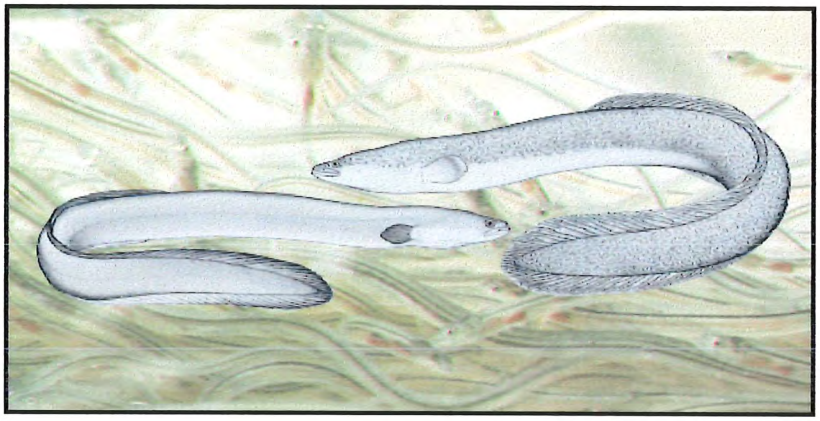
ASSESSMENT OF EASTERN AUSTRALIAN GLASS EEL STOCKS AND ASSOCIATED EEL AQUACULTURE

Edited by

G. J. Gooley and B. A. Ingram

Final Report
FRDC Project No 97/312 (and No. 99/330)



February 2002

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Further acknowledgments for the specific participants and associated supporters of the various components of this relatively large project, which was effectively spread across more than three years, four Australian states, two anguillid species and at least two different fisheries disciplines, are provided in the respective chapters of this report. The collective contributions to this project of these people and the actual project team of researchers and technicians, the latter of whom have mostly contributed to the preparation of this report as authors of various chapters, are also gratefully acknowledged by the Principal Investigator and his R&D colleagues at the Marine and Freshwater Resources Institute in Victoria.

NON-TECHNICAL SUMMARY

97/312 ASSESSMENT OF EASTERN AUSTRALIAN GLASS EEL STOCKS AND ASSOCIATED EEL AQUACULTURE*

*** Incorporating FRDC Project 99/330 Validation of Longfin Eel Aquaculture Potential***

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OBJECTIVES

1. To characterise migrations and assess stocks of glass eels in coastal catchments of southern Queensland, NSW, Victoria and Tasmania to enable evaluation of the potential of seedstock supply for Australian eel aquaculture and wild fisheries.
2. To develop pond and tank culture technology for commercial Australian eel production, with an emphasis on the use of eastern Australian glass eel seedstock.
3. To contribute to the development of eel aquaculture industry development and fisheries management plans through the provision of relevant information in the form of reports, publications, seminars, newsletters and workshops.

It should be noted that the specific objectives for the linked FRDC Project 99/330 *Validation of Longfin Eel Aquaculture Potential* are detailed in Chapter 5 of this report.

SUMMARY

The world aquaculture production of freshwater Anguillid eels (Anguillidae) currently exceed an estimated 216,000 tonnes per annum, worth over US$915 million. This production is predominantly based on the culture of the European eel *Anguilla anguilla* in Europe and China, and the Japanese eel, *A. japonica* in predominantly China, Taiwan and Japan. Most of the increase in production in China, the major producer, has come about through the increasing intensification of farming systems and the diversification from *A. japonica* alone into *A. anguilla* as an additional species. Likewise, the increase in European production of *A. anguilla* from farms in the Netherlands and Denmark appears to have occurred as a result of the introduction of more intensive production techniques, including the use of commercially available recirculating aquaculture systems. In summary, the combined effect of new species and systems intensification has substantially increased the production and value of the global eel aquaculture industry over the last decade. By contrast, in Australia, total production is

presently in the order of 5-700 tonnes per annum, worth AUD$4-7.5million, the vast majority of which comes from wild fishery harvest, and much of which historically comes from stock enhanced wild fisheries (also referred to by industry as 'cultured eels'). Further expansion of the industry is presently constrained by limited application of intensive production techniques and limited access to local glass eel supplies.

In this context the present study has been initiated to facilitate development of the Australian eel aquaculture industry, with the specific emphasis on investigations into glass eel resource identification for two endemic culture species, viz. the Australian shortfin eel *A. australis* and the longfin eel *A. reinhardtii*, and the further development of intensive culture techniques for these two species. This study builds on a previous FRDC funded project (No. 94/067) investigating aspects of Australian shortfin glass eel assessment and aquaculture development.

Global eel market dynamics and associated access for cultured Australian eel products, along with existing Australian industry structure, operational philosophy and associated state-based legislative regimes, are also relevant factors in defining production status, but are not specifically addressed in this project.

The project has been effectively managed as two components, each with a series of specific strategies designed to address the relevant project objectives. Key research methods employed during the Project include:

1. Assessment component

- Collate existing information for *A. australis* and *A. reinhardtii* glass eels and establish a long term monitoring database of distribution and catch statistics for eastern Australia.
- Develop indices of relative abundance/catch rates for glass eels within selected catchments over the full range of the study area and over a three year time frame.
- Validate and further refine a preliminary model for Australian glass eel recruitment which factors in spatial and temporal variability and includes key environmental gradients at both the estuarine and oceanic scale along the east Australian coast.
- Investigate and further refine glass eel fishing techniques and equipment, including options for minimising bycatch and maximising survival of glass eels.
- Investigate genetic discrimination of eastern Australian and New Zealand glass eel stocks to determine the most appropriate management units.

2. Aquaculture component

- Investigate optimal production parameters and associated husbandry requirements for short and long-finned glass eels and subsequent developmental stages under both tank and pond culture conditions where appropriate.
- Undertake a pilot commercial scale grow-out of short and long-finned glass eels under both tank and pond culture conditions where appropriate.
- Develop nursery phase tank and pond-based culture strategies and technologies
- Undertake a desktop cost-benefit analysis of available commercial aquaculture options, including a comparison of tank and pond culture options as stand-alone and/or combined systems.

The project was a collaborative effort incorporating input from state-based fisheries agencies/research institutions in Queensland, NSW, Victoria and Tasmania, as well as Deakin University. This Final Report summarises the various investigations for the two key components undertaken as part of this project. The report is in the form of a book consisting of discrete chapters each authored by the relevant researchers responsible for each of the specific project components and/or associated sub-projects. The aquaculture component was

further supplemented by an additional FRDC Project No. 99/330 *Validation of longfin eel aquaculture potential*, specifically (as the title implies) to provide additional information on the suitability and needs of intensive culture techniques for longfin eels. This work was carried out by the Principal Investigator Dr Clive Jones of the Queensland Department of Primary Industries, and is included as part of an all inclusive summary (Project No. 97/312 and No. 99/330) for longfin eel aquaculture under Chapter 5 in this report. The genetic work undertaken in this study is not included in this report due to late stage technical problems with the samples. This work will however be subsequently reported at a later date in a supplementary report once the relevant information is finally collated.

In summary, key results and conclusions for the major project components include:

- Suitable sites and fishing techniques have been identified and/or further elucidated in the present study for harvesting of longfin and shortfin glass eels in Victoria (Snowy River) and Queensland (Albert River), albeit in the absence of any absolute estimate of the total size of the resource. Quantities of glass eels in the order of 100-200 kg per species per site are considered reasonable to be harvested in the first instance on an annual basis, subject to appropriate, site specific and fishery-wide guidelines.
- Clearly much of the risk associated with glass eel harvesting in Australia, for whatever species, needs to be managed within an ESD framework and adopting a 'precautionary approach', as the underpinning principles of formal eel fishery management plans.
- Although suitable sites for harvesting of commercial quantities of glass eels at similar scales have not yet been confirmed in NSW and Tasmania, both species were collected in the present study at Port Hacking in NSW, and at least shortfin glass eels were taken in the Prosser River in Tasmania. This suggests therefore that a significant glass eel resource may be accessible in these areas, if in fact suitable collection sites and/or associated fishing techniques can be subsequently identified and/or refined.
- Glass eel-based seedstock is considered to offer distinct advantages over 'later stage' wild caught juveniles (eg. elvers) for stock enhancement and aquaculture, including the fact that they are of a single size and age cohort, can be to some extent selected for specific characteristics (eg. size, development stage), and can be reasonably assured to be disease-free once contained and acclimated. Financial cost-benefit and environmental sustainability imperatives will ultimately determine industry preference for the eel seedstock of choice.
- Glass eels of both shortfin and longfin species have proven to be readily adaptable to a variety of culture system designs, broadly summarised in the present study as semi-intensive, pond-based systems and intensive, tank-based systems. Although still not widely practised in Australia, simulative modelling in the present study clearly shows that the use of glass eel seedstock for semi and fully intensive production of both species can be quite profitable (as measured by standard financial indicators) under Best Practice conditions.
- As evaluated in the present study, the use of fish roe from species such as carp, *Cyprinus carpio*, warehou, *Seriolella brama*, and mackerel (Scomberomorini and Scombrini – various species) for initial weaning of Australian anguillid glass eels, appears to offer great advantages to local producers.
- As a result of the present study, species specific diet formulations, which are more nutritionally complete than presently available commercial alternatives, are now available to aquafeed companies for shortfin and longfin eels, if and when aquaculture industry demand in Australia dictates the need.

