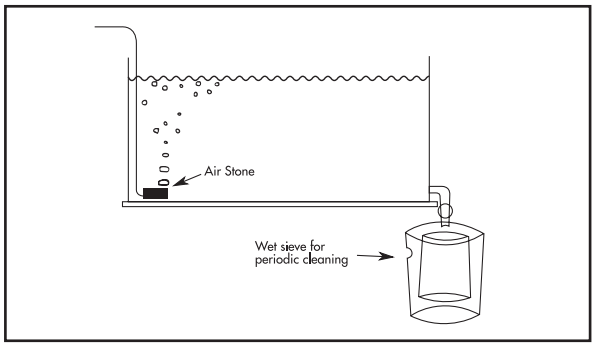


Figure 9. larval rearing system using the batch method (From Hone et al.,1997).

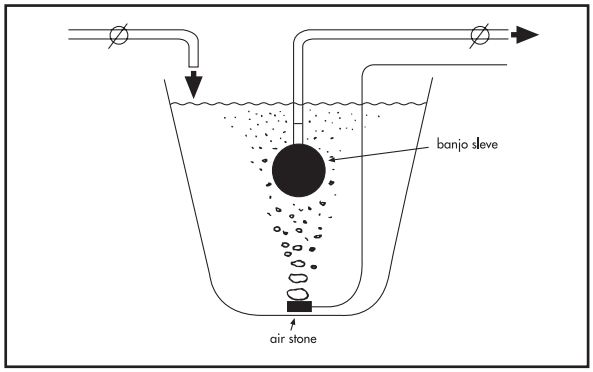


Figure 10. Larval rearing system using the flow-through method (From Hone et al.,1997).

3.5.2. Nursery systems

3.5.2.1. Settlement tanks

Several abalone settlement tanks that have been tried in Australia include the 220 litre hemispherical bowl (developed in North America/Mexico), the V-shaped tank (New Zealand design) and the rectangular tank with plates (developed in Japan/China) (for reviews see Hahn, 1989; Shepherd *et al.*, 1992). Modifications of these designs have been used by Australian farmers, however the current technique proving most successful is the Japanese/Chinese plate method. This technique uses long raceways about 40 cm deep, 1.5 m wide and up to 3-5 m long (Figure 11). Filtered water (10 – 20 μm nominal) or raw seawater can be used, however if the water contains high levels of biological or sediment material, sock filters attached to the intake water are advised (manufactured by Swiss Screens). Two rows of baskets containing vertically stacked plates (diatom plates about 30 x 60 cm in size) are placed into the raceways. Each rack consists of approximately 10 – 15 plates each (Hone *et al.*, 1997). Plates made from PVC are commonly used (S. Parsons, pers. comm., 2000). Two – four airlines are placed lengthways along the base of each raceway to encourage plant growth on the diatom plates.

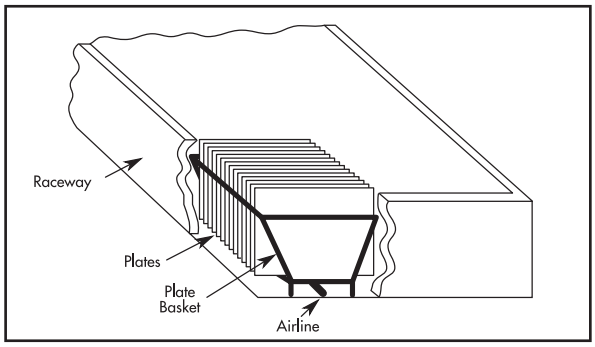


Figure 11. Abalone settlement tank system (Adapted From Hone et al.,1997).

The tanks are set up about 1 – 4 weeks prior to spawning to ensure that a biofilm of microalgae has developed on the plates before the abalone are ready to settle (to the naked eye this layer appears as a brownish film). In high light conditions, covering outdoor settlement tanks with shade cloth can slow algal growth to prevent overgrowth. Moreover, adding plant nutrients (e.g. Aquasol) encourages algal growth in low nutrient conditions. The microalgal layer is examined regularly under a microscope to ensure individual microalgae do not exceed 12 – 15 microns (upper size limit of food particle that newly settled abalone can ingest) (Hone *et al.*, 1997). Species composition is also important and can be influenced by degree of shading and turbulance (S. Daume, pers. comm., 2001).

When adding larvae to the settlement tanks, the water is turned off and a banjo sieve is added to the outlet. Larvae are added at a rate that allows for 50% survival during settlement, 5 – 20% survival to day 150 and 35 square centimeters for each juvenile at 150 days. The water is turned on after 24 hours, however, the banjo sieve should not be removed until it is observed that < 5% of the larvae remain in the water column. Generally, ready to set larvae will settle and attach within 3-6 hours of being added to the tank. However this stage should be monitored carefully as it can take longer for the larvae to settle (Hone *et al.*, 1997).

3.5.3. Growout Systems

3.5.3.1. Production systems

Over the past few years a major component of FRDC funded research has focused on developing a tank system suitable for manufactured diets. A series of trials (initiated in 1993/4) were set up to compare the performance of abalone in various tank systems developed by Australian abalone farmers. Table 6 outlines the types of systems that have been tested. Figures 12-20 show diagrammatic representations of these systems. Circular control tanks also were set up adjacent to the trial tanks. These enabled the experimental tanks to be ranked relative to the control tanks as each site had three replicates for both trial

and control tanks (Figure 20). Sea-based barrels, used by Huon Aquaculture (HA) in Southern Tasmania also were included in the trial to assess the performance of sea-based operations compared to land-based ones (Hone, 1996).

Marine Shellfish Hatcheries (MSH) and University of Tasmania TASMANIA

Tank Trial No. 1 [see Figure 12] A hyperbolic-shaped tank, designed to remove particulate wastes with minimal labour input – using an automatic siphon, a false mesh floor and aeration-generated water movement. The bottom of each tank was divided into three sections, each of which were angled and sloped into a central drain. Results revealed that the mesh was too small and tended to trap larger particles. The tank had a 100% mesh floor. A cover (to prevent overgrowth of algae) and some hides for protection of the abalone were also included (Hindrum, 1996).

Tank Trial No. 2 [see Figure 13] This tank was designed to improve on the problems of tank 1. Its base was changed from a relatively flat one to a V-shape with a centre underdrain. The aeration was situated closer to the bottom of the V and a larger mesh size of 8 mm was used. The automatic siphon was retained. The main intention for tank 2 was to reduce the flow of water as this proved quite costly. The tank had a 100% mesh floor. As with tank 1, a cover and hides were used (Hindrum *et al.,* 1996a).

Tank Trial No. 3 [see Figure 14] The mesh floor in this tank design was 28% of the available surface area. The mesh size also was 8 mm. By reducing the amount of mesh floor the problems associated with a 100% mesh floor were eliminated. It was hard to access the bottom of the tank for cleaning and maintenance, and wastes were getting trapped in the fastening and support straps. In tank 3 these straps/bolts were replaced with fibreglass slats. Removal of wastes was improved by using a steeper slope, and placing the aeration at the bottom of the V (as with tank 2). Increasing the aeration also improved waste removal but also caused food to break up and accumulate in piles, which was not appropriate. Hides were used, however, shading was not used. A solid section was also added to the base of this tank to allow for less "wasted space" and also to improve waste removal (Hindrum *et al*., 1996b)

South Australian Abalone Development (SAABDEV) SOUTH AUSTRALIA

Tank Trial No. 1 [see Figure 15] A V-tank, 3 m long, 1.5 m wide and 0.9 m high, was fitted with a false floor to allow faeces to fall through while retaining most of the food. Problems included wasted space and inefficient removal of wastes. Abalone hides were also used (Grove-Jones, 1996b).

Tank Trial No. 2 [see Figure 16] This tank was designed to fix the problems of tank 1. – Changed to a flat bottom tank with a small narrow mesh strip and a small underdrain (Grove-Jones, 1996b).

Tank Trial No. 3 [see Figure 17] A modular raceway system – 3 m x 0.3 m. Light, durable and operated with a very low depth of water. Initial depths were deeper but not as efficient. High flow rates of water were used to prevent dead spots of poor circulation or the need for aeration, and allow for self cleaning of tanks. Water exchange was complete due to the strong directional flow of water straight from inlet to outlet. Could be set up in a cascading series (Grove-Jones, 1996c).

South Australian Mariculture (SAM) SOUTH AUSTRALIA

Tank Trial No. 1 [see Figure 18] A large tank with a W-shaped base which minimized cleaning events due to its aeration regime that separated abalone faeces from food pellets (tank with slope

of 10 cm – to allow food to distribute across bottom of tank efficiently) (Morrison, 1996a).

Tank Trial No. 2 [see Figure 19] Tank 2 was similar to tank 1 however the W-shape in the bottom was relatively flat and two more airlines were added. This resulted in less effort expended in moving for food, and suspending wastes by the aeration (Moore, 1996).

Tank Trial No. 3 [Figure not available] The third trial tank for SAM consisted of a round tank with a similar cross section to half of a tray. Stair-steps were included along the side of the tank to promote the spread of abalone. Aeration and quickly circulating the water by directional flow was used to force uneaten food and faecal material to the central well. This outlet was covered with a mesh to prevent the escape of abalone (Morrison, 1996b).

Table 6 Tank systems used in the FRDC Systems Developments trials.

Results and conclusions for these trials have been reported in the Proceedings of the Annual Abalone Aquaculture Workshop series (1st-5th), as well as, the Abalone Aquaculture Workshop held in Albany (1995).

Land-based growout systems can also include large, deep concrete tanks (as used in Taiwan), specialized tanks (as outlined above) and outdoor ponds (McShane, 1988). The major development arising out of FRDC tank research has been the evolution of very shallow high flow rate tanks. Refinement and scaling up has produced a tank system first designed and established at South Australian Mariculture (SAM) (design is considered proprietary). Water through this system flows as a unit which ensures that bacteria and wastes can be easily flushed from the system. Production is estimated at 1 000 kg/tank/year, 25 times more than the previous maze tank and pipe systems used at this farm (Morrison and Smith, 2000). Sea-based growout methods also are available in many forms (O'Brien, 1996b). Old juice concentrate barrels or PVC manufactured tubes are inexpensive but can only hold a small number of abalone. The low price is the most attractive feature of this type of culture and they are ideal for research trials, but they necessitate high labour costs.

Small to medium size cages can be used in most conditions and in a range of depths. They can be attached to long lines and rafts, or placed on the sea-floor. These cages can hold more abalone and can provide better water circulation than barrels. Large sea cages can be placed in

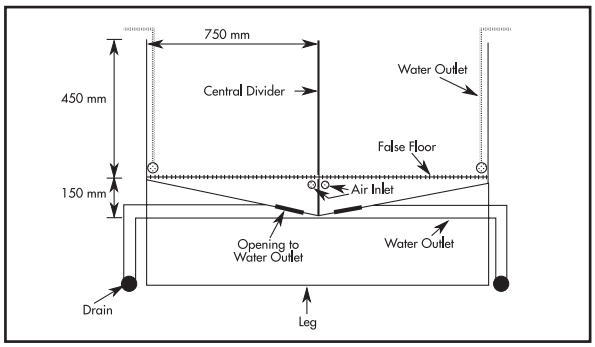


Figure 12. Tank trial No.1 (end view) - Marine Shellfish Hatcheries (From Hindrum et al.,1996a).

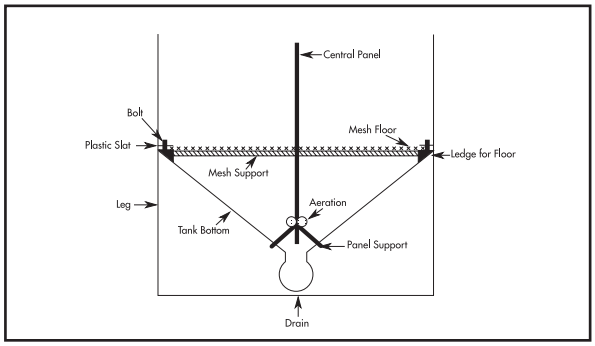


Figure 13. Tank trial No.2 (end view) - Marine Shellfish Hatcheries (From Hindrum et al.,1996a).

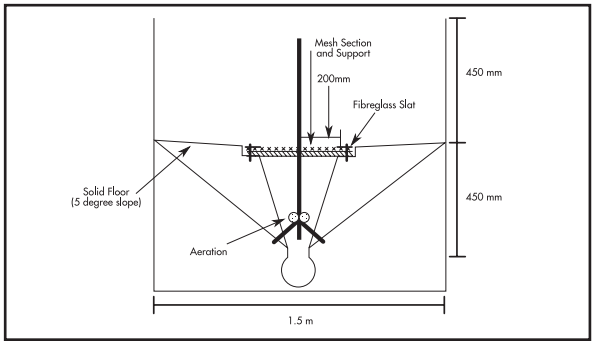


Figure 14. Tank trial No.3 (end view) - Marine Shellfish Hatcheries (Adapted from Hindrum et al.,1996a)

areas with a large supply of drift seaweed. While the cages can house large quantities of abalone, they are expensive to construct and maintain. The advantages of sea-based systems over land-based facilities include lower capital costs, better water exchange, more stable water temperature and feed supplementation from algal growth within the culture unit, however, the systems can be difficult to maintain (especially in rough weather), have difficulties in retaining food and excluding undesirable organisms. Moreover, there may be less environmental control (Hindrum *et al*., 1996b).

Aviles and Shepherd (1996), found growth to be relatively low (9.4 μm per day) in barrel culture of *H. fulgens* in California. In Australia, Cropp (1989) achieved a growth rate of 60 μm per day in Tasmania as did Hindrum *et al*., (1996b). However, higher average growth rates (107 μm per day) were found by Franco Santiago (1986, cited in Mazon-Suastegui *et al*., 1992). Moreover, Fisheries Western Australia achieved growth rates of 110 μm per day in summer with greenlip abalone (see Freeman *et al*., 2000b).

McShane (1988) states that a successful growout depends on the provision of clean, oxygenated seawater, and a means of accommodating and feeding abalone in commercially viable densities. However, it must be noted that the systems vary considerably in effectiveness. Castanos (1997) reported that the use of hanging net cages or barrels for the culture of Donkey-ear abalone was a viable culture method for this species of tropical abalone. Preliminary results showed that the growth rate of abalone decreased as stocking density increased. High densities in the cage probably makes it difficult for all abalone to access feed easily.