- The simulative cost-benefit analysis in this study clearly suggests that either purchasing acclimated and weaned glass eels and/or larger, pigmented elvers (collected initially as glass eels) is likely to be cost-effective, and that growing eels out to a larger size (up to 1kg) over a longer growing period (up to 24 months total) is potentially more profitable than producing smaller fish (up to 300g) over shorter production cycles (up to 15 months). Additionally, all production scenarios are sensitive to market prices, with farm-gates prices at less than $15/kg being only marginally profitable at best, and with higher prices unlikely to be realised for anything other than the larger fish.
- Given the likelihood that Australian anguillid species represent single, genetically panmictic stocks, there is also a need for a degree of coordination of management arrangements across state boundaries in Australia, and possibly even including New Zealand in the case of shortfin eels. This places an additional premium on fisheries managers in the respective state agencies having ready access to more reliable, accurate and comprehensive life history and fisheries assessment information on Australian eel resources, to enable them to better understand all aspects of the differing and very complex life history stages, from marine (oceanic and inshore) through to freshwater. Furthermore, the extensive range, complex life history, relatively long life span, age at first maturity/spawning, and associated spatial and temporal variability of recruitment in glass eels of all species dictates the need for establishment and maintenance of long term databases (> 10-20 years?) to be at all effective. The outcomes of this project provide the basis for some of these databases, particularly in relation to CPUE in the Snowy River in Victoria, which is likely to be a key monitoring site for the Victorian/south-eastern Australian extent of the shortfin eel distribution.

Future Australian eel aquaculture R&D needs to focus on industry development and specifically an analysis of the prevailing industry investment climate and associated risks, market dynamics and legislative constraints. Further, it is necessary to identify key areas of market failure as opposed to industry failure, and where appropriate to identify R&D priorities designed to address such failure. It is likely that in the process it will be necessary to prescribe broad, nationally-based resource management guidelines and to develop a suitable industry development model upon which state-based sectors may be structurally reformed if required. Many such tasks are presently being addressed as part of FRDC Project No. 2000/264 entitled *Australian Eel Aquaculture Industry Development Strategy & Associated Investment Analysis*.

This is a one year project, which was undertaken in 2000/01 by the Marine and Freshwater Resources Institute (Fisheries Victoria, Department of Natural Resources and Environment) and is presently being written up as a draft Final Report before submission to FRDC and subsequent publication

KEY WORDS

Australia, *Anguilla*, glass eels, assessment, aquaculture

1 EEL AQUACULTURE AND THE GLASS EEL FISHERY: SYNOPSIS OF GLOBAL PRODUCTION AND AUSTRALIAN DEVELOPMENTS

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1.1 GLOBAL EEL AQUACULTURE PRODUCTION

The world aquaculture production of freshwater anguillid eels (Anguillidae) currently exceeds an estimated 216,000 tonnes per annum, worth over US$915 million (FAO 2000a). This production is predominantly based on the culture of the European eel *Anguilla anguilla* in fresh and, to a lesser extent, saline waters in Europe (notably Italy, the Netherlands and Denmark) and China, and the Japanese eel, *A. japonica* in freshwaters in predominantly China, Taiwan and Japan. The bulk of anguillid production comes from Asia, particularly China, which produces both species, as well as very small quantities of the American eel, *A. rostrata*. Eel production in Europe is restricted exclusively to *A. anguilla* (FAO 2000a) (Table 1.1).

At least 18 European countries and five Asian countries contribute to the total global eel aquaculture production according to the most recent FAO data (FAO 2000a). Of these countries, Chinese eel aquaculture production has increased the most dramatically over the last decade or so (>170% between 1989-1998), and now accounts for more than 75% of the total annual world tonnage. In 1996, the farming area in China for eel was reported to be in the order of 12,700 ha, with annual production of 147,000 tonnes and a value of US$1.2 billion. Approximately 75% of this was exported, mostly to Japan, which represented about 30% of China's total fisheries exports (Jiaxin 1999). Although the reported trading value for China in 1996 far exceeds that reported by FAO (2000a) (US$265 million for 1996), it does indicate that eel aquaculture in China now effectively dominates world production and that much of this production is dependent on the demand of the Japanese market. For the period from 1989 to 1996, the average annual amount of farmed eel supplied from all countries into the Japanese market alone was > 108,000 tonnes (Jiaxin 1999). It is also noted that the recent

increase in eel production from China has been partly offset over the same period by a significant decline in production in other countries such as Taiwan and Japan (FAO 2000a).

1.1.1 Eel Culture Systems

Most of the increase in production in China has come about through the increasing intensification of farming systems and the diversification from *A. japonica* alone into *A. anguilla* as an additional species. This diversification was largely in response to the limited availability of *A. japonica* glass eel seedstock, and occurred at a time when the production levels of this species in Japan and Taiwan was in decline (Table 1.1). Likewise, the increase in European production of *A. anguilla* from farms in the Netherlands and Denmark appears to have occurred as a result of the introduction of more intensive production techniques, including the use of commercially available recirculating aquaculture systems, and has occurred at the expense of production in Italy in which more traditional, pond-based aquaculture systems are employed.

Culture techniques in Europe vary between countries, with super-intensive, controlled environment recirculating aquaculture systems preferred in countries such as Holland and Denmark, and semi-intensive pond culture under ambient conditions preferred in Italy. Asian farming systems typically prefer intensive pond culture under ambient conditions and/or semi-controlled conditions using greenhouse structures over the ponds, with the latter systems being the preferred and most productive.

The relative efficiency of the different species of glass eel for aquaculture is measured in terms of biomass produced/kg of glass eel initially stocked in the culture system. It has been recently estimated that for *A. japonica*, at approximately 6,000 pieces/kg, up to 1,200 kg of marketable (200-250 g) eels are produced for every kg of glass eels, whereas for *A. anguilla*, at approximately 3,000 pieces/kg, up to 350-400 kg of marketable eel (120-170 g) are produced (A. Kamstra, Rivo-dlo, The Netherlands, pers. comm.)

1.1.2 Cultured Eel Markets

The major market for cultured eels of both species continues to be Japan, targeted primarily by the Asian producers as both a live and processed 'Kabayaki' (roasted/grilled) product and, to a lesser extent, several European countries, targeted primarily by the European producers as both a fresh and smoked product of mostly *A. anguilla* (Gooley 1998). The majority of the recent increase in Chinese production of *A. anguilla* has been targeted at the Japanese market and has resulted in China now being also a major processing centre with a total presently of 57 Kabayaki plants established to meet this need (source: UK Glass eels website - www.glasseel.demon.co.uk).

1.2 GLASS EEL FISHERY

Although the prospects of developing artificial propagation techniques for Anguillid eels are improving, with an ongoing research and development focus in several countries (Satoh *et al.* 1992; Yu *et al.* 1993; Lokman and Young 2000; Tanaka *et al.* 2000), the eel aquaculture industry is still reliant solely on the supply of wild caught juveniles as seedstock. Indeed, glass eels specifically remain the seedstock of choice by most eel farming countries around the world. Accordingly, and notwithstanding the inherent vagaries of market supply and demand for finished product, the single greatest constraint on eel aquaculture production worldwide continues to be in relation to the supply of glass eels.

Table 1.1 Summary of global *A. anguilla* and *A. japonica* production for 1989 and 1998 (FAO 2000a).