3.5.3.2. Acclimatization to grow out environment

Some farms use an intermediate system between the diatom plates and growout tanks. For example, round tanks with flow through water, semi-closed recirculated water with shallow tanks, or extensive systems of enclosed round pipes with rapid water flow.

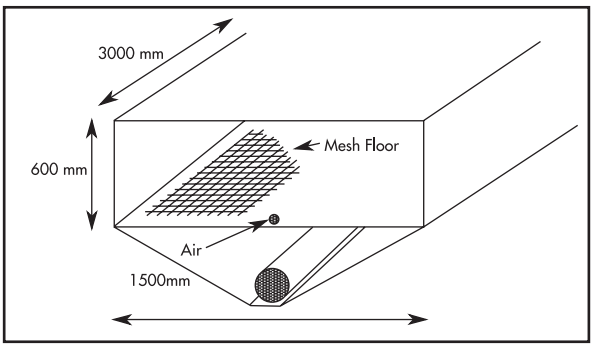


Figure 15. Tank trial No.1 - South Australian Abalone Development (SAABDEV) (From Grove-Jones,1996b)

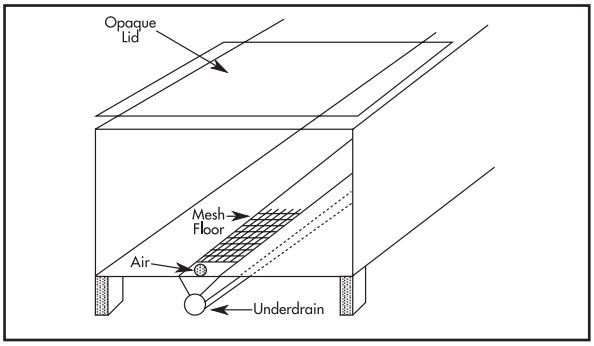


Figure 16. Tank trial No.2 - South Australian Abalone Development (SAABDEV) (From Grove-Jones,1996b)

Figure 17. Tank trial No.3 - South Australian Abalone Development (SAABDEV)

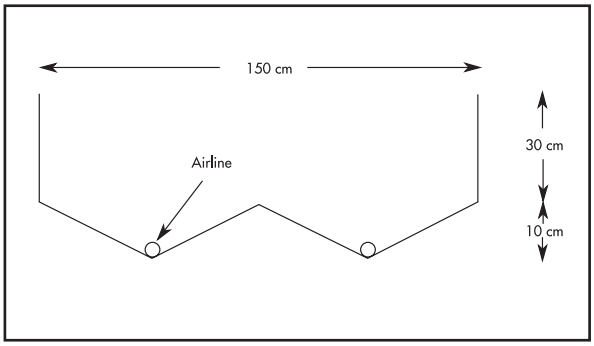


Figure 18. Tank trial #1 - South Australian Mariculture (From Morrison, 1996a).

3.5.3.3. Anaesthetics

In experiments on anaesthetics for greenlip and blacklip abalone, 100 mg L^{-1} of benzocaine (10% in ethanol) at an exposure time of 20 minutes was found to have the least negative effect on growth in abalone. In contrast, ethanol (3%) and potassium chloride (10 g L^{-1}) at 20 minutes exposure time caused the least reduction in respiration rates during recovery (Edwards *et al*., 2000). The alternative to using anesthetics is to physically remove individual abalone from tank systems using a plastic spatula (already available in the market) or homemade plastic cards for smaller abalone.

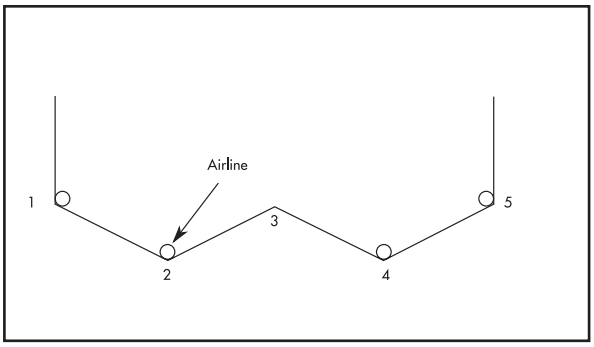


Figure 19. Tank trial #2 - South Australian Mariculture (From Moore, 1996).

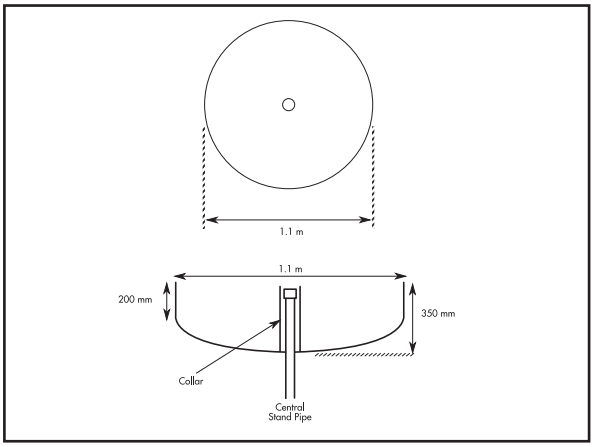


Figure 20. Circular control tank. Top view and side view (From Hindrum et al., 1996a).

3.5.3.4. Water quality requirements

Excessive warming, dilution by rainfall or entrapment of seaweed debris in bays can pose problems prior to the water entering the farm. McShane (1988) reported that the water supplied to grow-out systems would need to be filtered (40 μm) to prevent invasion of fouling organisms, although this would be expensive.

In an abalone growout system a reduction in water quality can result from the decomposition of faeces and uneaten food, which is a primary concern of growers. The rate of water flow is also important in the growout of abalone. Water movement stimulates the feeding behavior, which enhances the growth of abalone (Shepherd, 1973). One blacklip culture facility in Tasmania used a continuous sampling system with electronic probes that measure dissolved oxygen, pH and temperature to monitor water quality (O'Sullivan, 1994).

3.5.4.5. Age and size at stocking (growout tanks)

Published estimates are provided in Table 7, however the size and age for transfer to grow-out systems may be dictated by food limitations in nursery systems.

Abalone species	Age at stocking	Size at stocking	Reference
Greenlip	–	7 mm	McShane, 1988
Blacklip	3-6 months	–	O'Sullivan, 1994
	–	≥3 mm	D. Johns, pers. comm., 1999
	–	7 mm	McShane, 1988
Donkey-ear	–	15 mm	Castonas, 1997

Table 7 Size and age at stocking growout tanks for three species of abalone.

4. 0 PRODUCTION EFFICIENCY

4.1. Growth Rate

Growth is depressed at lower than optimum water temperatures due to the metabolism being regulated by temperature. A food absorption efficiency of 80% (dry matter) was recorded for temperatures between 14.0°C and 27.0°C but absorption efficiency was only 21% at 9.8°C (Peck, 1989).

Shepherd (1988) found a 1.69 mm/month mean growth rate in his trials with wild Greenlip abalone and this rate was linear for the first five years. These results were based on data from individuals with size ranges of 0.5-2.0 mm and 30-70 mm. However, after this period the growth rate was found to decline with increasing length. In comparison, an earlier study carried out by Shepherd and Hearn (1983) showed that the growth rate was twice as fast. The most obvious reason for this observation is that the Shepherd (1988) study was carried out on individuals from an under-boulder habitat where other grazing gastropods lived that had similar diets to abalone. However, Shepherd and Hearn (1983) paper involved abalone kept in experimental cages where all other algivorous molluscs had been removed and boulders with natural algal growth were added as an extra food source.

In commercial systems it has been difficult to achieve as high absolute growth rates (microns per day) in nursery systems as has been achieved in growout systems.

The growth rate of abalone is highly variable depending on the quality and quantity of food provided (Joll, 1996). However, it is expected that cultured individuals with a constant food supply will have the greatest growth during the warmer months. Growth rates are affected by several variables including genotype (Brown, 1991a), density, type and amount of feed (Day and Fleming, 1992), water flow, water quality (Higham *et al*., 1998), and handling techniques. Growth rates also may vary between land and sea-based culture (Table 8).

Abalone species	Maximum growout size	Minimum legal size	Reference
Greenlip	250 mm (W)	–	Shepherd, 1975
	220 mm (W)	140 mm (W) (5-6 years old)	Wells & Mulvay, 1992; Joll, 1996
	130-140 mm (U)	–	Hahn, 1989
Roe's	120 mm (W)	60-70 mm (W)	Wells & Bryce, 1987; Keesing & Wells, 1989; Joll, 1996
	120 mm (W)	–	Shepherd, 1975
	70-80 mm (U)	–	Hahn, 1989
Blacklip	200 mm (W)	–	Shepherd, 1975
	120-140 mm (U) (some 200 mm)	–	Hahn, 1989
Brownlip	250 mm (W)	–	Shepherd, 1975
	+200 mm (W)	140 mm (W)	Joll, 1996
Donkey ear	70-100 mm (U)	–	Hahn, 1989

(N.B: W = Wild, U = Unknown).

* Legal minimum size is subject to revision by individual states.

Table 8 Maximum observed size and minimum legal size for five species of-abalone.*

It has been estimated that Donkey-ear abalone can grow in shell length to 35.6 mm in six months and 55-70 mm in one year (McNamara and Johnson, 1995; Williams and Degnan, 1998). In seacage trials in the Philippines, results indicate that this species can reach commercial size of 60 mm in one year (Capinpin *et al.*, 1999).

Keesing and Wells (1989) report that Roe's abalone grows rapidly in the first year and reaches up to 40 mm in shell length (size of maturity) but slow down in the following years. Shepherd and Hearn (1983) believe this reduction in growth is due to energy expenditure during gonad development.

Currently, it takes between 2-3 years of growout for Greenlip and Blacklip abalone to reach market/ harvest size (between 50-80 mm) (Fleming, 2000a). Hopefully growth rates will improve (thus the time to harvest will decrease) as artificial diets and culture systems become more refined. Another factor that could lower the required time for growout is the use of triploid abalone. Triploid abalone are reproductively sterile, therefore it is believed that the energy that is used for gonad development, could be available for growth (Refer to section 8).

4.2. Density Dependence

In growout systems, Moore and Hone (1996) and Hindrum *et al*. (1998) found that the growth rate is reduced at high densities, even when the food supply per animal is kept constant. However, abalone held at high densities generally have a higher meat to shell length ratio due to the reduced growth. Abalone in very high densities tend to grind their shells against their neighbors resulting in fragments of shell being chipped off. The probable cause of this observation is the competition for food between individuals in the tank. Even though, the amount of food is the same on a 'per individual' basis, it does not mean that each individual is able to eat the same amount of food.

It has been suggested that the growth rate can be increased by grading of the individuals (separating into groups of similar sized animals). Abalone that had been graded had an overall growth advantage (Mgaya and Mercer, 1995). Growth of smaller abalone improved in the absence of larger ones.

Hindrum *et al*. (1999c) found that the effect of higher stocking density on the growth rate of greenlip abalone is dependent on the degree of refuge provision. Providing refuges during higher stocking densities can lead to improved growth rates, however, higher densities may lead to suppressed growth rates due to an increase in physical interaction. Highest growth rates were recorded at the lowest stocking density of 14 kg/m3, which was only a little more than half the common commercial stocking rate. It was found that twice the commercial stocking rate (40 kg/m3) resulted in a reduced growth rate, but the results were not statistically significant especially when shelters were provided (Hindrum *et al*., 1999c). Hindrum *et al*. (1999b), also observed that higher densities led to more uniform spatial distribution of greenlip abalone, at least within round tanks similar to Fig. 20.

In sea cage trials in the Philippines, Capinpin *et al*. (1999) also observed a decrease in individual growth for *H. asinina* (15 – 40 mm) as stocking densities were increased. However, survival was not significantly affected by density.

4.3. Shading and Refuges

Farmers and researchers have often provided shading and hides in growout systems for abalone to take into account their cryptic and nocturnal behaviour. It was found that shading was not required if refuges were provided for Greenlip abalone in Tasmanian culture systems. Moreover with 100% shading (comparable to night conditions) refuges were not needed. However, 50% shade without refuges decreased growth by 32% (Maguire *et al*., 1996a). The need for refuges probably depends on the size of Greenlip abalone as larger abalone are less cryptic in the wild (see 6.1.4).

Shading has various potential advantages for aquaculture. These include:

a) Reducing light intensity for the abalone
b) Shading may extend foraging periods
c) Help divert rainfall
d) Offer some predator protection (has not been a problem in Australian farms)
e) Reduce algal biofouling

Temperature differences associated with different levels of shading were minor in flow-through tanks (Maguire *et al*., 1996a). Refuges also offer a number of potential advantages that include:

a) Allow easy manipulation of stocking density through the removal of refuges and attached abalone
b) Increase surface area
c) Add some predator protection (not usually a problem in land-based systems)

They found that while both shading and refuges present a number of advantages, they also have several disadvantages, including:

a) Securing shades to tanks increases labour costs, especially when considering the time to access tanks for feeding and maintenance
b) Refuges also add to costs and could inhibit foraging behaviour
c) Refuges may hinder efficient tank cleaning procedures
d) Refuges may inhibit good water circulation and cause localized water quality deterioration by trapping uneaten food and faeces
e) Covers and refuges impede regular observation

4.4. Meat Recovery

4.4.1. Meat weight : shell length ratio

Moore and Hone (1996) found that abalone reared at high densities have a higher meat to shell length ratio. Moreover, in comparison to individuals from the wild, hatchery-reared abalone have a thin flatter shell yielding a higher meat weight : whole body ratio but a lower meat weight : shell length ratio (K. Hahn, pers comm., 2000). Maguire (1998) found that one group of cultured Greenlip abalone had equal weight ratios of shell:viscera:meat.

The Donkey-ear abalone has been found to have the highest proportions of flesh to shell with a flesh yield of 80-85% (Williams and Degnan, 1998). However, the amount of edible meat is very low in this animal due to the extensive epipodium. This feature makes this abalone a lower quality product with a corresponding lower wholesale price.

Shell growth to meat growth ratio is also highly influenced by water quality factors. For example, Harris *et al*. (1998) found that in terms of shell length, growth rate declined with increasing ammonia concentration (range of 0.006 to 0.188 mg FAN L^{-1}) in fact, at 0.054 to 0.188 mg FAN L^{-1} significant growth rate reductions occurred ($P<0.05$). However, in terms of whole wet body weight gain significant reductions only occurred from levels of 0.110 to 0.188 mg FAN L^{-1} ($P<0.05$).

4.5. FCE/FCR

There are two standard measurements of the relationship between food and growth – FCE and FCR. FCE (food conversion efficiency) is the amount of growth per unit of food given and may be expressed as a percentage, and FCR (food conversion ratio), which is the inverse of the FCE, can be described as the amount of food (g) given to produce 1 g of animal growth (Fleming *et al*., 1996).

When dealing with abalone, FCE values should be used with caution. Difficulties related to collecting food waste, measuring growth rate and associated leaching of nutrients all contribute to incorrect estimation of FCE. Moreover, the absorption of nutrients from the surrounding environment (e.g., calcium for shell growth) will be variable and make FCE values uninterpretable. Abalone fed kelp as the food source have very poor food conversion ratios (i.e. 20-30:1) because of the high water content of the kelp. The moisture content of food is a highly influential factor, so seaweeds and formulated feeds only should be compared on a dry matter basis. Theoretically, the higher the FCE value, the greater the efficiency of conversion of food to abalone flesh (Fleming, 1995b; Fleming *et al*., 1996).

Coote *et al*. (1996) under research conditions achieved a FCR (not corrected for uneaten food) of 1:1 for diets with appropriate phosphorous content. Greater temperature variations and larger harvest sizes occur at commercial operations, so Maguire (1998) assumed a FCR of 1.3-1.5:1 for abalone fed artificial diets under commercial conditions when estimating a nitrogen budget for a land-based farm.

Abalone display low and variable food conversion efficiencies. While a FCE near 15% has been reported for relatively small, fast growing juveniles, a FCE of around 5-10% is more appropriate for juvenile growth in commercial hatcheries in the United States and Japan (Huner and Brown, 1985).

In sea cage trials in the Philippines using H. asinina, FCR did not increase with an increase in density, however it was observed to be higher for larger animals (Capinpin *et al*., 1999).

4.6. Handling Live Product

In aquaculture, the abalone product is sold either live, fresh, frozen, or canned. Abalone are generally harvested from their growout tanks the day before shipment and held in a temporary tank with good water exchange. This helps identify abalone that may die as a result of being cut during harvesting. Abalone do not have a blood clotting agent and can therefore bleed to death if damaged with the spatula during collection for market. The abalone are packed in plastic bags that are placed inside airline-approved foam containers. Water is not used since excessively deoxygenated and ammonia laden water can kill the abalone during transport. The plastic bag is filled to approximately 20-30% with medical grade oxygen and sealed. This bag is then placed inside another bag. Oxygen is only needed if the transport period is greater than twelve hours. A damp cloth is included in the package to maintain a high humidity inside containers without plastic bags. Fresh-frozen and canned product can be harvested on site by placing them directly into an ice slurry that will maintain high tissue quality (Hone and Fleming, 1998).

5.0 FEEDS AND FEEDING (JUVENILE – ADULT STAGE)

In aquaculture situations, abalone are usually fed artificial foods but these are sometimes supplemented with natural algae (Joll, 1996). An experiment on the economics of feeding strategies and recommended practices has shown that the nutritional and economic success of an artificial feed is based upon several linked factors. No one factor should be considered alone. Results for Greenlip abalone have indicated the highest growth rates may be achieved by maintaining high feed rates all year round. However, in terms of temperature, at certain times of the year this high feed rate will in fact depress growth rates in particular tank designs. Therefore an option considered was to decrease feed rates during winter, which resulted in reduced feed costs (Lorkin *et al*., 1999). A feeding chart with recommended feed rates at specific abalone size and temperature has been produced by a commercial abalone feed producer in South Australia. The feeding chart can be used as a general guideline, but each farm will have to determine the optimum feeding rate in their own systems to maintain maximum profitability and efficiency.

5.1. Species

5.1.1. Blacklip abalone

Adult Blacklip abalone primarily feed on drift algae, which they catch by positioning themselves in areas where drift weed accumulates. However, when drift weed is less abundant, Blacklip will emerge from their caves and crevices at night to graze on attached algae growing on nearby rocks (Brown, 1991a). Blacklip will feed on a variety of algae, however, they prefer red algae (Shepherd, 1973; Shepherd, 1975) with a lower preference for brown 'kelps' (*Phyllospora comosa* and *Ecklonia radiata*) (Foale and Day, 1992). They showed that gut contents can be misleading as red algae are digested much faster than kelp. Abalone can be induced to feed on some less preferred algae after an extended period of starvation.

An experiment assessing the movement of gut contents in blacklip abalone has shown that the movement is mediated by the following:

a) pumping action as a result of the intimate association of the gut with the heart in this species

b) currents generated by movement of cilia (also used as a sorting mechanism) (Edwards *et al*., 1999)

5.1.2. Brownlip abalone

Shepherd (1975) observed that, on the basis of gut contents, this species of abalone shows a preference for kelps.

5.1.3. Staircase abalone

Individuals opportunistically catch drift weed or graze algae like Blacklip abalone (Shepherd, 1973).

5.1.4. Greenlip abalone

This species is a less versatile feeder than Blacklip abalone. They appear to be dependent on the availability of drift weed and rarely move to graze on attached algae (Brown, 1991a).

The natural diet of both Greenlip abalone and Staircase abalone was studied at West Island in South Australia. Crustose coralline algae are the principal food eaten by this species from a length of 5-10 mm. Moreover, at 10-20 mm, the diet is primarily composed of dead seagrass blades and drift algae, such as, *Lobospira bicuspidata* and *Asparagopsis armata*. The large brown algae (e.g., *Ecklonia radiata*, *Sargassum* spp. and *Cystophoras* spp.) are avoided even though they dominate the area where this abalone species lives. It is thought they migrate to deeper waters at about three years of age where they feed on their preferred red algal species, which are abundant as drift weed (Shepherd and Cannon, 1988).

Greenlip abalone can produce different types of faeces (Wee *et al*., 1994) which can differ in nutrient composition (Shipton, 1999).

5.1.5. Roe's abalone

Roe's abalone feeds on a variety of macroalgae that are present as drift. Although algal consumption of Roe's abalone has been reported to vary by site and season, the gut contents are greatest in winter, which corresponds to the time when food is most abundant (Wells and Keesing, 1989). Shepherd (1975) found that Roe's abalone has a preference for red algae but also will eat small brown algae and kelps.

Shepherd (1973) reported that Roe's abalone is exclusively a grazer in its South Australian habitat, but drift algae were rare in his study areas. In addition, Wells and Keesing (1989) stated that Roe's abalone

graze on small red and brown algae at night and do not catch drift weed in its habitat in South Australia. However, in the area around Perth, Roe's abalone feed primarily by catching drift weed as do Greenlip abalone and Blacklip abalone (Wells and Keesing, 1986; 1989). The presence of Roe's abalone in the barren zone along the coast near Perth had a much smaller effect on attached algal abundance than limpets and chitons (Scheibling, 1994). Depending on availability and time of year, Roe's abalone also will consume large amounts of *Ulva* spp. Red algae and *Sargassum* spp. are both substantial components of the diet of Roe's abalone (Shepherd and Steinberg, 1992).

5.1.6. Donkey-ear abalone

The macroalgae *Gracilariopsis herteroclada* can maintain growth of Donkey ear abalone for extended periods of time. It has a high protein content (17.32%) and promotes fast growth. In Asia this alga is abundant, farmed in drainage canals and brackish water ponds, and available year-round (Castanos, 1997). In the Philippines, *H. asinina* growth was sustained on a single species diet of the red alga *Gracilariopsis bailinae* for 150 days for 15-20 mm juveniles and 180 days for 35-40 mm animals (Capinpin *et al*., 1999).

5.2. Requirements of Juveniles

Hone *et al*. (1997) suggest that in the wild, small juveniles (southern Australian species) graze on microscopic algae or diatoms, and ingest and utilize a range of bacteria.

Fleming *et al*. (1996), in a major review of nutritional requirements of abalone, found that the ability of juvenile abalone to digest various nutrients may vary by age and size. Furthermore, there may be differences in nutritional requirements between juvenile and adult abalone, although no comparative studies have been carried out. Juveniles are likely to require more protein and energy per body weight than adults as they have higher specific growth rates. Also, small juveniles may require a different amino acid balance because of different growth requirements as viscera (muscle tissue etc.) and physiological processes develop, and adults may require more dietary lipid during gonad development. Dunstan *et al*. (1998) studied feeds for small juvenile abalone and found diatoms, crustose coralline algae, turf algae and epiphytic bacteria to be significant natural food sources. Moreover, fatty acid and sugar compositions of the 'natural' feeds of juveniles were similar to cultured monospecific feeds, however, supplementing diatom covered plates with a powdered formulated diet did not increase abalone growth rates.

5.3. Commercial Feeds (Existing artificial diets)

Fleming *et al*. (1996) showed that the composition of existing artificial diets are similar in proximate composition (Table 9).

Table 9 Proximate composition (% dry matter) of commercial abalone diets in the market (from Fleming et al., 1996).

Proximate	Range	Average
Protein	20-50%	30%
Carbohydrate	30-60%	47%
Lipid	1.5-5.3%	4%
Crude Fibre	0-3%	–
Moisture	–	12%

5.3.1. Protein

Fishmeal, defatted soybean meal and casein are all commonly used sources of protein for abalone diets. It should be noted that diets containing high levels of fishmeal (>20%) are detrimental to the general environment as they contain high levels of phosphorus (Rumsey, 1993 in Fleming *et al*., 1996). Soybean is potentially a good protein source because its amino acid profile is close to fish, and its protein is highly digestible (Fleming *et al*., 1996).

Coote *et al*. (2000) found that a protein level of 27.0% CP (CP = crude protein) gives the maximum growth for juvenile Greenlip abalone. In this experiment, the protein and energy components of the feed were estimated to have digestibilities of 71.7% and 55.6%, respectively.

An experiment carried out by Vandepeer *et al*. (1999), has shown that *Lupinus luteus* appear to be suitable as a protein source for use in abalone artificial diets. They have a comparable gross energy digestibility and a significantly higher protein digestibility than soya flour. In addition, the utilization of the small intestine brush border membrane vesicles in greenlip abalone has been studied to assess suitability of grain legumes as dietary ingredients. This study showed that there is potential for legumes to be a source of protein for abalone diets, however, further research was necessary (Kemp *et al*., 1999).

5.3.2. Energy and carbohydrate sources

Abalone have enzymes capable of hydrolyzing complex carbohydrates. Carbohydrate (the energy source) makes up between 30 and 60% of an artificial diet. In contrast, the natural diet of an abalone consists of 40-50% carbohydrate (Fleming *et al*., 1996). Fleming (1991) reported that the maintenance requirement for a 25 g Blacklip abalone at 18°C was about 0.2-0.3 kJ day^{-1}. Moreover, on the preferred alga, *Jeannerettia lobata*, the daily intake of digestible energy was found to be 1.2 kJ day^{-1} (2 kJ day^{-1} of gross energy). Cheap sources of carbohydrates include wheat, corn flour, soybean meal, maize and rice starch. It is believed that too much carbohydrate in the diet may lead to poor utilization of protein (Fleming *et al*., 1996).

5.3.3. Fiber

Abalone have a limited ability to digest fiber, despite the presence of cellulases in the gut. Some artificial diets contain fiber for binding purposes with the level as high as 6% of the dry weight (Fleming *et al*., 1996). Maguire *et al*. (1997) used graded levels of ground rice husks as a source of fiber (approximately 0, 7.5 or 15% of diet on a dry matter basis) in an experiment on Greenlip abalone in Tasmania. No significant differences ($P > 0.05$) in growth rate due to diet were found.

5.3.4. Lipid requirements

Lipids are important because of their high energy value. Also, they are source for essential fatty acids and fat-soluble vitamins. It has been found that an abalone's lipid requirement is very low as it is highly efficient in utilizing lipid (Castanos, 1997). Moreover, Wee *et al*. (1994) reported a relatively high lipid digestibility of 84.7%.

Several studies have investigated the influence of oil types and oil inclusion levels in abalone feed for Greenlip abalone. It has been found that abalone show a poor response to elevated lipid levels. Addition of marine or vegetable oil to manufactured abalone diets should be limited to 3% if it is not to affect the digestibility of N and amino acids, and gross energy (van Barneveld *et al*., 1998). However, another species from South Africa, *H. midae* grows well at up to 6% dietary lipid, indicating that nutrient requirements of abalone can be species specific (Britz and Hecht, 1997). Dietary lipids have been shown to be important nutrients for maximising growth rates and health of many marine animals. In Greenlip abalone, maximum growth rates were obtained when they were fed formulated feeds that contained

lipids at 2.5% in summer and 3.5% in winter (Dunstan *et al*., 1997). In a more recent experiment, Dunstan *et al*. (1999) found growth rates were increased when abalone were fed a diet containing 3.8% total lipid (only 1.5% added fish oil). Moreover, other diets with total lipid contents of 2.6 and 4.2% (with only 1 and 2.5% added fish oil respectively) also improved growth rates. Formulated abalone diets from around the world contain a wide range of total lipid content (2-11% wet wt). In most cases the total lipid comprised less than 5% of the diet (Dunstan *et al*., 1999). In these diets, a large variation in fatty acid composition was evident, particularly for the fatty acids 18:2w6 and 22:6w3. High lipid level diets and those that contain no fish products are not recommended. In regards to abalone flesh, the lipid content is low and made up of the fatty acids; 16:0, 18:0, 18:1w9, 18:1w7, 20:4w6, 20:5w3 and 22:5w3 (Dunstan *et al*., 1999). However, proportions of 20:5w3, 20:4w6 and 22:5w3 were high. The fatty acid composition of Australian abalone was similar to other species of abalone from around the world.