European eel industry	**1989**		**1998**	
(A. anguilla)	**tonnes**	**US$,000**	**tonnes**	**US$,000**
Italy	3,700	39,111	3150	30,845
Netherlands	350	2,800	2510	21,335
Denmark	620	6,115	2468	24,680
Other	1,378	9858	1711	14,695
Total	**6,048**	**57,884**	**9839**	**91,555**

Asian Eel Industry	**1989**		**1998**	
(*A.japonica* - except China)	**tonnes**	**US$,000**	**tonnes**	**US$,000**
China (+ *A. anguilla*)	60,000	90,000	163,098	293, 576
Japan	39,704	460,566	21,971	314,526
Taiwan	43,008	403,538	17,241	180,079
Other	1,046	21,111	4,463	35,526
Total	**143,758**	**975,215**	**206,773**	**823,707**
Global Total (both species)	**149,806**	**1,033,099**	**216,612**	**915,262**

Not surprisingly, anguillid glass eels form the basis of important fisheries in many parts of the world. Commercial catches of *A. anguilla, A. japonica* and, to a much lesser extent *A. rostrata,* are taken annually from Europe, northern Asia and North America respectively.

1.2.1 European fishery

The supply of *A. anguilla* glass eels to the European and Asian aquaculture industries is exclusively sourced from within the natural European range of the species, with the majority of production coming from the west coasts of Portugal, Spain, France and the United Kingdom. The glass eel fishery in Europe historically has ranged from about 100 to 1,000 tonnes production per annum, the majority of which has been traditionally used directly for human consumption and, to a lesser extent, for re-stocking purposes. The use of glass eels for aquaculture seedstock in Europe is a somewhat more recent development which has gained considerable prominence over the last 10-15 years or so.

In 1924 France exported 750 tonnes of glass eels to Spain; the commercial catch including 12-15 tonnes from one short section of the Loire River (Tesch 1977). In 1976, the Loire River alone produced 770 tonnes of glass eels (Moriarty 1999). Catches of 350-500 tonnes of *A. anguilla* glass eels were reportedly taken from European waters in 1993 and 1994 (Moriarty 1996), however recruitment of *A. anguilla* glass eels has been in decline for the last 15 years (Dekker 2000), with the majority of the catch presently (conservatively estimated at > 50%) being exported to China for farming purposes. The balance is still sold to varying

degrees in Europe for direct human consumption, for restocking local waters to supplement wild fisheries production, and for use as aquaculture seedstock by European farmers. Historically, the bulk of the glass eel catch (typically > 50%, and previously estimated to be as high as 95%) was sold for direct human consumption, but the increased demand for aquaculture seedstock from China of recent years has seen a significant reduction in this trade, presumably as a result of the more lucrative financial returns to the fishers resulting from the Chinese market.

At a recent meeting of the Joint European Inland Fisheries Advisory Commission (EIFAC)/International Council for Exploration of the Sea (ICES)Working Party on Eels in Denmark (September, 1999), it was indicated that the eel fisheries throughout Europe were in decline and that recruitment of glass eels from the ocean was at a very low level. It was further suggested that these problems were mainly caused by "..overexploitation of the resource and the export of glass eel to Asia for aquacultural purposes…" (FAO 2000b). Furthermore, it has been recently reported that recruitment failure is more specifically due to decrease in escapement of mature spawning fish, also referred to as 'silvers' (EIFAC/ICES 2001). Actual glass eel harvest levels in Europe have recently decreased steadily from > 500 tonnes in 1994/95 to between 100-200 tonnes/annum in the two years from 1997/98 to 1998/99 (source: Fish Information Services International Co. Ltd – www.fis.com).

The consensus view (A. Kamstra, Rivo-dlo, The Netherlands, pers. comm.) is that any actual recruitment failure of *A. anguilla* is likely to be a result of the cumulative effect of several threatening processes within both the freshwater and oceanic stages of the eel lifecycle, viz.:

- overexploitation of glass eels and escaping spawners (returning to the sea to breed)
- loss of freshwater habitat and associated impacts of pollution, within freshwater
- effects of the endemic disease *Anguillicola*
- possible impacts of inappropriate restocking practices
- changes in oceanic currents and/or water temperatures

It has also been claimed by the European Eel Fisheries Conservation Group that the mortality rate of *A. anguilla* glass eels sold and transported to Asian producers is in the order of 70% at the point of reaching harvest weight (250g), and that about 50% mortality is incurred as a direct result of transportation problems alone (Anon 1999). This latter point is somewhat contentious and has been refuted by industry representatives (Wood 1999), but at the very least it does highlight key issues pertaining to the sustainability of the European glass eel resource and the economic viability of the associated eel aquaculture industry in Asia and Europe.

Commercial catching methods are many and varied, often limited by local licensing laws. For example, the glass eel fishers in the Severn River, England, are restricted to using hand held dipnets, whereas those in the Vilaine River, France, use boat-operated trawl nets, and in the Rio Miñho, Portugal, large stow nets, or 'hamennets' are used. In general, limited regulation of the European glass eel fishery occurs through input controls based on licensing, gear, seasonal and geographic restrictions, all of which vary from country to country. There are presently no fishing quotas or other forms of output control, although these are now under consideration (A. Kamstra, Rivo-dlo, The Netherlands, pers. comm.)

In recent years, *A. anguilla* glass eels traded in Europe have typically ranged in price between AUD$300-700/kg at a size of approximately 3,000-4,000 pieces (individual fish)/kg, which equates to a price range of about AUD$0.075-0.23/piece. For the specific period from 1996/97 to 1998/99, the average weekly glass eel price in Europe actually ranged from about AUD$150/kg to about AUD$900/kg, although for much of the time the price ranged between

AUD$300-600/kg (A. Kamstra, RIVO, pers. comm.). This price typically often fluctuates markedly from year to year subject to the inherent dynamics of the eel aquaculture market supply and demand and, to a lesser extent, natural glass eel recruitment variability.

1.2.2 Asian Fishery

The supply of *A. japonica* glass eels to the Asian aquaculture industry is sourced exclusively from within the natural range of the species, predominantly in China, Taiwan, Japan and Korea. In total, the production of *A. japonica* from Asia is thought to range from 100 to 150 tonnes per annum, although reliable data are difficult to obtain. Commercial catches of *A. japonica* were reported to be between 90-100 tonnes in 1999 (Court 1999). Ishikawa (1999) states that the commercial catch of *A. japonica* in Japan ranged from around 10 tonnes in 1989 to only 4 tonnes in 1997, but was as high as 32 tonnes in 1999 (Court 1999).

The glass eel harvest from China alone averaged > 40 tonnes/annum during the period from 1990 to 1997 (range 21.3-51.9 tonne/annum), with annual production varying by up to almost 60% over any one twelve month period (Jiaxin 1999). In 1996, > 51 tonnes of *A. japonica* glass eels were harvested in mainland China for aquaculture, of which 28-30 tonnes were utilised by farmers. An additional 140 tonnes of *A. anguilla* glass eels were imported from Europe in the same year (Jiaxin 1999) in order to supplement supplies of the more limited and expensive *A. japonica*.

There are effectively no formal input or output controls on glass eel fishing in Asia based on biological sustainability alone, and the reported variation in annual harvest is thought to be primarily the result of highly variable annual recruitment levels within the natural range of the species. However, in China at least, the annual glass eel harvest is also known to be regulated to some extent by Government and industry imposed quotas designed to avoid over production and associated reduced prices in established export markets such as Japan (Gooley 1999). National quotas for glass eel in China are reported to have ranged from 70 to 150 tonnes in recent years (source: UK Glass eels website - www.glasseel.demon.co.uk).

Overall, despite periodic, often unpredictable peaks in production, the trend in the harvest of *A. japonica* glass eels appears to indicate a steady decline in recent years, probably for similar reasons to that expressed for *A. anguilla* ie. a combination of environmental degradation and overfishing.

A. japonica glass eels in the major Asian markets are claimed to have fetched in excess of $AUD10,000/kg for 5-6,000 pieces/kg in recent times. In China for example, the *A. japonica* seed price in the 1990's was approximately AUD$4.50/piece, peaking at about AUD$6.00/piece in 1996 due to a poor wild catch and widespread shortage of supply. At this time *A. anguilla* was introduced into China also as a means of alleviating seedstock supply problems for the eel aquaculture industry. More recently, glass eel prices for *A. japonica* have stabilised at about AUD$0.60-1.40/piece (and about AUD$0.225/piece for *A. anguilla*) (Gooley 1999; Jiaxin, YSFRI, pers. comm.; UK Glass eels website - www.glasseel.demon.co.uk)). The price differential reflects the local industry preference for *A. japonica* seedstock based on the better aquaculture performance and broader market acceptance of this species in Asia (Gooley 1999).

As in Europe, catching methods for glass eels in Asia are varied. In Taiwan and Japan, the Japanese glass eel net, or 'Hell' net was commonly used however, because of its highly efficient catching ability, commercial glass eel fishers in Japan and Taiwan are now generally restricted to the use of hand-held dip nets. In China, fine mesh drift nets, usually several

hundred metres in length, are drawn between small vessels set into the prevailing flow in larger rivers such as the Yangtze River to collect *A. japonica* glass eels.