5.3.5. Vitamins and minerals

Boarder and Maguire (1998) found that increasing the dietary vitamin mix levels from 0.3% (ABCHOW control diet) to 0.6% and 1.2% improved the growth rate of the Greenlip abalone but inclusion of a mineral mix in the diet depressed growth unless there were elevated levels of vitamin mix. Vitamin C is being investigated further to determine its requirement as another important dietary component (Fleming *et al*., 1996).

5.3.6. Binders

A binder is used in aquatic animal feeds to keep them intact. The most common forms of binder include starches, gluten or alginates typically in dry diets. However, gels also are used quite frequently in experimental diets but are not seen to be economically viable for commercial feeds (Fleming *et al*., 1996).

5.3.7. Stability

The average stability of abalone feeds is about 2-3 days (Fleming *et al*., 1996). Diets can lose approximately 30% of the dry matter content after being immersed for 48 hours (Maguire, 1996), however, inclusion of algal products can greatly affect stability. Maguire *et al*. (1996b) found that diets supplemented with whole, freeze-dried *Chaetoceros muelleri* paste, 'Filipino Gracilaria' meal or fresh diatom film were not stable with about 38 – 66% dry matter loss. Knauer *et al*. (1993) found that the greatest water stability was obtained for a diet containing a 1:3 agar/gelatin mixture, which retained 70.7 + 2.7% of its dry weight after 24 hours.

Edwards and Cook (1999) reported that dry matter loss is not a good indicator for determining the amount of leached minerals from abalone diets utilising different binders.

5.3.8. Feed stimulants and attractants

Feed stimulants, such as algae and seaweeds, are added to the diet to enhance food intake and growth rate (Fleming *et al*., 1996). If given a choice of diets, abalone will actively seek out and consume the diets that contain the preferred attractants (Dunstan *et al*., 1998). The feeding stimulant activity of algal glycerolipids for the abalone *Haliotis discus hannai* was examined by Sakata *et al*. (1991). Digalactos yldiacylglycerol (DGDG) showed strong activity in all test animals; however, 6-sulfoquinovosyldiacyl glycerol (SQDG) showed much less activity.

Currently the artificial diet most commonly used in abalone culture is based in part on the "ABCHOW" research diet. This diet was formulated by staff at SARDI (South Australian Research Development Institute) based on FRDC and CRC (Cooperative Research Centre) funded research; however, some of the information is proprietary.

5.4. Major Nutritional Requirements

The estimates provided in Table 10 reflect the herbivorous nature of abalone (low protein requirement) and the low tolerance to elevated dietary lipid typical of many invertebrates that have been studied.

Required nutrient	Optimum level of required nutrient	Reference
Protein	28%	Uki & Watanabe, 1992
	27%	Coote *et al*., 2000
Lipid	5%	Uki & Watanabe, 1992
	2.5% (summer)	Dunstan *et al*., 1997
	3.5% (winter)	
Minerals	8%	Uki & Watanabe, 1992

Table 10 Reported optimum protein, lipid and minerals requirements for abalone.

5.5. Nutritional Limitations

McShane (1988) states that the large brown kelps typical of Western Australia's southern coastline are not eaten by the abalone that inhabit the area. The kelps contain chemicals that discourage feeding (probably due to their high content of phenolic compounds). Moreover, the preferred red algal species are less abundant than kelp and cannot be relied upon to sustain abalone farms in Australia. The culture of red algae could provide a source of good quality abalone food but the quantities required for an abalone farm make the sole reliance on cultured seaweed impractical in Australia especially as government policies inhibit longer term reliance on harvesting seaweeds.

Fleming (1995a) states that nitrogen is a limiting factor in a herbivore's natural diet. Herbivores must spend a great deal of time eating and processing large amounts of food through their alimentary tract because plants have a low ratio of nitrogen to fiber and carbohydrates. The amount of nitrogen readily available for incorporation into body protein can be limiting, even though carbohydrates are abundant and the energy supply does not limit growth (Fleming, 1995a).

5.6. Commercial Availability of Formulated Feeds

In Japan and China, many abalone growers use artificial foods consisting of a protein source, lipid, minerals and an attractant. However, Australian abalone farmers found that Japanese artificial abalone food was too expensive for commercial use, consequently, considerable effort was needed improve both the nutritional value and price of abalone feed (McShane, 1988).

Abalone farmers, for economic viability require diets that are about $AUS 2.00-3.50 per kg and produce growth of between 70 and 100 μm per day. Nutritional research, higher product volumes and market place competition have reduced prices from $AUS 5 and 7 per kg to about $AUS 2.75-3.90 per kg (higher for specific requirements i.e. A$3.90 – 5.90/kg for sea cage diets) (Vandepeer, 2000). The desired growth rate of 100 μm per day, set within the FRDC Abalone aquaculture subprogram, is being met routinely on South Australian farms with larger abalone but growth rates for small juveniles are still considered sub-optimal (P. Hone, pers. comm., 1998). There are two feed companies in Australia producing manufactured diets for abalone. Diets from both companies vary in performance from farm to farm but this is dependent on several factors such as water temperature, abalone species being cultured and the culture system used (Vandapeer, 2000).

Studies on artificial diets for abalone was being carried out by 28 research groups from around the world (Fleming *et al*., 1996). "The development of artificial feeds or culture of preferred alga species will be a prerequisite for cultivation of the major Western Australian species of abalone" (Lawrence,

1995). However, it was evident in Hone (1992), that abalone fed several different artificial diets grew faster than abalone fed on fresh seaweed (*Gracilaria* spp).

Excellent formulated feeds have now been developed for Greenlip abalone. However, information is needed on the appropriate formulations for Roe's abalone as recent growth trials indicate that current formulations for other abalone species are not providing growth rates comparable to greenlip abalone (Freeman *et al*., 2000b). However, maximum growth rates of 90 μm/day have been recorded for wild-caught Roe's abalone fed a greenlip diet (S. Boarder, pers. comm., 2000).

Over the next few years, abalone nutrition research is aimed at determining whether the nutritional requirements of *H. rubra* are the same as those for *H. laevigata* and thus whether it is appropriate to use formulated diets based on *H. laevigata's* nutritional requirements, to feed *H. rubra* (Vandepeer, 2000). Currently most feeds produced for Australian farms are based on the nutritional requirements of *H. laevigata*, however feeds for other species are produced for world-wide distribution (J. Scanlon, pers. comm., 2000).

5.7. Feeding Frequency and Feeding Rates

Research by Clarke (1988) revealed that juvenile abalone eat approximately 10% of their body weight per day (as wet seaweed), and that during growout (either in cages in the sea or tanks/raceways on land) they need to be fed about 20% of their body weight because of the loss and decomposition of food within these farming systems. Such high rates of wastage would be unacceptable in systems supplied with formulated diets, both on a cost, water quality and best practice environmental standards basis.

Hindrum (pers. comm., 1998) suggests that on a research basis, an artificial diet feeding rate of 1% of body weight per day should be fed to juvenile abalone for land-based systems and a feeding rate of >1% should be applied to sea-based systems since the food is more likely to be wasted. However, opportunities for abalone to graze on biofouling are greater in sea-based systems as indicated by rapid growth of Greenlip abalone held in barrels near Albany for 12 months (Freeman *et al*., 2000b).

It has been reported that commercial abalone farmers generally feed artificial diets 2-3 times per week. New Zealand research indicates that feeding every four days rather than every two days results in faster growth rates (Maguire, 1996). Similarly in a growth trial at Marine Shellfish Hatcheries, Bicheno, Tasmania it was observed that the use of autofeeders depressed growth by 48% relative to abalone fed once per day (at dusk). Feeding and cleaning (by tank drainage that resulted in 7 minutes immersion) every 2 or 4 days improved growth by 41% and 52% respectively (relative to abalone fed on a daily basis). Preleaching the feed for two days reduced growth by 14% and 12.5% for abalone fed at full rate and half rate respectively indicating the importance of soluble nutrients. Moreover, reducing the feed rate by half, for leached and unleached diets resulted in a 6% and 9% decline in growth respectively (Maguire, 1996). Feeding formulated diets every two days is common practice on Australian abalone farms (P. Hone, pers. comm., 2000). At one farm in Tasmania, Blacklip abalone were fed either once per week or every fortnight during the growout phase, which involved a mixture of red drift-weeds and brown seaweeds as well as artificial diets (O'Sullivan, 1994).

Castanos (1997) reported that in cage culture experiments, small Donkey-ear juveniles (16-20 mm) had feeding rates of 35-40% body weight with seaweeds, however, for larger abalone (>50 mm) feeding rates were about 5-10%.

5.8. Impact on Discharge Quality

The use of natural and artificial feeds in culture systems causes feed decomposition and therefore deterioration of the water quality (Fleming *et al*., 1996). However, high water exchange rates result in

very dilute discharge from abalone farms. The major potential concern with discharge is the nitrogen content (Maguire, 1998), however, in general abalone farms are likely to have only minor environmental impact, provided there is efficient removal of solid wastes.

A project demonstrating the use of the sea lettuce *Ulva* spp. to strip dissolved organic nutrients from aquaculture effluent, has been carried out at the Fremantle Maritime Centre, Western Australia. In addition, researchers have found that *Ulva* has a better nutritional profile when grown in aquaculture effluent rather than collected from the wild (Shpigel *et al*., 1996). This indicates that it might be possible to use *Ulva* as a nutritional supplement particularly for broodstock.

6.0 ENVIRONMENTAL REQUIREMENTS

6.1. Preferred Natural Habitat

6.1.1. Roe's abalone

Roe's abalone occur in narrow crevices in granite habitats (mainly in South Australia) or in higher densities over areas of limestone platforms in the upper sublittoral on rough water coasts (Shepherd, 1973) where their favoured food, red drift algae, accumulates (Lawrence, 1995). This species occurs from Wilsons Promontory in Victoria to Shark Bay (Zuytdorp Cliffs, WA) (Fig. 1) and is most abundant in shallow water (3-4 m but mostly 0-2 m) on limestone rocks (Shepherd, 1973; Wells and Keesing, 1986).

6.1.2. Blacklip abalone

Brown (1991a) found that adult Blacklip abalone prefer cryptic habitats in the warmer parts of their distribution, i.e. WA, SA and NSW. They range from southern NSW to Great Australian Bight and Tasmania (Fig. 1), and are found in greatest numbers on high energy reefs. They are rarely more than 10 m deep and are hidden in crevices, under ledges and inside caves (Shepherd, 1973; Brown, 1991a; Hone *et al*., 1997).

6.1.3. Brownlip abalone

This species inhabits the south coast of Western Australia to Cape Naturalist (Fig. 1) and is found in calm water in depths from 2-3 m to 30+ m. It prefers substrata of granite (occasionally limestone) and is found in caves and deep cracks (Joll, 1996).

6.1.4. Greenlip abalone

Greenlip abalone generally occur from western Victoria and Tasmania to Cape Naturaliste (Wells and Mulvay, 1992) (Fig. 1) in depths between 2-3 m and 30 m (Joll, 1996). Greenlip abalone is a 'rough water' species that generally prefers substrata of granite and occasionally limestone. Adults accumulate at the rock-sand interface, while juveniles prefer to reside in cracks and crevices (Joll, 1996).

This species is found in two types of habitats. At the eastern end of its range it is found at depths of 5-40 m on rock surfaces in areas that are almost entirely sand and rock. These areas are associated with sea grass communities, sheltered locations near islands, and headlands or reefs. The second type of habitat (related more to the western end of its distribution) are very rough water areas at the base of cliffs. The abalone are found in crevices or on boulders near the sand line around depths of 10-25 m. Greenlip abalone are found in both habitats in the central and western regions of South Australia (Brown, 1991a).

6.1.5. Staircase abalone

Staircase abalone lives under boulders or crevices in areas with slight to moderate water movement (Shepherd, 1973; Joll, 1996). It occurs on rough water or sheltered coasts to a depth of about 50 m, although it is mostly a shallow water species. It inhabits West Island and Tipara Reef, South Australia (Wells and Bryce, 1987) and is also found in low densities in Western Australia as far north as Cervantes/Jurien area (S. Slack-Smith, pers. comm., 2000).

6.1.6. Donkey-ear abalone

This is a tropical species that is most commonly found under rocks and in crevices (Joll, 1996). It inhabits tropical reefs in Queensland, Northern Territory, and northwest West Australia to as far south as Exmouth Gulf (S. Slack-Smith, pers. comm., 2000), and is widely distributed over the Indo-western Pacific area (Singhagraiwan and Sasaki, 1991). Donkey ear abalone is an intertidal species and can be observed grazing on top of coral boulders at night (R. Counihan, pers. comm., 1999).

6.2. Temperature

Mozqueira (1996) outlines the importance of temperature for temperate abalone. Water temperatures below 7°C will cause temperate abalone to stop feeding and become dormant. Feeding, respiration and growth rates will increase as the water temperature increases until reaching levels that cause stress. He concluded that temperatures greater than 24°C will cause stress in temperate abalone which will decrease their survival rate. Research indicates major differences in the water temperature requirements of Australian abalone species (Table 11).

Abalone Species	Temperature Range for Growth [min-max]	Preferred Temperature	Reference
Greenlip	12°-22°C	18°C	Hone and Fleming, 1998
		18.3°C*	Edwards, 1996
Roe's	14°-26°C		Lawrence, 1995
Blacklip	10°-22°C	16°-18°C	Hone and Fleming, 1998
		17.0°C*	Edwards, 1996
Donkey ear	20°-32°C	28°C	Hone and Fleming, 1998

N.B: * These values are the optimum temperatures which were calculated using the CTM, the preferred temperatures reported in Edwards (1996) experiment and the model equations outlined by Jobling (1981).

Table 11 Responses of four species of abalone to water temperature.

Although the optimal temperatures for some of the Western Australian species are not known, the natural temperature ranges are likely to be a useful indicator to lethal temperature limits.

6.2.1. Greenlip abalone

Edwards (1996) found that the CTM50 [critical thermal maximum temperature when 50% of the abalone lost attachment as temperature was increased by 1°C hour^{-1}] for Greenlip abalone (30-100 mm) was at 27.0°C. The CTM ranged from 25.0°C when the first abalone began to lose attachment to 30.0°C when the last abalone lost attachment.

6.2.2. Blacklip abalone

Edwards (1996) found the CTM50 for Blacklip abalone (30-100 mm) was 27.0°C with a CTM range from 24.4°C to 29.9°C.

6.2.3. Donkey-ear abalone

This species can tolerate higher temperatures than southern abalone (Fallu, 1994).

6.3. Salinity

Greenlip and Blacklip abalone can tolerate salinity levels within the range of 23 to 40 ppt (Boarder *et al*., 2000). Moreover, Boarder and Maguire (1998) found that Greenlip abalone can survive 96 hours at a salinity of 28 ppt and, depending on their prior dietary history, 23 ppt.

6.4. Diurnal cycle

Juvenile Greenlip abalone are known to feed throughout the night. Fleming (1996) found that at any given time over a 24 hr period, at least 4-10% of abalone would be resting. The most active period occurred between 8 pm and midnight (26-31% active). However, the activity declined from midnight to 8 am (15-7% active) and no movement was observed between midday and 8 pm. Similarly, abalone feeding, occurred most frequently between 8pm and midnight (25-31%). However this decreased gradually between midnight and 8am (from 14% to 4%). Again, feeding did not occur between 8am and 8pm.

6.5. Other Water Quality Variables

Abalone are naturally adapted to relatively turbulent open sea conditions and should be held in flowing high quality, well oxygenated, fully marine seawater (Lawrence, 1995). However, one farm is being established towards the mouth of the Tamar River in Tasmania and Sea-based systems have been evaluated in the Huon estuary in that state.

6.5.1. pH

The average pH for natural seawater, unaffected by estuarine discharge, is slightly alkaline, 8.0-8.2. Abalone reared in areas with strong water exchange usually do not have a problem with pH. However, low pH [acidic conditions] can be detrimental to abalone reared in recirculation systems or in systems with accumulated wastes (Mozqueira, 1996).

In growth trials on Greenlip abalone, the EC5 (5% growth reductions based on whole weight) occurred at the pH extremes of 7.78 and 8.77, and the EC50 (50% growth reduction) occurred at pH 7.4. The EC5 for Blacklip abalone occurred at pH extremes of 7.93 and 8.46, and the EC50 occurred at 7.37 and 9.02 (Harris *et al*., 1999a). Moreover, significant mortalities for both species occurred at a pH lower than 7.16 or greater than 9.01 (Harris *et al*., 1999a).

6.5.2. Dissolved oxygen (DO)

In a farm situation it is very important to have aeration to maintain oxygen levels. Oxygen depletion can occur quite rapidly during periods of low water flow or high temperatures (Mozqueira, 1996).

Harris *et al*. (1999b) found in Greenlip abalone that the EC5 and EC50 values (on a whole weight basis) for oxygen levels occurred at 7.36 and 5.91 mg $O_2 L^{-1}$ (96% and 77% saturation with a water

temperature range from 17.1° to 19.4°C) respectively. Significant mortality occurred at concentrations lower than 4.9 mg $O_2 L^{-1}$. In addition, the EC5 and EC50 values (5% and 50% reduction in respiration rate) were 6.16 and 5.19 mg $O_2 L^{-1}$ (80% and 68% saturation), respectively. Harris *et al*. (1999b) found there was not a consistent advantage on survival or growth by increasing dissolved oxygen concentration to super saturation for Blacklip abalone held at 17°C and 19°C. Hindrum *et al*. (1999a), examined growth effects of both elevated ammonia and low dissolved oxygen levels on Greenlip and Blacklip abalone. Overall growth of Greenlip abalone was < 47 μm day^{-1} (for the control) and much lower for Blacklip abalone (< 11 μm day^{-1} for the control). However, when given as pulses of raised ammonia and low dissolved oxygen, growth rates for Greenlip abalone were much higher at ≈100 μm day^{-1} but still very low for Blacklip abalone (≈15 μm day^{-1}) (Hindrum *et al*., 1999b).

6.5.3. Ammonia

Greenlip abalone are quite sensitive to ammonia with an EC5 value (5% growth reduction as a whole weight basis) of 0.041 mg FAN L^{-1} (Free Ammonia-Nitrogen) (Harris *et al*., 1998). Growth was significantly reduced in both Greenlip and Blacklip abalone when they were exposed simultaneously to high ammonia (5-197 μg FAN L^{-1}) and subsaturation of DO (4.3-7.2 mg L^{-1}) over an 8 week period (Hindrum *et al*., 1999b).

6.5.4. Nutrient levels

It has been found that high levels of nutrients can pose an indirect problem for abalone. Although abalone may not be adversely affected by the nutrients, the increased biological activity (i.e. bacterial growth) and associated chemical factors may have a detrimental effect on the abalone. Therefore it has been suggested that high nutrient level areas be avoided for farms (Mozqueira, 1996). However, Greenlip abalone are considered to be quite tolerant to eutrophic tank bottom conditions, although these should be avoided. In fact, it has been shown that abalone in tanks cleaned every 12 days grow faster than abalone in tanks cleaned every four days (Maguire *et al*., 1997). This suggests that Greenlip abalone are more robust to chemically reduced micro-environments in flowthrough tanks than would be expected on the basis of bioassay data for soluble nitrogenous wastes (Harris *et al*., 1997; 1998).

6.5.5. Nitrite

Harris *et al*. (1997) found that the specific growth rates (SGR) of Greenlip abalone (mean whole weight, 5.61 g) measured on a whole-weight and shell-length basis were significantly affected by nitrite. Nitrite concentrations in the range of 0.56-7.80 mg of NO2-N L^{-1}, produced growth rates (weight) that were 67.2% of controls (0.024 mg of NO2-N L^{-1}), while growth rates (length) were 17.7% of controls. However, in contrast to other bioassay trials conducted by these authors there was considerable variation among replicates.

6.5.6. Water velocity

The key to maintaining optimal environmental conditions in a tank system is to ensure that the wastes, either by the abalone or the feed, are quickly washed away (Fleming *et al*., 1997). Strong aeration, tank design (i.e. sloping floor) and water movement are all ways to remove wastes.

The latter is becoming the most favoured option. However, there are negative effects of fast water movement:

a) affects animal behaviour – at high water flows animals move upstream and aggregate (Greenlip abalone move and aggregate upstream while Blacklip abalone tend to aggregate downstream)

b) washes feed away

There is likely to be an optimum water velocity flow that produces maximum growth (Fleming *et al*., 1997). Higham *et al*. (1998) concluded that a flow rate of 2.5-3.0 L min^{-1} improved growth for Greenlip abalone (carried out in raceways with dimensions of 1 m long x 75 mm wide x 50 mm deep). Moreover, they observed that abalone adopt a distinctive feeding posture under conditions of high water flow. The abalone were observed to form two 'hands' with their foot and grasp the food as it passed by and contacted the epipodial tentacles. However, Roden (1998) and Freeman *et al*. (2000b) did not detect an improvement in growth of Greenlip abalone at elevated current speed. Several of the commercial growout tank systems designed in Australia are relatively shallow to allow for higher current speeds.

7.0 COMMERCIAL VIABILITY

Very recent modelling of abalone aquaculture undertaken by ABARE (Australian Bureau of Agricultural Resource Economics) concluded that land-based abalone farms producing 100-200 tonnes annually had a high probability of viability (Weston *et al*., 2001). In addition, Aquaculture SA, Primary Industries and Resources South Australia have developed an on-shore abalone financial planning model which is designed to help potential investors and managers develop their own business plan. It provides the user with output figures for a period of 10 years. Outputs include cashflow budgets, annual profit and loss statements, balance sheets for each year and a cost-benefit analysis (CBA) performed over both 10 and 20 years. For example over 10 years you can expect a 6.3% internal rate of return after tax and similarly over 20 years, a 17.7% internal rate of return can be expected after tax. The sensitivity analysis allows 6 parameters that can be varied including product price, growth rate (number of months to sale), FCR, mortality rate, feed cost and labour. It presents a set of results for each of the 6 parameters (EconSearch, 2000).

7.1. Infrastructure

7.1.1. Capital requirements

7.1.1.1. Hatchery

The following estimates for a hatchery-based production are based on the production of 2 million abalone at a size of 5 mm of which 1 million are grown through to 10 mm in size. A stocking density of 150 abalone per plate (plate = a system used in the nursery phase) at 5 mm in size and about 20,000 abalone per growout tank at 5-10 mm in size were assumed. The sale of 1 million abalone at 10 mm in size (per annum) and 1 million abalone of the size 5 mm (per annum) to growout facilities (O'Brien, 1996a) was projected.

O'Brien (1996a) calculated the total establishment costs as $729,500 (or without juvenile tanks $654,500) and operating costs (hatchery/nursery), estimated from figures provided by Tasmanian and South Australian farmers, as $248,150.

7.1.1.2. Land-based growout

The following estimates for a land-based growout production are derived from the estimates for a hatchery-based production. The establishment costs are based on tanks costing approximately $1,000 and on a stocking density of 2,500 individual abalone of saleable size, and twice that for the next year class. Therefore the total estimated cost for establishing a land-based production is approximately 3 million dollars. This excludes the cost of the hatchery, temperature regulation, broodstock and spawning facilities, micro-filtration, laboratory equipment, nursery tanks and substrata, diatom culture facilities and juvenile tanks, but includes additional costs for land acquisition or rental, abalone seed and grading facilities (O'Brien, 1996a).

7.1.1.3. Sea-based growout

The following estimates for a sea-based production are based on the following assumptions including the purchasing of 1 million seed from a hatchery, at either 5 mm or 20 mm in size. The abalone will be sold at a size of 50 g (approximately 70 mm). It will take 20-30 months starting with a 20 mm abalone and 28-36 months starting with a 5 mm abalone. Costs for sea-based farming of abalone can vary considerably depending on the type of system you choose for your operation. O'Brien (1996a), outlines the establishment and operational costs for several usable sea-based systems (Table 12).

	Cage 1	**Cage 2**	**Cage 3**	**Barrels**	**Large cage**	**Self feeder**
Stocking density	4,000	8,000	4,000	150	40,000	150
Total Establishment costs	1,550,744	1,398,300	2,806,590	3,310,500	2,773,000	3,093,214
Total Operational costs	401,000	423,000	400,000	560,000	592,000	193,000

N.B: For cages 1 and 2, 5 mm abalone seed were used and for the rest of the systems 20 mm abalone seed were used.

Table 12 Establishment and operational costs ($A) for six types of sea-based production systems with stocking density for each system (adapted from O'Brien, 1996a).

7.2. Production Costs and Profitability

O'Brien (1996a), suggested abalone can be produced in a hatchery at a production cost of 16c per abalone on the basis that 2 million seed are produced per year. Selling individuals for 3 cents/mm, will give a return of 15 cents per abalone at 5 mm and 30 cents for 10 mm individuals. On the basis of selling these numbers, the hatchery will gross approximately $125,000 per year. A recommendation of selling the individuals at a minimum of 4 cents/mm for the first 3-4 years was made to reduce the risk of financial trouble. However, this may be too expensive for growout operators and large orders may need to be reduced from that figure.

There are a number of interesting comparisons to be made with regard to the cost of production figures for different growout systems (Table 13).

a) **Cage size** – There are large savings to be made by increasing the size of the cages/holding units.

b) **Seed cost** – Buying smaller seed will reduce cost, however, survival of abalone seed less than 10 mm is not yet clearly established in sea-based culture (larger seed [+20 mm] would be beneficial).

c) **Barrels versus Cages** – Labour costs for barrels are far greater than cages as they need to be fed and cleaned regularly.

d) **Land-based production versus Sea-based production** – Labour costs appear to be the primary cost. While it would seem that sea-based farming is cheaper than land-based farming, it would be fair to say that both systems merit consideration, and that individual farmers will have their own preferences.

	Cage 1	**Cage 2**	**Cage 3**	**Barrels**	**Large cage**	**Self feeder**	**Land**
Total Cost of Production	$1.36	$1.23	$1.62	$1.79	$1.78	$1.30	$1.43
Farm gate Value	$2.50	$2.50	$2.50	$2.50	$2.50	$2.50	$2.50
Total Profit	$1.14	$1.27	$0.88	$0.71	$0.72	$1.20	$1.07

Table 13 Cost of production (per abalone) farm gate value and an estimated total profit for each type of growout system mentioned (adapted from O'Brien, 1996a).

8.0 SITE ISSUES

8.1. Site Selection

Mozqueira (1996) stated that one of the main factors to consider when determining the overall success of a farm is the selection of an appropriate site. This is relevant to both land and sea-based sites, however the characteristics of the ideal site will be different for each type. In general, a land-based site will require easy access and a continuous supply of high quality seawater. The location of an intake pipe is of importance when dealing with water quality as changes in pH, salinity and dissolved oxygen can be detrimental to a farming operation. The desired water quality will be dependent on the species to be cultured.

Finding a 'perfect' sea-based site is becoming increasingly difficult due to competition from other sectors like commercial and recreational fishing. As these sites move nearer to urban areas, commercial fishing grounds, or environmental reserves, the competition increases. This results in new aquaculture ventures being pushed to the edge of already developed areas that offer little in the way of infrastructure (e.g. roads, ports or power supply).

A preliminary question that should be asked is whether the species already lives in the selected site. If the species is not found in the area, then this is a good indication that it might not grow well at the site. It should be determined, before going ahead with the farming operation, if the site is suitable for the species to be cultured.

8.2. Site Availability

Currently, abalone aquaculture in Western Australia is in its infancy. There is only one commercial hatchery operating in Albany (southern Western Australia) and a major farm under construction and partly stocked at Bremmer Bay, near Albany. There are a limited number of potential sites for sea-based abalone aquaculture in warm temperate areas as much of the coast is exposed to rough sea conditions. However, there is far more potential for land-based systems. It must be remembered that these sites may also be good for other aquaculture ventures, recreational use, or for environmental purposes, and therefore competition or conflict may arise about the use of these particular sites. Currently, the Department of Fisheries has been involved in a GIS (global information system) study for potential land-based abalone culture sites.

9.0 POTENTIAL FOR CLOSED LIFE CYCLE, INTENSIVE PRODUCTION

Grove-Jones (1996a) stated that currently it is not possible to produce abalone within a closed life cycle system. However, feasibility of using second generation farmed broodstock has been established commercially. However, the feasibility of growing abalone commercially in recirculating rather than flowthrough systems has not been established. Sensitivity to sub optimal water quality (see 6.0) will be a limiting factor.