1.2.3 Other anguillid species

The American eel, *A. rostrata* was first introduced to Asia, via Taiwan, from North America in 1993, followed in 1996 by an introduction into mainland China (Jiaxin 1999). Asian eel production presently has a small but growing contribution from this species, estimated at <10 tonnes per annum. Commercial catches of *A. rostrata* from Canada ranged from 1.5-4.1 tonnes between 1994 and 1998 (Jessop 1999) and catches of *A. rostrata* are reported to have ranged between 3.3-7.5 tonnes in the United States (ASMFC 2000). In the USA and Canada, the Japanese glass eel net is commonly used, as are hand held-dipnets and elver traps (Sheldon 1974; Jessop 1998).

In New Zealand a commercial glass eel fishery for *A. australis* operated between 1970 and 1974 in the Waikato River to supply local and Japanese eel farms. Total annual catches ranged from 0.7 tonnes- 6.4 tonnes (Jellyman 1979). Presently there is no commercial fishery for glass eel in New Zealand, however there is renewed interest by Maori groups in accessing glass eels under Maori customary fishing rights.

1.2.4 Australian Eel Production

Australian eel production is based on two endemic species, the shortfin eel, *A. australis*, and the longfin eel, *A. reinhardtii*. Total annual production is in the order of 400-750 tonnes per annum, worth AUD$4-6.5million, the vast majority of which comes from wild fishery harvest, and much of which historically comes from stock enhanced wild fisheries (also referred to by industry as 'cultured eels'). The latter is currently based on the harvest of natural stocks of juvenile *A. australis* elvers and sub-adults. These eels, also referred to as 'restock', are primarily sourced from natural populations in Tasmania and Victoria, and then stocked into selected public and private waterways for on-growing under natural, ambient conditions to a marketable size (Gooley 1998; Gooley *et al.* 1999). A summary of present annual Australian eel production on a state by state basis is provided in Table 1.2 for both wild capture and aquaculture sectors.

By comparison to other forms of production, the intensive farming of *A. australis* and *A. reinhardtii* is a relatively recent development within Australia, with an estimated maximum production of 25 tonnes of both species since 1998. Aquaculture production methods within Australia presently vary from semi-intensive, pond culture under ambient conditions at more northerly climes in northern NSW and Queensland, to super-intensive production under controlled environment in tank-based, recirculation aquaculture systems in Victoria (Gooley 1998). In most cases, the seedstock of choice for Australian producers has been glass eels, although trials have also been undertaken using later developmental stages, including elvers (Gooley 1998; Gooley *et al.* 1999). Aquaculture production, husbandry, post-harvest requirements and markets for Australian eels are described in Gooley (1998). Existing and potential markets for wild and farmed Australian eels are also summarised in Table 1.3.

Table 1.2 Australian Annual Eel Production (based on estimates for 1999/2000 or most recent available data); LF, longfin eel; SF, shortfin eel; na, not available.

		Wild capture		Cultured	
		Annual tonnage (T)	**Value ($,000's)**	**Annual tonnage (T)**	**Value ($,000's)**
QLD[1]	LF*	42.3	na	21.5	235
	SF	-	-	-	-
NSW[2]	LF	av. 150 (range 100-400)	na	2	16.5
	SF	-	-	0.4	1
VIC[2]	LF	25.9	518	-	-
	SF**	60.3	482	42.2	338
TAS[2]	LF	-	-	-	-
	SF	44.6	178	-	-

***** likely to be predominantly longfin eel, although may include some shortfin
****** cultured shortfin eel in Victoria predominantly from stock enhanced waters

Source:

1. Lobegeiger, R. (2001) Report to Farmers. Queensland Aquaculture Production Survey 1999-2000, QDPI.

2. Lachlan McKinnon, MAFRI, unpublished data

Table 1.3 Summary of existing and potential markets for wild and farmed Australian eels (from Gooley 1998).

Product (export, unless otherwise stated)	**Wholesale Price (FOB) AUD$/kg**
Large longfin (>2-15kg), live (to Asia)	***7-17***
Large shortfin (>1kg), live (to Asia)	***12.5***
Large shortfin (>1kg), whole, chilled/frozen	***8-12***
Large shortfin (>1kg), gutted, skin on, frozen	***12-15***
Kabayaki (150-200g; whole, live/frozen)	***estimates 10-18; 25-30****
Processed Kabayaki	***estimate >50****
Processed/smoked whole/gutted large eels - export	***estimate >50****
Processed/smoked whole/gutted large eels - local	***12***
Restock (5-10g eels for stock enhancement) - local	***estimate $350-750****

* estimates based on industry advice

In recognition of the market potential within Asia for farmed eel products, and with an increasing trend towards intensification of production for what is otherwise a valuable and limited natural resource, there is an increasing premium being placed on juvenile eel resources within Australia, particularly for glass eels. The potential exists for significantly increasing the overall production of the Australian eel industry through the sustainable utilisation of the glass eel resource for both *A. australis* and *A. reinhardtii*. This will require the adoption of intensive farming systems for grow-out of such seedstock to produce both marketable and restock eels for the aquaculture and wild fishery sectors respectively (Gooley 1998; Gooley *et al.* 1999).

1.3 RECENT AUSTRALIAN EEL AQUACULTURE AND GLASS EEL R&D

A recently completed Fisheries R&D Corporation project (No. 94/067)(1994/95-1996/97), undertaken by the Victorian Marine and Freshwater Resources Institute, in collaboration with the Inland Fisheries Service Tasmania, focussed primarily on assessing the potential for the commercial harvest of *A. australis* glass eels in Victorian and Tasmanian waters (Gooley *et al.* 1999). Some limited investigations were also undertaken in southern NSW. This work, completed in mid-1997, identified important glass eel waters within the study area, key environmental and lunar-tidal cues triggering initial glass eel invasion into estuaries and appropriate methods for glass eel harvesting, and established a short-term database of catch rate indices for management purposes. The spatial and temporal dimensions of glass eel invasions in south-east Australia were better elucidated during the project, and were found to be of a broader scale than previously thought. It is therefore apparent that a larger scale, more comprehensive and detailed stock assessment is warranted over a broader geographic basis and over a longer timeframe. This will provide resource managers and industry with a more reliable basis upon which to allocate what is otherwise a limited and increasingly valuable natural resource. However, there has been no systematic assessment of *A reinhardtii* glass eel stocks to date, and there is little understanding of the dynamics of interactions between the two species where they cohabit. This is particularly so in relation to the respective mechanisms of the invasion and migration phases.

Preliminary culture techniques and handling, transport and acclimation methods were also developed during this project for *A. australis* glass eels. Aspects of intensive culture development included the evaluation of different weaning diets and rearing temperatures, a comparison between glass eel and elver production, and tank and pond culture methods at different stocking densities and feed rates.

1.3.1 The Present Study

Due to the demand for glass eel seedstock worldwide, the apparent decline of these stocks and their consequent high value, it is expected that increasing pressure will be placed on Australian stocks of glass eels, from both local overseas producers. It is therefore critical that both *A. australis* and *A. reinhardtii* glass eel resources are identified and quantified over a wider spatial and temporal scale so that appropriate management can be determined on a national basis.

The establishment of key glass eel waters for both species, modelling of the major environmental, climatic and oceanographic migration stimuli, the development of sustainable harvesting methods and an improved understanding of the population biology are critical for

the appropriate management of Australian glass eel stocks. This project identifies the need for coordinated research over the entire known range of both species (Queensland, NSW, Victoria and Tasmania), hence the collaborative approach taken between each of the relevant state agencies.

There is also a need to further develop the culture technology for *A. australis* and to adapt and trial the same technology for *A. reinhardtii*. One area of specific need is to define nutritional requirements of both species, and to develop and test artificial diets for intensive production.

Fisheries R&D Corporation, Fisheries Victoria, Inland Fisheries Service Tasmania, NSW Fisheries and Queensland Department of Primary Industries have jointly funded the present study. The Project has been managed and implemented by the Marine and Freshwater Resources Institute, Victoria, in collaboration with each of the above mentioned State agencies and Deakin University, Victoria. The Project commenced in June, 1997 for three years (1997/98-99/00).

The aquaculture component was further supplemented by an additional FRDC Project No. 99/330 *Validation of longfin eel aquaculture potential*, specifically (as the title implies) to provide additional information on the suitability and needs of intensive culture techniques for longfin eels. This work was carried out by the Principal Investigator Dr Clive Jones of the Queensland Department of Primary Industries, and is included as part of an all inclusive summary (Project No. 97/312 and No. 99/330) for longfin eel aquaculture under Chapter 5 in this report.

1.3.1.1 Project Objectives

1. To characterise migrations and assess stocks of glass eels in coastal catchments of southern Queensland, NSW, Victoria and Tasmania to enable evaluation of the potential of seedstock supply for Australian eel aquaculture and wild fisheries.
2. To develop pond and tank culture technology for commercial Australian eel production, with an emphasis on the use of eastern Australian glass eel seedstock.
3. To contribute to the development of eel aquaculture industry development and fisheries management plans through the provision of relevant information in the form of reports, publications, seminars, newsletters and workshops.

1.3.1.2 Project Methods

The project has been effectively managed as two components, each with a series of specific strategies designed to address the relevant project objectives, viz.

(i) Assessment component

- Collate existing information for *A. australis* and *A. reinhardtii* glass eels and establish a long term monitoring database of distribution and catch statistics for eastern Australia.
- Develop indices of relative abundance/catch rates for glass eels within selected river systems over the full range of the study area and over a three year time frame.
- Validate and further refine a preliminary model for Australian glass eel recruitment which factors in spatial and temporal variability and includes key environmental gradients at both the estuarine and oceanic scale along the east Australian coast.
- Investigate and further refine glass eel fishing techniques and equipment, including options for minimising bycatch and maximising survival of glass eels.
- Investigate genetic discrimination of eastern Australian and New Zealand glass eel stocks to determine the most appropriate management units.

(ii) Aquaculture component

- Investigate optimal production parameters and associated husbandry requirements for short and long-finned glass eels and subsequent developmental stages under both pond and tank culture conditions.
- Undertake a pilot commercial scale grow-out of short and long-finned glass eels under both tank and pond culture conditions.
- Develop nursery phase tank and pond-based culture strategies and technologies
- Undertake a desktop cost-benefit analysis of available commercial aquaculture options, including a comparison of tank and pond culture options as stand-alone and/or combined systems.

This report summaries the investigations and key findings of the present study with each of the two main components addressed by various specific chapters. At the end of the report the broad management implications are summarised and discussed in terms of flow of benefits to the Australian industry and future directions of R & D and industry development. It should be noted that for technical reasons the outcomes of the study into genetic discrimination of Australian and New Zealand glass eel stocks (referred to above) is not included in this document and will be reported separately at a later date.

1.4 REFERENCES

Anon. (1999). Save our eels! - call as European stock crisis threatens ongrowing worldwide. *Fish Farming International* 26(Feb.): 1-2.

ASMFC. (2000). *Interstate Fishery Management Plan for American Eel*. Atlantic States Marine Fisheries Commission. 79 pp.

Court, B. (1999). Eel Market Report. V.

Dekker, W. (2000). The fractal geometry of the European eel stock. *ICES Journal of Marine Sciences* 57: 109-121.

EIFAC/ICES. (2001). *Report of the EIFAC/ICES Working Group on Eels*. ICES CM 2002/ACFM:03. International Council for the Exploration of the Sea. Copenhagen. 59 pp.

FAO. (2000a). *FISHSTAT Plus Version 2.3*. FAO Fisheries Department Statistical Databases and Software. www.fao.org/fi/stat.

FAO. (2000b). *Report of the twenty-first session of the European Inland Fisheries Advisory Commission. Budapest, Hungary, 1-7 June 2000.* FAO Fisheries Report No. 625. FAO. Rome. 33 pp.

Gooley, G. (1999). *Eel Breeding Research Mission to the Freshwater Fisheries Research Centre, Wuxi, China 19-29 March, 1999. Final Report*. Marine and Freshwater Resources Institute, Department of Natural Resources and Environment. Alexandra, Victoria. 31 pp.

Gooley, G.J. (1998). Eels. In: *The New Rural Industries - A Handbook for Farmers and Investors* (ed. by K. Hyde), pp 101-107. Rural Industries Research and Development Corporation, Canberra.

Gooley, G.J., McKinnon, L.J., Ingram, B.A., Larkin, B., Collins, R.O. and de Silva, S.S. (1999). *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production. Final Report FRDC Project No 94/067*. Marine and Freshwater Resources Institute, Alexandra, Australia. 124 pp.

Ishikawa, S. (1999). Regional Overview: Japan. In: *Strategies and Techniques for Sampling Adult Anguillid Eels. Vol. 5* (ed. by T. Walford and B. Pease), pp 29-31. NSW Fisheries Research Institute, Cronulla, NSW.

Jellyman, D.J. (1979). Upstream migration of glass-eels (*Anguilla*- spp.) in the Waikato River. *New Zealand Journal of Marine and Freshwater Research* 13(1): 13-22.

Jessop, B. (1999). Size, and exploitation rate by dip net fishery, of the run of American eel (*Anguilla rostrata*) elvers in the East River, Chester, Nova Scotia. In: *ICES/EIFAC Working Group on Eel*., Silkeborg, Denmark.

Jessop, B.M. (1998). The management of, and fishery for, American eel elvers in the maritime provinces, Canada. *Bulletin Francais de la Peche et de la Pisciculture* 349: 103-116.

Jiaxin, C. (1999). China's eel culture industry. *Eurofish* 3/99: 64-67.

Lokman, P.M. and Young, G. (2000). Induced spawning and early ontogeny of New Zealand freshwater eels (*Anguilla dieffenbachii* and *A. australis*). *New Zealand Journal of Marine & Freshwater Research* 34(1): 135-145.

Moriarty, C. (1996). The European eel fishery in 1993 and 1994. *Fisheries Bulletin* 14: 1-52.

Moriarty, C. (1999). Glass eel and elver catches 1996-1999. In: *EIFAC/ICES Working Group on Eel*., Silkeborg, Denmark.

Satoh, H., Yamamori, K. and Hibiya, T. (1992). Induced spawning of the Japanese eel. *Nippon Suisan Gakkaishi Bull. Jap. Soc. Sci. Fish.* 58(5): 825-832.

Sheldon, W.W. (1974). *Elvers in Maine. Techniques of Locating, Catching and Holding.* Department of Marine Resources, Maine. 25 pp.

Tanaka, H., Ohta, H. and Kagawa, H. (2000). Development of techniques for artificial induction of maturation and rearing larvae of Japanese eel. *Nippon Suisan Gakkaishi* 66(4): 623-626.

Tesch, F.-W. (1977). *The Eel. Biology and Management of Anguillid Eels*. Chapman and Hall, London. 434 pp.

Wood, P. (1999). What crisis? *Fish Farming International* 26 March 1999: 11.

Yu, T.-C., Tsai, C.-L., Tsai, Y.-S. and Lai, J.-Y. (1993). Induced breeding of Japanese eels, *Anguilla japonica*. *J. Taiwan Fish. Res.* 1(1): 27-34.

2 ASSESSMENT OF EASTERN AUSTRALIAN *ANGUILLA AUSTRALIS* AND *A. REINHARDTII* GLASS EEL STOCKS

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McKinnon, L., Gasior, R., Collins, A., Pease, B. and Ruwald, F. (2002). Assessment of eastern Australian *Anguilla australis* and *A. reinhardtii* glass eel stocks. In: *Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture* (ed. G.J. Gooley and B.A. Ingram), pp 13-82. Final Report to Fisheries Research and Development Corporation (Project No. 97/312 and No. 99/330). Marine and Freshwater Resources Institute, Alexandra, Victoria, Australia.

CONTENTS

2.1 INTRODUCTION

2.1.1 Early Life History

The life-history of all anguillid eel species is both similar and relatively complex. Although thought to spend most of its life in freshwaters, the sexually mature adult eel makes an extensive journey seaward to spawn. For *Anguilla anguilla* (European eel) and *A. rostrata* (American eel), spawning takes place in the Sargasso Sea, up to 6000km from the European coast and 2-4000km from the North American coast respectively (Tesch 1977). The Japanese eel, *A. japonica*, spawns off the north-east coast of The Philippines near the Mariana Islands, some 3000km from where it is found in the freshwaters of northern Asia (Tsukamoto 1992). Conversely, there is some conjecture over the location of the spawning areas for *A. australis* and *A. reinhardtii*. Schmidt (1925) suggested the spawning area of *A. australis* is in the Coral Sea, in the vicinity of New Caledonia. Castle (1963) suggested that the spawning ground for *A. australis* and *A. reinhardtii* lies between Fiji and Tahiti, the centre of which is 18^{o}S and 170^{o}W (Tesch 1977). Aoyama *et al.* (1999) also suggest this is the area in which *A. australis* spawns, while Jellyman (1987) proposed that the spawning area of *A. australis* is in the vicinity of 5-15^{o}S and 150-170^{o}W, south-east of the Solomon Islands. The evidence for the proposed locations of the spawning ground of these species is sparse. A total of 79 larval specimens (leptocephali) of *Anguilla* spp. have been recorded in the South Pacific region

(Jespersen 1942; Castle 1963; Aoyama *et al.* 1999). Of these, 13 leptocephali were identified as *A. australis* (Jespersen 1942; Castle 1963; Aoyama *et al.* 1999), and 13 confirmed as *A. reinhardtii* (Jespersen 1942; Aoyama *et al.* 1999). These leptocephali were collected between 10^{o} 24' S and 24^{o} 46' S, and 146^{o} 27' E and 147^{o} 51' W (Jespersen 1942; Castle 1963; Aoyama *et al.* 1999). It appears that the spawning area of *A. australis* is in the order of 2000-5000km from much of its freshwater habitats in Australia and New Zealand (Jellyman 1987; Aoyama *et al.* 1999), however a spawning area for *A. reinhardtii* has not yet been proposed.