10.0 AMENABILITY OF GENETIC IMPROVEMENT

Genetic studies of abalone have focused on hybridization (e.g. Leighton and Lewis, 1982), and induction of triploidy (e.g. Arai *et al.*, 1986). In addition, Li (1998) indicated that the most current genetic based programs under consideration in Australia include the activities described in 10.1 - 10.5.

10.1. Chromosome Manipulation

This is the process where chromosomes are manipulated to result in triploids and tetraploids. Triploids are expected to be sterile and grow faster than diploids as less energy is expended for reproduction. While tetraploids may not exhibit any superior commercially valuable features, they produce exclusively diploid gametes. Crossing these gametes with normal haploid gametes will result in 100% triploid offspring.

10.2. Selective Breeding (Including Mass Selection and Family Selection)

Mass selection is selecting individuals (from a genetic pool contributed to by many individuals) in accordance to their phenotype, while family selection consists of selecting separate families based on family means and /or performance within a family. Currently, a national project funded by the FRDC is being established entitled *Selective breeding of farmed abalone to enhance growth rates*. The principal investigator is Dr Xiaoxu Li from the South Australian Research & Development Institute and participating farms from around Australia include South Australian Mariculture, Port Lincoln, Great Southern Marine Hatcheries, Albany and Southern Ocean Mariculture (SOM), Port Fairy. Several Victorian farms will contribute larvae from local stock to SOM who will host the nursery and growout phase (Fleming, 2000b).

10.3. Transgenesis

This is the introduction of genetic material into the egg in order to produce abalone with faster growing traits or to encourage other desirable traits (e.g. disease resistance) (R. Counihan, pers. comm., 1999). It is therefore considered a desirable method for broodstock development for abalone aquaculture; however, some thought should be given to the potential impact of transgenic abalone on the environment, through competition or by altering heterogeneity of local populations.

10.4. Hybrid Abalone

Hybrid animals have been produced by crossing female Blacklip abalone with male Greenlip abalone. These individuals have been produced in an attempt to find an abalone that has the best characteristics in terms of growth rate, meat to shell ratio, meat texture and market appeal. Hahn (1989) suggests that hybrid abalone may have potential for stock improvement in aquaculture and fishery enhancement. Hybrids usually have morphological characteristics intermediate between the two parent species. Faster growth, adaptation to environmental conditions, and better quality of meat are the principal characteristics selected for in hybrids (Hahn, 1989). Hone and Fleming (1998) believe naturally occurring 'tiger' abalone may be just a colour variation of Blacklip abalone. They suggest that crossing the cold water species *H. rubra* with *H. cyclobates* will result in individuals that may have a broader temperature tolerance.

10.5. Cryopreservation

Cryopreservation of sperm offers many advantages in the fields of medicines, genetics, toxicology, agriculture and aquaculture. Within farmed aquatic animals, cryopreservation has been achieved for fish but limited information is available for invertebrates. However, in sea urchins, rotifers, mussels and oysters cryopreservation of spermatozoa, eggs and embryos have shown promising results (Xiaoxu, 2000). Moreover, abalone (*H. diveriscolor*) hatcheries in Taiwan have successfully used cryopreservation techniques, and in some cases for controlled breeding programs using chromosome manipulations. Recently, a project involving the development of cryopreservation techniques with spermatozoa for farmed abalone was funded by the FRDC. This project was identified as a relatively high priority for research and development within Australia (Xiaoxu, 2000).

11.0 HEALTH ISSUES

11.1. Disease Problems

Limited research has been conducted into diseases in Australian abalone, however it is expected that as more studies progress, more diseases will be found (Handlinger, 1998). The known problems associated with abalone culture include a protistan parasite (*Perkinsus* spp.) mudworm colonization (*Polydora* spp. and *Boccardia* spp) and a bacteria infection (*Vibrio* spp.) (Landau, 1992; Handlinger, 1998). Hindrum *et al*. (1996b) believed that the mud worm was the cause of mortalities (>40%) in at least one sea based trial in Tasmania. The mudworm has been examined by Lleonart and Handlinger (1997; 1998) who emphasized that control of this spionid polychaete was needed, particularly in sea-based systems. In addition, a boring sponge (*Cliona* sp.), common in Western Australia, results in infestation of the shell, particularly in Roe's and Brownlip abalone in the wild (A. Hancock, pers. comm., 2000).

Lleonart's laboratory and field trials on Blacklip abalone have shown that emersion of abalone can significantly reduce infestation by polychaete worm species including *Boccardia knoxi* and *Polydora hoplura*. Exposure to an air temperature of 24°C and 46% humidity for four hours produced a significant reduction ($P<0.001$) in Blacklip abalone (Lleonart, 1998 in Leonart, 1999). However, recent studies have revealed that it is not the temperature per se that is important in the treatment of mudworm but the actual drying out of the shell (Lleonart, 1999). At 21°C in the laboratory, air exposure times of 2, 3 or 4 hours treated *B. knoxi* on Blacklip abalone (mean length 47.1 mm). Field studies also showed similar results.

Avoiding the settlement periods of both mud worm species will be beneficial to the control of this problem in sea-based systems. Lleonart (2000) found the months of September, October and November (1998 and 1999) to be the main settlement times for *B. knoxi*. However, occurrence for *P. hoplura* was much more variable with planktonic stock settling in late spring and summer. Moreover, *P. hoplura* larvae were produced at other times during the year by adult worms within infested shells. In addition, the presence of spirorbid fouling was also shown to significantly increase mud worm settlement.

12.0 ACKNOWLEDGMENTS

The author would like to thank Dr Kirk Hahn amd Dr Greg Maguire for their constructive input and Steve Nel, who participated in the selection of specific subject headings used in the Department of Fisheries series of species profiles.

13.0 REFERENCES

ABARE 1998, *Australian fisheries statistics* 1998, Canberra.

Arai, K., Naito, F. and Fujino, K., 1986. 'Triploidization of the Pacific abalone with temperature and pressure treatments.' *Bulletin Japan Society of Science and Fisheries*, 52: 417-422.

Aviles, J.G.G. and Shepherd, S.A., 1996. Growth and survival of the blue abalone *Haliotis fulgens* in barrels at Cedros island, Baja California, with review of abalone barrel culture. *Aquaculture*, 140: 169-176.

Bardach, J.E., Ryther, J.H. and McLarney, W.O., 1972. *Aquaculture - The farming and husbandry of freshwater and marine organisms*. John Wiley and Sons Inc., New York. 868 pp.

Benzie, J., 1996. *Report on the risk to the genetic integrity and diversity of wild abalone, of farming abalone at sea*. Australian Institute of Marine Science, Townsville. 25 pp.

Boarder, S.J. and Maguire, G.B., 1998. 'Evaluation of vitamin and mineral requirements for Greenlip abalone *Haliotis laevigata* – a progress report'. In: Hone, P. (Ed)., *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 76-87.

Boarder, S.J., Maguire, G.B. and Harris, J.O., 2000. 'Effect of salinity on survival and haemolymph parameters for greenlip abalone'. In Burke, C.M., Harris, J.O., Hindrum, Edwards, S.J. and Maguire, G.B., 2000. *Environmental Requirements of Abalone. Final Report Project 97/323*. Fisheries Research and Development Corporation, Canberra, Australia. Tasmanian Aquaculture and Fisheries Institute, Hobart. pp 97-109.

Britz, P.J. and Hecht, T., 1997. 'Effect of dietary protein and energy level on growth and body composition of South African abalone', *Haliotis midae*. *Aquaculture*, 156:195-210.

Brown, L.D., 1991a. *Evolutionary genetic and population structure in abalone (*genus *Haliotis)*. Unpublished PhD Thesis, La Trobe University, Bundoora, Victoria.

Brown, L.D., 1991b. 'Genetic variation and population structure in the Blacklip abalone, *Haliotis rubra*.' *Australian Journal of Freshwater Research*, 42: 77-90.

Brown, L.D. and Murray, N.D., 1992. 'Population genetics, gene flow and stock structure in *Haliotis rubra* and *Haliotis laevigata*.' In: Shepherd, S.A., Tegner, M.J., Guzman del Proo, S.A (Eds). *Abalone of the world, biology fisheries and culture*. Blackwell Scientific Publications Ltd., Oxford. pp 24-33.

Brown, D, Van Landeghem, K. and Schuele, M., 1997. *Australian aquaculture – Industry profiles for selected species*. Australian Bureau of Agricultural and Resource Economics – ABARE Report, 97/3. 102 pp.

Capinpin, E.C., 1995. 'Spawning and larval development of a tropical abalone *Haliotis asinina'* (Linne). *Philippine Journal of Science,* 124(3): 215-221.

Capinpin Jr., E.C., Toledo, J.D., Encena II, V.C. and Doi, M., 1999. 'Density dependent growth of the tropical abalone *Haliotis asinina* in cage culture.' *Aquaculture*, 171:227-235.

Castanos, M., 1997. 'Abalone R&D at AQD.' *SEAFDEC Asian Aquaculture*, XIX (2): 18-23.

Clarke, S.M., 1988. 'Abalone mariculture: the significance of algae.' *Austasia Aquaculture Magazine*, 3(3): 9-11.

Coote, T.A., Hone, P.W., Kenyon, R. and Maguire, G.B., 1996. 'The effect of different combinations of dietary calcium and phosphorus on the growth of juvenile *Haliotis laevigata.' Aquaculture*, 145: 267-279.

Coote, T.A., Hone P.W., Van Barneveld, R. and Maguire, G.B., 2000. 'Optimal protein level in a manufactured diet for juvenile greenlip abalone *(Haliotis laevigata).' Aquaculture Nutrition*, 6(4).

Cropp, R.A., 1989. *Abalone culture in Tasmania*. Department of Sea Fisheries, Tasmania Technical Report 37, 26 pp.

Cuthbertson, A., 1978. *The abalone culture handbook*. Technical Report 1, Marine Laboratories, Department of Sea Fisheries, Tasmania. 38 pp.

Daume, S., Brand-Gardner, S. and Woelkerling, W.J., 1999. 'Preferential settlement of abalone larvae: diatom films vs non-geniculate coralline red algae.' *Aquaculture*, 174(3-4): 243-254.

Daume, S., Krsinich, A., Farrell, S. and Gervis, M., 2000. 'Settlement, early growth and survival of *Haliotis rubra* in response to different algal species.' *Journal of Applied Phycology*, 12:479-488.

Day, R.W. and Fleming, A.E., 1992. 'The determinants and measurement of abalone growth.' In: Shepherd, S.A., Tegner, M.J., Guzman del Proo, S.A. (Eds). *Abalone of the world, biology fisheries and Culture*. Blackwell Scientific Publications Ltd., Oxford. pp 141-165.

Dunstan, G.A., Volkman, J.K., Maguire, G.B., Augerinos, M., Johns, D. and Hindrum, S.M., 1997. 'Abalone growout diets: which oil and how much?.' In: Hone, P. (Ed)., *Proceedings of the 4th Annual Abalone Aquaculture Workshop*, July, 1997, Port Fairy, Victoria. Fisheries Research and Development Corporation. pp 73-77.

Dunstan, G.A., Brown, M.R., Augerinos, M., Johns, D.R. and Knuckey, R., 1998. 'Formulated feeds for juvenile abalone: based on natural feeds (diatoms and crustose coralline algae).' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1997, Hobart, Tasmania, Fisheries Research and Development Corporation, pp 16-21.

Dunstan, G.A., Volkman, J.K. and Maguire, G.M., 1999. *Optimisation of essential lipids in artificial feeds for Australian abalone*. CSIRO Project No. 94/85, 68 pp.

EconSearch, 2000. *Abalone planner: user guide*. Primary Industries and Resources SA and Aquaculture SA, Adelaide. 32 pp.

Edwards, S., 1996. 'Thermal preferences and tolerances of Greenlip and Blacklip abalone.' In: Hone, P. (Ed). *Proceedings of the 3rd Annual Abalone Aquaculture Workshop,* August, 1996, Port Lincoln, South Australia. Fisheries Research and Development Corporation. pp 60-62.

Edwards, S. and Cook, K., 1999. 'Rapid leaching of minerals from abalone dietary binders is determined by ionic mobility and competition between cations. Dry matter loss is not a good indicator.' In: Hone, P. (Ed). *Proceedings of the 6th Annual Abalone Aquaculture Workshop*, April, 1999, Sydney, NSW. Fisheries Research and Development Corporation.pp. 112-112.

Edwards, S., Ralph, J. And Geraghty, D., 1999. 'Movement of gut contents in blacklip abalone *(Haliotis rubra* Leach) is not mediated by peristalsis.' In: Hone, P. (Ed). *Proceedings of the 6th Annual Abalone Aquaculture Workshop,* April, 1999, Sydney, NSW. Fisheries Research and Development Corporation. pp.102-111.

Edwards, S., Johns, D., and Burke, C.M., 2000. 'Recovery and growth effects of anaesthetics on greenlip and blacklip abalone.' In: Burke, C.M., Harris, J.O., Hindrum, Edwards, S.J. and Maguire, G.B., (Eds). *Environmental Requirements of Abalone*. Final Report Project 97/323. Fisheries Research and Development Corporation, Canberra, Australia. Tasmanian Aquaculture and Fisheries Institute, Hobart. pp. 116-128.

Elston, R.A., 1990. *Mollusc diseases – a guide for the shellfish farmer*. University of Washington, London, 73 pp.

Fallu, R., 1994. *All about abalone*. Department of Conservation and Natural Resources, Melbourne. 56 pp.

Fisheries Western Australia (2000). *State of fisheries* 1999-2000. Fisheries Western Australia, Perth, 176pp.

Fleming, A.E., 1991. *The nutritional biology of the Blacklip abalone*, Haliotis rubra. PhD Dissertation, Melbourne University, Australia, 99 pp.

Fleming, A.E., 1995a. 'Digestive efficiency of the Australian abalone *Haliotis rubra* in relation to growth and feed preference.' *Aquaculture*, 134: 279-293.

Fleming, A.E., 1995b. 'Growth, intake, feed conversion efficiency and chemosensory preferences of the Australian abalone, *Haliotis rubra.' Aquaculture,* 132: 297-311.