Ocean currents carry the leptocephali to their various destinations. *A. rostrata* leptocephali are transported by the North Equatorial Current and Gulf Stream to the continental shelf of North America, and the North Atlantic Current transports *A. anguilla* leptocephali to Europe (Wang and Tzeng 2000). The North Equatorial and Kuroshio Currents are the proposed modes of transport of *A. japonica* (Kimura *et al.* 1994). The South Equatorial and East Australian Currents are thought to transport both *A. australis* and *A. reinhardtii* from the spawning locality to the Australian continent (Jellyman 1987; Aoyama *et al.* 1999). The transport of *A. australis* to New Zealand is also thought to be facilitated by the East Australian Current and the eastward zonal flow of the Tasman Front (Aoyama *et al.* 1999; Jellyman *et al.* 1999), while the transport of *A. dieffenbachii* to New Zealand is considered to be facilitated by the Trade Wind Drift (Sloane 1984) and the south-west flowing portion of the South Equatorial Current (Jellyman 1987; Jellyman *et al.* 1999).

The recent description of *A. reinhardtii* from northern New Zealand (Jellyman *et al.* 1996), and the recruitment of at least eight consecutive year classes of this species, have posed some interesting questions regarding the transport mechanisms of anguillid eels (McDowall *et al.* 1998). Reasons for the recent, but sustained recruitment of *A. reinhardtii* to New Zealand waters may include changes in oceanic currents which may be related to the El Niño whereby *A. reinhardtii* glass eels became entrained within anticyclonic eddies which break off from the East Australian Current and migrate across the Tasman Sea to the west coast of New Zealand (Jellyman *et al.* 1996; McDowall *et al.* 1998). The most probable reason for the occurrence of *A. reinhardtii* however, is transoceanic dispersal, probably from subtropical oceanic spawning grounds north of New Zealand (McDowall *et al.* 1998).

As leptocephali, eels feed and grow, but in the vicinity of the continental shelf they commence metamorphosis into the glass eel phase and are thought to temporarily cease feeding (Deelder 1970; Tesch 1977). Stomachs of *A. australis* glass eels collected from estuaries in south-eastern Australia at pigmentation stages VA and VB (Strubberg 1913) were found to be empty (Allan 1995) supporting the idea that glass eels do not feed prior to their arrival at estuaries. Following metamorphosis, glass eels migrate toward coastal waters utilising various modes of transport, including active swimming and advection (McCleave 1993; Jessop 1998). It is not clear whether leptocephali are also transported in this manner (McCleave 1996). Glass eels change from a diel rhythm to a tidal rhythm of vertical migration and selectively use tidal stream transport for migration towards and within estuaries (McCleave and Kleckner 1982). A schematic summary of the life history stages of anguillid eels is provided in Figure 2.1.

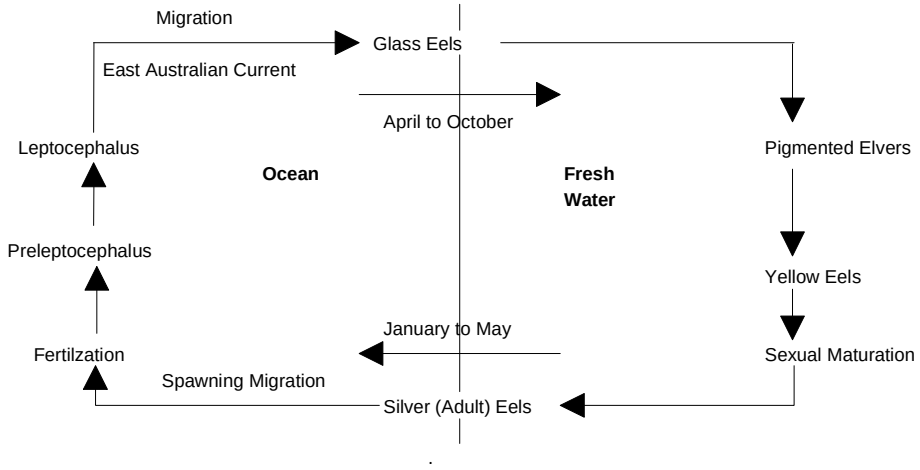


Figure 2.1 Life cycle of *Anguilla australis* eels. After Gooley *et al.* (1999).

2.1.2 Age and Growth

Age at metamorphosis from leptocephalus to glass eel varies considerably from species to species, largely in relation to distance travelled from spawning grounds (Tzeng 1990; Guerault *et al.* 1992). Growth increments have been found to be formed on a daily basis in *A. japonica, A. rostrata* and *A. celebesensis* glass eels (Umezawa and Tsukamoto 1991; Martin 1995; Arai *et al.* 2000). Age estimates of leptocephali and glass eels are therefore often made by counting such daily growth rings in otoliths (Tzeng 1990; Tzeng and Tsai 1992; Cheng and Tzeng 1996; Wang and Tzeng 1998; Arai *et al.* 1999a; Arai *et al.* 1999b). However, the presence of a diffuse zone in the otolith at the point of metamorphosis (Cheng and Tzeng 1996; Wang and Tzeng 1998; Wang and Tzeng 2000) is suggested to render any daily growth rings in this zone uncountable, and thus daily age determination is argued to be not possible (Antunes and Tesch 1997). In *A. japonica*, a relationship between otolith radius and the number of increments has been established which has been used to estimate age when otolith increments are not discernible (Otake *et al.* 1994). Otherwise, daily age is calculated from otolith growth rate and otolith radius (Cheng and Tzeng 1996; Wang and Tzeng 1998; Wang and Tzeng 2000). The period of metamorphosis from the leptocephalus to the glass eel is thought to be indicated by a marked increase in otolith increment width (Tzeng 1990; Otake *et al.* 1994; Arai *et al.* 1997; Arai *et al.* 1999a; Arai *et al.* 1999b). Likewise, strontium:calcium (Sr/Ca) ratios reach a maximum during this period and subsequently decrease rapidly (Otake *et al.* 1994; Tzeng and Tsai 1994; Tzeng 1996; Arai *et al.* 1999a; Arai *et al.* 1999b).

Age at metamorphosis of *A. japonica* is estimated to be 116-138 days, with time from metamorphosis to arrival at estuaries in Taiwan, China and Japan estimated at between 32-45 days (Cheng and Tzeng 1996). The mean age at metamorphosis of *A. rostrata* is estimated to be 189-214 days, with time from metamorphosis to arrival at estuaries in Haiti, the Atlantic coast of the USA and Canada between 32-80 days (Wang and Tzeng 1998; Wang and Tzeng 2000). The duration of metamorphosis is thought to be about one month in *A. anguilla* and *A. rostrata* (Wang and Tzeng 2000) while in *A. japonica* metamorphosis is thought to last for only about 12 days (Tsukamoto and Umezawa 1994). The age at metamorphosis of *A. anguilla* has been estimated at around 350 days, and about 450 days at estuarine arrival (Wang and Tzeng 2000). Tesch (1998) suggests that age determination of eel larvae is best achieved using length-frequency distribution. Using this information collected from different seasons and different areas of the North Atlantic, Tesch (1998) proposes that *A. anguilla* and *A. rostrata* glass eels are in the order of 2-3 years old before entering estuaries. Although

unvalidated, age at the commencement of metamorphosis of *A. australis* has been estimated at between 138-198 days, with age at recruitment to the estuary between 186-239 days for *A. australis* glass eels from the Albert River, Queensland by counting putative daily growth increments (Arai *et al.* 1999b). Prior to the present study, there has been no published age data for *A. reinhardtii* glass eels.

2.1.3 Estuarine Invasion and Freshwater Migration of Glass Eels

The mechanisms of invasion and migration of glass eels of the genus *Anguilla* are well documented, and commercial glass eel fisheries around the world use such information to target peak periods of glass eel movement. Typically, the initial invasion by anguillid glass eels, including *A. australis*, into estuaries and their subsequent active upstream migration into freshwater habitats is facilitated by tidal movement, using flood tides and generally at night during new and full moon phases (Creutzberg 1961; Deelder 1970; Jellyman 1977a; Tesch 1977; Jellyman 1979; Beumer and Harrington 1980; McCleave and Kleckner 1982; Gascuel 1986; McCleave *et al.* 1987; McCleave and Wippelhauser 1987; McKinnon and Gooley 1998). Specific observations on the invasion and migration of *A. australis* glass eels in Australian estuaries have been reported (Beumer and Harrington 1980; Beumer 1983b, 1983a; Sloane 1984; Beumer and Sloane 1990), including reference to distribution and abundance and suitability for aquaculture (McKinnon and Gooley 1998; Gooley *et al.* 1999).

For the purposes of this report, glass eel invasion is defined as the migration of unpigmented (Stage VA-VB, Strubberg 1913) glass eels into and within the estuary, including flow-assisted migration via tidal bore. This is distinct from the active swimming phase of upstream glass eel and pigmented elver migration, which is generally considered to commence at or near the upper limit of the tidal zone (Jellyman 1979; Sloane 1984; Gascuel 1986). A summarised description of terms used in the present study is provided in Table 2.1.

Table 2.1 Descriptions of developmental stages of Anguillid eels.

Developmental Stage	Description
Leptocephalus	Larval form. Narrow, deep-bodied, shaped like a willow leaf
Glass eel	All stages from metamorphosed larva to pigmented elver (Stages VA-VIB). Transparent juvenile found between region of continental shelf and freshwater interface
Pigmented elver	Fully pigmented juvenile, typically found in freshwater. Less than 30cm long. Larger elvers often referred to as ‘snigs’
Yellow eel	Eel has completed its migratory phase. Generally over 30cm long
Silver eel	Adult eel migrating to spawning grounds

2.1.4 Invasion and Migration Cues

Several environmental cues are thought to influence the invasion and migration patterns of anguillid glass eels. Tosi *et al.* (1990) concluded that salinity is the most important factor directing *A. anguilla* glass eels toward fresh water. Tongiorgi *et al.* (1986) demonstrated that temperature, although not the sole cue, is an important factor in glass eel orientation as thermal gradients between fresh and sea water often exist, the direction of which depends on latitude. Chen *et al.* (1994) showed that a direct relationship exists between catches of *A.*

japonica glass eels and rainfall, which consequently results in an indirect relationship between sea water temperature and glass eel abundance in the commercial catch. However, the effect of rainfall on other environmental variables, such as decreased salinity, increased terrestrial runoff and increased flow, is also thought to confound the specific response of glass eels to temperature change (Chen *et al.* 1994). Domingos (1992) demonstrated that glass eel abundance is favoured by high river flow and that rainfall increases the ascent of glass eels, although it was noted that heavy rainfall can have a negative effect on migration by producing river flows which are too high for successful upstream migration.

It is considered that natural fresh water contains organic chemoattractants that act as cues for *A. anguilla* glass eels at sea to locate estuaries (Creutzberg 1961). Such chemoattractants are thought to originate largely from decaying vegetation (Sorensen 1986), and from soil as chemical compounds which produce odours similar to that of geosmin (Sola 1995). The attraction of *A. anguilla* glass eels to organic chemicals has been found to be related to decreasing salinity (Sola and Tongiorgi 1996). Lunar phase, in terms of light level, is thought to also influence the migration of glass eels (de Casamajor *et al.* 1996) with greatest commercial catches occurring during new moon periods when light level is low. It was also noted by de Casamajor *et al.* (1996) that light has an increasingly repellent effect on glass eels as pigmentation increases.

Glass eel invasion and migration in estuaries also appears to show a relationship with lunar phase, in terms of tide height, with many commercial glass eel fisheries operating only around new and full moon periods (eg. Antunes 1994). This is thought to be due to the effect of lunar phase on tidal magnitude, with the higher spring tides occurring at new moon and full moon (Jellyman 1979). McKinnon and Gooley (1998) found that low (<10,000 μS/cm) electrical conductivity, medium (10-14^{o}C) water temperature and high (>0m AHD) tide height showed significant correlation with abundance of *A. australis* glass eels, measured as catch per unit effort (CPUE), but lunar phase (as moon age in days) did not. Further investigation by Gooley *et al.* (1999) suggested that many environmental factors can correlate with *A. australis* glass eel invasion and migration in estuaries in any given year, and that time of year, or season, may dictate the degree of abundance of glass eels. It has been suggested that water temperature may be useful in determining the initial invasion phase of *A. australis* glass eels, and that significant invasions of glass eels may occur in estuaries which have recently experienced high river flows at certain times of the year (Gooley *et al.* 1999).

2.1.5 Pigmentation Stages and Length/Weight Relationship

The term 'glass eel' refers to the transparent nature of the post-larval juvenile, and is due to the lack of sub-epidermal pigmentation. Progress of migration and associated physiological development can be measured by the rate of change of pigmentation seen in glass eels (Tesch 1977). The development of pigment enables the classification of different ontogenetic stages in the eel (Tesch 1977), in particular, throughout the larval/glass eel/elver stages (Deelder 1970). Strubberg (1913) developed a pigmentation classification table for *A. anguilla* which is still widely used (see Table 2.6) and which can be used to describe the development of pigment in *A. australis* (Jellyman 1977a) during glass eel invasion and migration.

Strubberg (1913) found that temperature is important in pigmentation development of *A. anguilla* and, as pigmentation progresses, a concomitant reduction in length and weight occurs (Deelder 1970; Tesch 1977; Guerault *et al.* 1992) until Stage VIAIII2 (Tesch 1977). Length and weight reduction and a decrease in condition have also been found for pigmenting *A. australis* glass eels (Jellyman 1977a; Sloane 1984) and for *A. rostrata* (Jessop 1998). Sloane (1984) found that mean length of *A. australis* glass eels decreased from Stage VB to

Stage VIAIII, and Jellyman (1979) found that the mean length of *A. australis* glass eels at Stage VIAIII was always greater than that at Stage VIAII, suggesting growth commences before Stage VIAIII in *A. australis*. Gooley *et al.* (1999) found that pigmentation in *A. australis* glass eels progressed over time, however a strong correlation between pigmentation stage and length and weight was not observed. There is some evidence to suggest that *A. anguilla* glass eels up to Stage VIAIII2 do not feed, but may commence feeding at Stage VIAIV1 in the wild (Tesch 1977). Stomachs of *A. australis* glass eels at pigmentation stages VA and VB have been found to be empty (Allan 1995) supporting the idea that unpigmented glass eels do not feed prior to their arrival at estuaries.

A. australis glass eels increase in pigmentation stage as the season progresses (Jellyman 1977a, 1979; Sloane 1984; Gooley *et al.* 1999) and glass eels at the estuary mouth are less pigmented than those found further upstream (Sloane 1984). Early studies of *A. australis* and *A. reinhardtii* suggested that pigmentation of glass eels was induced on contact with fresh water (Cairns 1941) but it has since been determined that pigmentation of glass eels proceeds at equal rates in seawater and freshwater (Jellyman 1977a). As such, pigmentation stage of invading glass eels thus would reflect the length of post-metamorphic sea life, and therefore late season glass eels are often more pigmented and also smaller than early season glass eels (Jellyman 1977a). Glass eels as early as Stage VA have been recorded previously in Victoria (Beumer and Sloane 1990; Gooley *et al.* 1999) but Stage VB is the earliest pigmentation stage previously reported for *A. australis* in Tasmania (Sloane 1984) and New Zealand (Jellyman 1977a). No Stage VA glass eels were reported by Gooley *et al.* (1999) from Tasmania in their recent study of glass eel resources in south-eastern Australia. Stage VA glass eels have been recorded in NSW and Queensland (Beumer and Sloane 1990; Russell 1995; Gooley *et al.* 1999).