Fleming, A.E., 1996. 'Does food availability influence consumption?' In: Hone, P. (Ed), *Proceedings of the 3rd Annual Abalone Aquaculture Workshop,* July, 1998, Hobart, Tasmania. Fisheries Reasearch and Development Corporation. pp. 75-86.

Fleming, A.E., 2000a. The current status of the abalone aquaculture industry in Australia. In: Fleming, A.E., (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation. pp 1-15.

Fleming, A.E., 2000b. 'Progress reports on new projects.' *AB~brief*, 4(2): 1-2.

Fleming, A. E., 2000c. *Conditioning Australian abalone broodstock, best practice manual*. A report for the Marine and Freshwater Research Institute, Queenscliff. FRDC Abalone Aquaculture Subprogram. 39 pp.

Fleming, A.E., van Barneveld, R.J. and Hone, P.W., 1996. 'The development of artificial diets for abalone: A review and future directions.' *Aquaculture*, 140: 5-53.

Fleming, A.E., Hone, P.W. and Higham, J., 1997. 'The effect of water velocity on consumption and growth of Greenlip abalone in tanks.' In: Hone, P. (Ed)., *Proceedings of the 4th Annual Abalone Aquaculture Workshop*, July, 1997, Port Fairy, Victoria. Fisheries Research and Development Corporation. pp 15-22.

Freeman, K., Friedman, K., Maguire, G.B and Hahn, K.O., 2000b. Effects of site and management variables on Roe's (Haliotis roei) and Greenlip abalone (H. laevigata) in Western Australia. In: Fleming, A.E., (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation, pp. 24-38.

Freeman, K., Rowe, M., Maguire, G.B, Parsons, S and Lambert, R., 2000a. 'A design for a broodstock conditioning trial with Greenlip abalone (*H. laevigata*) in Western Australia.' In: Fleming, A.E., (Ed) *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation, pp. 55-60.

Foale, S. and Day, R., 1992. 'Recognizability of algae ingested by abalone.' *Australian Journal of Marine Freshwater Research*, 43: 1331-8.

Garland, C. D., Cooke, S. L., Grant, J. F. and McMeekin, T. A., 1985. 'Ingestion of the bacteria on and the cuticle of crustose (non-articulated) coralline algae by post-larval and juvenile abalone (*Haliotis ruber* Leach) from Tasmanian waters.' *Journal of Experimental Marine Biology and Ecology*, 91: 137-149.

Gordon, H. R., 2000. 'World abalone supply, markets and pricing: historical, current and future prospectives.' *4th International Abalone Symposium*, Cape Town, South Africa. pp. 22.

Grove-Jones, R., 1996a. 'Hatchery production.' In: Forster, A. (Ed). *Proceedings of the Abalone Aquaculture Workshop*, December, 1995, Albany, Western Australia. Aquaculture Development Council and Fisheries Department of Western Australia. pp 14-16.

Grove-Jones, R., 1996b. 'South Australian abalone developments Pty. Ltd. (SAABDEV) – Progress report.' In: Hone, P.W. and Fleming, A.E. (Eds). *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop*. Fisheries Research and Development Corporation. pp 17-20.

Grove-Jones, R., 1996c. 'A tank for commercial abalone farming.' In: Hone, P.W. and Fleming, A.E. (Eds). *Proceedings of the 3rd Annual Abalone Aquaculture Workshop*, August, 1996, Port Lincoln, South Australia. Fisheries Research and Development Institute. pp 11-12.

Hahn, K.O., 1989. *Handbook of culture of abalone and other marine gastropods*. CRC Press, Boca Raton, Florida. 348pp.

Hancock, A., 2000. Genetic subdivision of Roe's abalone, *Haliotis roei* Grey (Mollusca : Gastropoda), in south-western Australia. *Marine and Freshwater Research*, 51:679-687.

Handlinger, J., 1998. 'Diseases in abalone - A review.' In: Hone, P. (Ed)., *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Department of Primary Industries and Fisheries, Tasmania. Fisheries Research and Development Corporation. 6 pp.

Harris, J.O., Maguire, G.B., Edwards, S. and Hindrum, S.M., 1997. 'Effect of nitrite on growth and oxygen consumption for juvenile Greenlip abalone, *Haliotis laevigata* Donovan.' *Journal of Shellfish Research*, 16 (2): 395-401.

Harris, J.O., Maguire, G.B., Edwards, S. and Hindrum, S.M., 1998. 'Effect of ammonia on the growth rate and oxygen consumption of juvenile Greenlip abalone,' *Haliotis laevigata* Donovan. *Aquaculture*, 160: 259-272.

Harris, J.O., Maguire, G.B., Edwards, S. and Hindrum, S.M., 1999a. 'Effect of pH on growth rate, oxygen consumption rate, and histopathology of gill and kidney tissue for juvenile Greenlip abalone, *Haliotis laevigata* Donovan and Blacklip abalone, *Haliotis rubra* Leach.' *Journal of Shellfish Research*, 18 (2): 611-619.

Harris, J.O., Maguire, G.B., Edwards, S. and Johns, D.R., 1999b. Low dissolved oxygen reduces growth rate and oxygen consumption rate of juvenile greenlip abalone, *Haliotis laevigata* Donovan. *Aquaculture*, 174: 265-279.

Heasman. M.P., Savva, N.M., McMahon, G.A. and Brand, C.P., 2000. 'Effect of temperature on metamorphosis and early post settlement growth and survival in blacklip abalone *Haliotis rubra*.' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation. pp. 77-85.

Higham, J., Hone, P., Clarke, S., Baudinette, R. and Geddes, M., 1998. 'The effect of flow on growth in juvenile Greenlip abalone, *Haliotis laevigata* (Donovan).' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1997, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 116-124.

Hindrum, S., 1996. 'Marine Shellfish Hatcheries (MSH) – Progress report.' In: Hone, P.W. and Fleming, A.E., (Eds)., *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop*. Fisheries Research and Development Corporation. pp 7-12.

Hindrum, S., Cropp, M. and Maguire, G. B., 1996a. 'Evolution of abalone growout tank design at Marine Shellfish Culture, Bicheno, Tasmania.' In: Hone, P. W. and Fleming, A.E., (Ed)., *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop,* July 1996. Fisheries Research and Development Corporation. pp 54-66.

Hindrum, S., Cropp, M., O'Brien, D., Savva, N., Maguire, G. B. and Johns, D.R., 1996b. 'Performance of Greenlip (*Haliotis laevigata*) and Blacklip*Greenlip Hybrid abalone in land-based or sea-based systems.' In: *Proceedings of the 3rd Annual Abalone Aquaculture Workshop*, August 1996, Port Lincoln, South Australia. Fisheries Research and Development Corporation. pp 13-36.

Hindrum, S., Maguire, G., Edwards, S., Burke, C. and Johns, D., 1998. 'Is the need for refuges in abalone culture dependent on stocking density for Greenlip abalone?' In: Hone, p. (Ed)., *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1997, Hobart.. pp 92-102.

Hindrum, S., Burke, C and Edwards, S., 1999a. 'Growth reductions in greenlip (*Haliotis laevigata*) and blacklip (*Haliotis rubra*) abalone resulting from chronic exposure to sublethal combinations of elevated ammonia and low dissolved oxygen levels.' In: Burke, C.M., Harris, J.O., Hindrum, Edwards, S.J. and Maguire, G.B., (Eds). *Environmental Requirements of Abalone*. Final Report Project 97/323. Fisheries Research and Development Corporation, Canberra, Australia. Tasmanian Aquaculture and Fisheries Institute, Hobart.

Hindrum, S., Burke, C and Edwards, S., 1999b. The effect of pulses of raised ammonia and low dissolved oxygen on the growth of greenlip (*Haliotis laevigata*) and blacklip (*Haliotis rubra*) abalone. In: Burke, C.M., Harris, J.O., Hindrum, Edwards, S.J. and Maguire, G.B., (Eds). E*nvironmental Requirements of Abalone*. Final Report Project 97/323. Fisheries Research and Development Corporation, Canberra, Australia. Tasmanian Aquaculture and Fisheries Institute, Hobart.

Hindrum, S., Edwards, S., Burke, C., Johns, D. and Maguire, G., 1999c. 'Exploring the dynamic relationship between water quality, stocking density and refuge provision for greenlip abalone (*Haliotis laevigata*).' In: Burke, C.M., Harris, J.O., Hindrum, Edwards, S.J. and Maguire, G.B., (Eds). *Environmental Requirements of Abalone*. Final Report Project 97/323. Fisheries Research and Development Corporation, Canberra, Australia. Tasmanian Aquaculture and Fisheries Institute, Hobart.

Hone, P.W., 1992. 'Preliminary results of artificial diet trials.' In: Hone, P. (Ed). *Proceedings of the Biotechnology Aquaculture Workshop: Abalone Artificial diets*, July, 1992. South Australian Department of Fisheries Research Branch.

Hone, P.W., 1996. 'The FRDC and CRC co-operative research program on abalone aquaculture.' In: Forster, A. (Ed). *Proceedings of the Abalone Aquaculture Workshop*, December, 1995, Albany, Western Australia. Aquaculture Development Council and Fisheries Department of Western Australia. pp 36-54.

Hone, P.W. and Fleming, A.E., 1998. 'Abalone.' In: K. Hyde, (Ed), 1998. *The new rural industries – A handbook for farmers and investors*. Rural Industries and Development Corporation, Canberra. pp 85-92.

Hone, P.W., Madigan, S.M. and Fleming, A.E., 1997. *Abalone hatchery manual for Australia*. South Australian Research and Development Institute, Adelaide. 33 pp.

Huner, J.V. and Brown, E.E., 1985. *Crustacean and mollusk aquaculture in the United States*. AVI Publishing Company Inc., Connecticut. 467 pp.

Jobling, M., 1981. 'Temperature tolerances of the final preferendum-rapid methods for the assessment of optimum growth temperatures.' *Journal of Fish Biology*, 19: 439-455.

Joll, L., 1996. 'Abalone in the wild- life history and habitat in WA.' In: Forster, A. (Ed). *Proceedings of the Abalone Aquaculture Workshop*, December, 1995, Albany, Western Australia. Aquaculture Development Council and Fisheries Department of Western Australia. pp 11-13.

Keesing, J.K. and Wells, F.E., 1989. 'Growth of the abalone *Haliotis roei* Gray.' *Australian Journal of Freshwater Research*, 40: 199-204.

Kent, G.N., Maguire, G.B., John, M., Cropp, M., and Frankish, K. , 1998. 'Broodstock conditioning, spawning induction, and larval rearing of the stepped venerid, *Katelysia scalarina* (Lamark 1818).' *Journal of Shellfish Research*, 17(4): 1065-1070.

Kemp, R.C., van Barneveld, R. And Tivey, D.R., 1999. 'Utilization of small intestine brush border membrane vesicles from abalone, Haliotis laevigata, for the assessment of grain legumes.' In: Hone, P. (Ed). *Proceedings of the 6th Annual Abalone Aquaculture Workshop*, April, 1999, Sydney, NSW. Fisheries Research and Development Corporation. pp 83-96.

Kiley, T., 1998. 'A market analysis of abalone in Hong Kong and Guangdong.' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1997, Hobart, Tasmania. Fisheries and Research and Development Corporation. pp 62.

Knauer, J., Britz, P.J. and Hecht, T., 1993. 'The effect of seven binding agents on 24-hour water stability of an artificial weaning diet for the South African abalone, *Haliotis midae* (Haliotidae, Gastropoda).' *Aquaculture*, 115: 327-334.

Krsinich, A., Daume, S., Farrell, S., Gervis, M. and Thompson, P., 2000. 'Towards intensification of an abalone (*Haliotis rubra*) nursery operation via inoculation with benthic diatom *Navicula* sp. and seeding with the macroalga *Ulvella* lens.' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation. pp.86-99.

Landau, M., 1992. *Introduction to aquaculture*. John Wiley and Sons Inc., New York. 440 pp.

Lawrence, C., 1995. Greenlip, brownlip and Roe's abalone. Aquaculture WA, No. 7. Fisheries Department of Western Australia. 4-pp.

Lee, C., 1998. 'Tropical abalone – a neglected aquaculture species.' *Western Fisheries*, Winter 1998: 46-47.

Leighton, D.L. and Lewis, C.A., 1982. 'Experimental hybridization in abalones.' *International Journal of Invertebrate Reproduction*, 5: 273-282.

Li, X., 1998. Genetics in Abalone. In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 132-140.

Lleonart, M., 1992. A gonad conditioning study of the Greenlip abalone (*Haliotis laevigata*). Unpublished Masters Thesis, University of Tasmania. 162 pp.

Lleonart, M., 1999. 'Mud worm treatment trials.' In: Hone, P. (Ed). *Proceedings of the 6th Annual Abalone Aquaculture Workshop*, April, 1999, Sydney, NSW. Fisheries Research and Development Corporation. pp 1-14.

Lleonart, M., 2000. 'Minimizing the risk of mud worm infection in farmed abalone.' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation. pp. 115-126.

Lleonart, M. and Handlinger, J., 1997. 'Mudworms in abalone.' In: Hone, P. (Ed). *Proceedings of the 4th Annual Abalone Aquaculture Workshop*, July, 1997, Port Fairy, Victoria. Fisheries Research and Development Corporation. pp 43-45.

Lleonart, M. and Handlinger, J., 1998. 'Treatment of abalone Mud worms.' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 64-66.

Lorkin, M.E., Hone, P.W., Fleming, A.E. and Vandapeer, M., 1999. 'Economics of on farm feeding strategies and recommended practices.' In: Hone, P. (Ed). *Proceedings of the 6th Annual Abalone Aquaculture Workshop*, April, 1999, Sydney, NSW. Fisheries Research and Development Corporation. pp 97-101.

Maguire, G.B., 1996. 'Effects of extended feed immersion, feed frequency and feed rate on growth of juvenile Greenlip abalone *Haliotis laevigata* and on composition and microbial colonisation of a formulated diet.' In: Hone, P. W. and Fleming, A.E., (Ed)., *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop*, July 1996. South Australian Research and Development Institute. pp 89-91.

Maguire, G.B., 1998. 'Nitrogen budgets for land-based abalone farms- A discussion document.' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 88-92.

Maguire, G.B. and Hone, P., 1997. 'Port Lincoln abalone culture workshop – R&D aids impressive industry expansion.' *Austasia Aquaculture*, 11(2): 37-39.

Maguire, G.B., Johns, D., Hindrum, S. and Cropp, M., 1996a. 'Effects of shading and refuges on the growth of juvenile Greenlip abalone Haliotis laevigata.' In: Hone, P. (Ed). *Proceedings of the 3rd Annual Abalone Aquaculture Workshop*, August 1996, Port Lincoln, South Australian. Fisheries Research and Development Corporation. pp 40-45.

Maguire, G.B., Dunstan, G.A., Mansour, P., Hindrum, S.M., Johns, D.R. and Cropp, M. 1996b. 'Effects of microalgal or macroalgal supplementation of an abalone diet on growth of juvenile greenlip abalone *Haliotis laevigata*.' In: Hone, P. (Ed). *Proceedings of the 3rd Annual Abalone Aquaculture Workshop*, August, 1996, Port Lincoln, South Australia. Fisheries Research and Development Corporation. pp 84-90.

Maguire, G.B., Roden, D.J., Burke, C.M., Johns, D.R. and Hindrum, S.M., 1997. 'Effects of dietary fiber on the performance of juvenile Greenlip abalone *Haliotis laevigata* and on the growout tank environment.' In: P Hone (Ed). *Proceedings of the 4th Annual Abalone Aquaculture Workshop*, July, 1997, Port Fairy. Fisheries Research And Development Corporation. pp 4-14.

Mazon-Suastegui, J.M., Bazua-Sicre, L., Lucero-Martinez, G. and Rodriguez-Ramos, R., 1992. Producción de semilla de abulón en el laboratorio: el método de Bahía Tortugas BCS, México. In: Shepherd, S.A., Tegner, M.J., Guzmán del Próo, S.A. (Eds). *Abalone of the world, biology fisheries and culture*. Blackwell Scientific Publications Ltd., Oxford, pp. 561-569.

McNamara, D.C. and Johnson, C.R., 1995. 'Growth of the ass's ear abalone (*Haliotis asinina Linne*) on Heron Reef, tropical eastern Australia.' *Marine Freshwater Research*, vol. 46(3):571-574.

McShane, P.E., 1988. 'World developments in abalone culture.' In: L. Evans and D. O'Sullivan (Eds). *Proceedings 1st Shellfish Aquaculture Conference*, Perth, Western Australia.

McShane, P.E., 1992. 'Early life history of abalone: a review.' In: Shepherd, S.A., Tegner, M.J., Guzmán del Próo, S.A. (Eds). *Abalone of the world, biology fisheries and culture*. Blackwell Scientific Publications Ltd., Oxford. pp 120-135.

McShane, P.E. and Smith, M.G., 1988. 'Measuring abundance of juvenile abalone, *Haliotis rubra* Leach (Gastropoda: *Haliotidae*); comparison of a novel method with two other methods.' *Australian Journal of Marine and Freshwater Research*, 39: 331-336.

Mgaya, Y.D. and Mercer, J.P., 1995. 'The effects of size grading and stocking density on growth performance of juvenile abalone,' *Haliotis tuberculata* Linnaeus. *Aquaculture*, 136: 297-312.

Moore, M., 1996. Description of SAM'S tank design. In: Hone, P. W. and Fleming, A.E., (Ed)., *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop*. Fisheries Research and Development Corporation. pp 71-73.

Moore, M. and Hone, P., 1996. 'Results of varying stocking density on growth and yield per unit tank area (FRDC).' South Australian Mariculture (SAM). In: P.W. Hone and A.E. Fleming. (Eds). *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop*. Fisheries Research and Development Corporation. pp 67-70.

Morrison, J., 1996a. 'South Australian Mariculture Pty. Ltd (SAM) – Progress report.' In: Hone, P.W. and Fleming, A.E. (Eds). *Proceedings of the 1st and 2nd Annual Abalone Aquaculture Workshop*. South Australian Research and Development Institute. pp 13-16.

Morrison, J., 1996b. 'South Australian Mariculture tank design.' In: Hone, P. (Ed). *Proceedings of the 3rd Annual Abalone Aquaculture Workshop*, August, 1996, Port Lincoln, South Australia. Fisheries Research and Development Corporation. pp 38-39.

Morrison, J. and Smith, B., 2000. 'Tank design changes direction.' In: Fleming, A. (Ed). *AB-brief,* 4(1):5-5.

Mozqueira, A., 1996. 'Site selection for land based abalone farming.' In: Forster, A. (Ed). *Proceedings of the Abalone Aquaculture Workshop,* December, 1995, Albany, Western Australia. Aquaculture Development Council and Fisheries Department of Western Australia. pp 17-21.

Oakes, F.R. and Ponte, R.D., 1996. 'The abalone market: Opportunities for cultured abalone.' Aquaculture, 140: 187-195.

O'Brien, D., 1996a. 'Preliminary analysis of the production costs and returns involved in abalone farming.' In: Forster, A. (Ed). *Proceedings of the Abalone Aquaculture Workshop*, December, 1995, Albany, Western Australia. Aquaculture Development Council and Fisheries Department of Western Australia. pp 67-83.

O'Brien, D., 1996b. 'Growing abalone at sea – the latest ideas from Tasmania and further afield.' In: Forster, A. (Ed). *Proceedings of the Abalone Aquaculture Workshop*, December, 1995, Albany, Western Australia. Aquaculture Development Council and Fisheries Department of Western Australia. pp 28-35.

O'Sullivan, D., 1994. 'Tasmanian abalone producer ready for market.' *Aquaculture Magazine*, March/April: 50-54.

Peck, L.S., 1989. 'Feeding, growth and temperature in the ormer, *Haliotis tuberculata* (L.).' *Progress in Underwater Science*, 14: 95-107.

Pillay, T.V.R., 1993. *Aquaculture principles and practices*. Fishing News Books, London. 575 pp.

Ritar, A., 2000. 'Conditioning of greenlip and blacklip abalone by temperature manipulation: development of an experimental protocol.' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. pp.52-54.

Roberts, R., Kawamura, T. and Nicholson, C., 1998. 'Overview of larval settlement and post-larval growth/ survival in abalone.' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 1-8.

Roden, D. J., 1998. *Micro environmental characterisation of decaying wastes in an abalone growout system*. Unpublished Honors Thesis, University of Tasmania. 83 pp.

Sakata, K., Kato, K., Iwase, Y., Okada, H., Ina, K. and Machiguchi, Y., 1991. 'Feeding-stimulant activity of algal glycerolipids for marine herbivorous gastropods.' *Journal of Chemical Ecology*, 17(1): 185-193.

Savva, N.M., Heasman, M.P. and Brand, C.P., 2000. 'A recirculating temperature controlled system for the reproductive conditioning of blacklip abalone, *Haliotis rubra*.' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. pp. 61-76.

Scheilbling, R.E., 1994. 'Molluscan grazing and macroalgal zonation on rocky intertidal platform at Perth, Western Australia.' *Australian Journal of Ecology*, 19:141-149.

Shepherd, S.A., 1973. 'Studies on southern Australian abalone (Genus *Haliotis*).' I Ecology of five sympatric species. *Australian Journal of Marine and Freshwater Research*, 24: 217-257.

Shepherd, S.A., 1975. 'Distribution, habitat and feeding habits of abalone.' *Australian Fisheries*, 34(1): 12-15.

Shepherd, S.A., 1988. 'Studies on southern Australian abalone (Genus *Haliotis*) VIII. Growth of juvenile *H. laevigata*.' *Australian Journal of Marine and Freshwater Research*, 39: 177-183.

Shepherd, S.A. and Cannon, J., 1988. 'Studies on southern Australian abalone (Genus Haliotis) X. Food and feeding of juveniles.' *Journal of the Malacalogical Society of Australia*, 9: 21-26.

Shepherd, S.A. and Hearn, W.S., 1983. 'Studies on southern Australian abalone (Genus *Haliotis*) IV. Growth of *H. laevigata* and *H. ruber.' Australian Journal of Marine and Freshwater Research,* 34: 461-475.

Shepherd, S.A. and Laws, H.M., 1974. 'Studies on Southern Australian Abalone (Genus *Haliotis*) II. Reproduction of five species.' *Australian Journal of Marine and Freshwater Research*, 25: 49-62.

Shepherd, S.A., and Partington, D. 1995. 'Studies on Southern Australian abalone (Genus *Haliotis*) XVI. Recruitment, habitat and stock relations.' *Australian Journal of Marine and Freshwater Research*, 46(3): 669-680.

Shepherd, S.A. and Steinberg, P.D., 1992. 'Food preferences of three Australian abalone species with a review of the algal food of abalone.' In: Shepherd, S.A., Tegner, M.J., Guzman del Proo, S.A. (Eds). *Abalone of the world, biology fisheries and culture*. Blackwell Scientific Publications Ltd., Oxford. pp 169-181.

Shepherd, S.A., Clarkson, P.S. and Turner, J.A., 1985. 'Studies on southern Australian abalone (Genus *Haliotis*) V. Spawning, settlement and early growth of *H. scalaris.' Transactions of the Royal Society of South Australia*, 109(2): 61-62.

Shepherd, S.A., Godoy, C. and Clarke, S.M., 1992. 'Studies on southern Australian abalone (Genus Haliotis) XV. Fecundity of *H. laevigata.' Journal of the Malacalogical Society of Australia,* 13: 115-121.

Shipton, T.A., 1999. *The protein requirements of the South African abalone*, *Halotis midae*, Unpublished PhD Thesis, Rhodes University.

Shpigel, M., Marshall, A. and Lupatsch, I., 1996. 'Acclimation and propagation of the abalone *Haliotis tuberculata* in a land-based culture system in Israel.' *Journal of the World Aquaculture Society*, 27 (4): 435-443.

Singhagraiwan, T. and Doi, M., 1992. 'Spawning pattern and fecundity of the donkey's ear abalone, *Haliotis asinina* Linne, observed in captivity.' *Thai Marine Fisheries Research Bulletin*, 3:61-69.

Singhagraiwan, T. and Sasaki, M., 1991. 'Breeding and early development of the donkey's-ear abalone, *Haliotis asinina* Linné.' *Thai Marine Fish Research Bulletin*, 2: 83-94.

Smith, P.J. and Conroy, A.M., 1992. 'Loss of genetic variation in hatchery-produced abalone, *Haliotis iris*.' *New Zealand Journal of Marine and Freshwater Research*, 26: 81-85.

Uki, N., 1989. 'Abalone seedling production and its theory (1).' *International Journal Aquaculture Fisheries Technology*, 1:3-15.

Uki, N. and Watanabe, T., 1992. 'Review of the nutritional requirements of abalone (*Haliotis* spp.) and development of more efficient artificial diets.' In: Shepherd, S.A., Tegner, M.J., Guzman del Proo, S.A. (Eds). *Abalone of the World, Biology Fisheries and Culture*. Blackwell Scientific Publications Ltd., Oxford. pp 304-591.

van Barneveld, R.J., Fleming, A.E., Vandepeer, M.E., Kruk, J.A. and Hone, P.W., 1998. 'Influence of dietary oil type and oil inclusion level in manufactured feeds on the digestibility of nutrients by juvenile Greenlip abalone (*Haliotis laevigata*).' In: Hone, P. (Ed). *Proceedings of the 5th Annual Abalone Aquaculture Workshop*, July, 1998, Hobart, Tasmania. Fisheries Research and Development Corporation. pp 24-42.

Vandepeer, M.E., 2000. 'Australian manufactured feeds: Research and commercial performance.' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation. pp. 16-21.

Vandepeer, M.E., van Barneveld, R.J., Hone, P.W. and Havenhand, J.N., 1999. 'The digestibility of raw, autoclaved and phytase treated legumes in greenlip abalone, *Haliotis laevigata*.' In: Hone, P. (Ed). *Proceedings of the 6th Annual Abalone Aquaculture Workshop*, April, 1999, Sydney, NSW. Fisheries Research and Development Corporation. pp 62-82.

Wee, K.L., Maguire, G.B. and Hindrum, S.M., 1994. 'Methodology for digestibility studies with abalone. 2. Comparison of markers in an artificial diet for blacklip abalone (*Haliotis rubra*) and greenlip abalone (*Haliotis laevigata*).' In: L.M. Chou, A.D. Munro, T.J. Lam, T.W. Chen, L.K.K. Cheong, (Eds), *Proceedings third Asian fisheries forum*, Singapore, October 26-30,1992. Asian Fisheries Society, Makati, Philippines, pp. 152-155.

Wells, F.E. and Bryce, C., 1987. 'West Australian abalone.' *Western Angler and Diver*. 2(5): 25-27.

Wells, F.W. and Keesing, J.K., 1986. *An investigation of mollusc assemblages on intertidal beachrock platforms in the Perth metropolitan area, with particular emphasis on the abalone Haliotis roei. Volume 2: The abalone Haliotis roei*. Western Australian Museum, Perth. 369 pp.

Wells, F.W. and Keesing, J.K., 1989. 'Reproduction and feeding in the abalone *Haliotis roei* Gray.' *Australian Journal of Marine and Freshwater Research*, 40: 187-197.

Wells, F.E. and Mulvay, P., 1992. *Reproduction and growth of the Greenlip abalone* Haliotis laevigata *on the south coast of Western Australia*. Western Australian Museum, Perth. 117 pp.

Weston, L., Hardcastle, S. and Davies, L., 2001. *Profitability of selected aquaculture species*. ABARE Research Report 01.3, Canberra. 95pp.

Williams, K. and Degnan, B., 1998. 'Development of a cocktail abalone aquaculture industry for tropical Australia.' In: P. Hone and A. Fleming (Eds). *AB-brief, Developments in abalone aquaculture*. Fisheries Research and Development Corporation. 2(2):3.

Xiaoxu, L., 2000. 'Sperm Cryopreservation with farmed abalone: How will we get there?' In: Fleming, A.E. (Ed), *Proceedings of the 7th Annual Abalone Aquaculture Workshop*, August, 2000, Dunedin, New Zealand. Fisheries Research and Development Corporation. pp 47-49.

Yearsley, G. K., Onley, A. C. and Brown, F. K., 2000. *Australian seafood users manual, making the most of the world's best*. Department of Primary Industries, Queensland and Fisheries Research and Development Corporation, Canberra. pp 128-129.