In Tasmania, Stage VB glass eels in the north-east of the State had higher condition (K) factors than in other parts of the State, and were heavier than glass eels at other pigmentation stages (Sloane 1984). Waters nearer the region of the onset of metamorphosis from the leptocephalus to the glass eel acquire glass eels earlier and in best condition (Sloane 1984). Gooley *et al.* (1999) found that an overall reduction in size and condition occurs in *A. australis* glass eels with time in any given season, and hypothesised that, at a given time, *A. australis* glass eels in Australia are smaller in the north, close to the spawning area, and larger in the south, further from the spawning area, while at a given location, larger glass eels arrive earlier and smaller glass eels arrive later. An inverse correlation between age in days and mean daily growth rate of *A. japonica* glass eels indicates that fast growing leptocephali reach estuarine habitats at a younger age than slow growing larvae (Tzeng 1990). In *A. anguilla*, the longest glass eels arrive earlier and are older than the smaller glass eels, suggesting that the size of a glass eel entering the estuary is determined by the size of the former leptocephalus at metamorphosis (Guerault *et al.* 1992). In *A. rostrata* glass eels, a seasonal decline in length, weight and condition occurs (Jessop 1998). The decline in weight reflects a decline in condition, and the seasonal decline in length is thought to be explained by larger glass eels arriving earlier and smaller glass eels arriving later (Jessop 1998; Gooley *et al.* 1999). Spatial differences in mean lengths of *A. rostrata* glass eels are thought to reflect the length distributions of leptocephali offshore, with length of glass eels further from the spawning area greater than that of glass eels closer to the spawning area (Jessop 1998). However Wang and Tzeng (1998) suggested that geographic variation in *A. rostrata* glass eel length was due to duration of the glass eel phase rather than the timing of metamorphosis, and that glass eel length was correlated with duration of post metamorphic sea life, but not with age at metamorphosis. Jessop (1998) suggests that the seasonal decline in glass eel weight can have an economic impact as glass eels may be sold by mass or by piece count.

2.1.6 Present Study

The invasion of Australian shortfin (*Anguilla australis*) and longfin (*A. reinhardtii*) glass eels into eastern Australian estuaries was investigated for the purpose of further characterising the environmental/climatic cues associated with such invasions and subsequent migration of glass eels, and to define the status of glass eel resources for both commercially important species. Establishment of key glass eel waters for both longfin and shortfin eels, modelling of key environmental, climatic and oceanic migration stimuli, development of sustainable harvesting methods and an improved understanding of the population biology are critical for the appropriate management of Australian glass eel stocks.

The primary objective of the Assessment Component of the project was to:

> *characterise migrations and assess stocks of glass eels in coastal catchments of southern Queensland, NSW, Victoria and Tasmania to enable evaluation of the potential of seedstock supply for Australian aquaculture*.

The project strategy was to:

- Collate existing information for shortfin and longfin glass eels and establish a long term monitoring database of distribution and catch statistics for eastern Australia.
- Develop indices of relative abundance/catch rate for glass eels within selected river systems over the full range of the study area over a three year timeframe.
- Validate and further refine a preliminary model for Australian glass eel recruitment.
- Investigate and further refine glass eel fishing techniques and equipment, including options for minimising bycatch and maximising glass eel survival.

2.2 MATERIALS AND METHODS

2.2.1 Site Description

One key site and several minor sites in Queensland, NSW, Victoria and Tasmania were sampled from 1997/98 to 1999/00 (Figure 2.2, Table 2.2). Waters studied in the glass eel assessment surveys were either selected from previously known glass eel survey sites (Figure 2.2) or were selected specifically for the purposes of this project.

Table 2.2 Total number of waters sampled in each state (*na*, not applicable).

Year	Queensland	New South Wales	Victoria	Tasmania	Total Waters Sampled
1997	1	0	3	2	6
1998	4	1	4	6	15
1999	1	1	1	1	4
2000	1	1	*na*	*na*	2

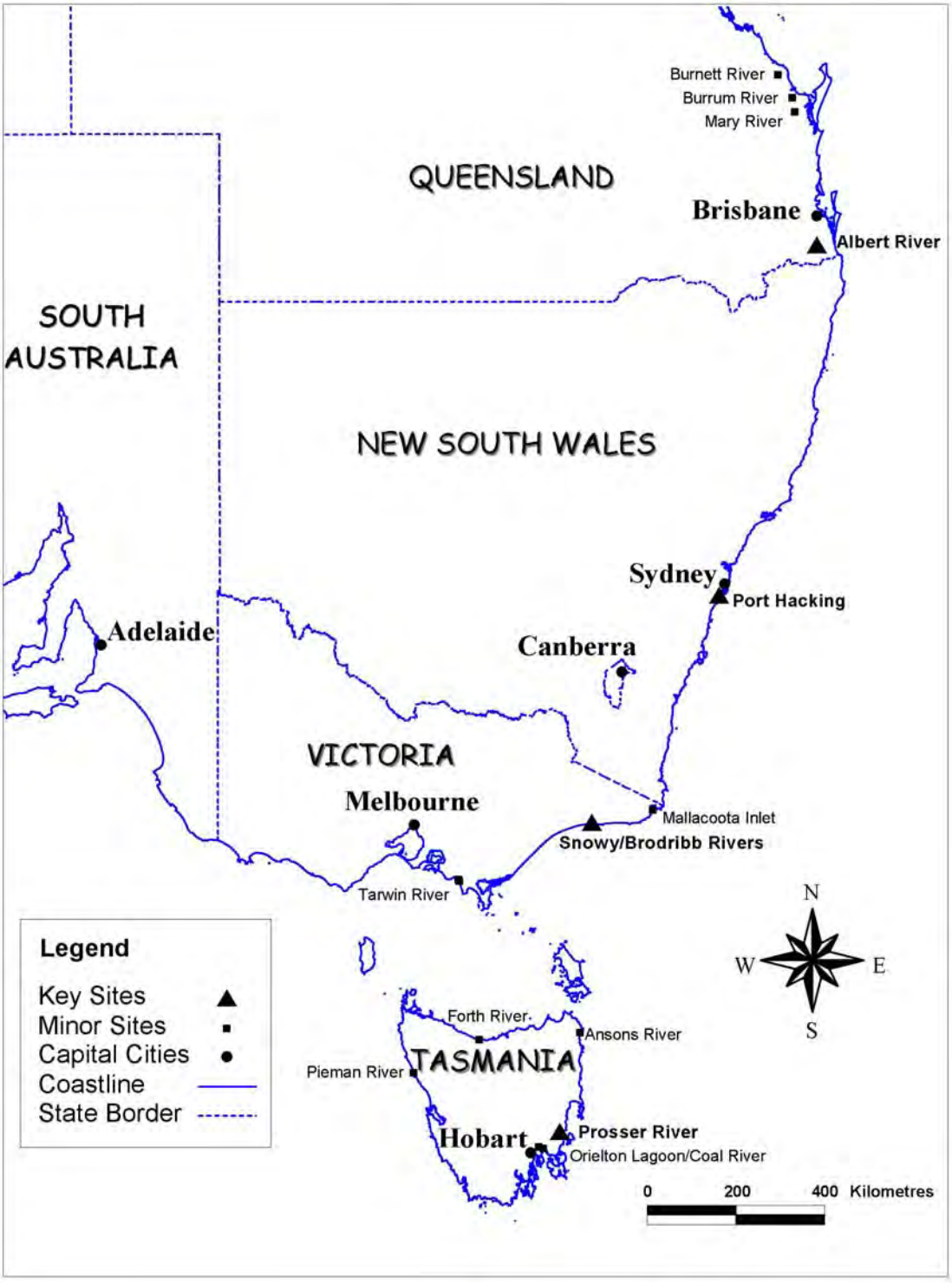


Figure 2.2 Map of eastern Australia indicating sites studied during the project.

2.2.1.1 Albert River, Queensland

The Albert River is 134 km long and joins the Logan River approximately 16 km upstream from its mouth in southern Moreton Bay. The Albert River catchment is 754 sq km in area and extends into the Gold Coast hinterland bordering Queensland and New South Wales (Figure 2.3, Table 2.3).

Based on the local authorities through which the Logan and Albert Rivers flow, the retail and manufacturing industries dominate employment within the catchment. While the agriculture, fishing and forestry industry only employs 2% of the catchment workforce, it occupies 46% of the land area within the catchment with sown pasture, beef and milk cattle representing over 20% of the production for their industry in the South East Queensland region. Other than glass eels, no commercial fishing is conducted in the Albert River, although some beam trawling, gill netting and crab potting takes place at the mouth of the Logan River.

Of particular significance in the catchment is the value of remnant bushland vegetation, especially vineforest remnants, which have been given conservation priority in South East Queensland due to their species diversity, number of rare and threatened species and likely roles as refugia for both fauna and flora. The catchment provides some freshwater discharge throughout most of the year, although flow rates can vary significantly according to season and localised climatic conditions.

Several sites were investigated for harvesting glass eels in the Albert River in riffle and channel areas throughout the tidal reaches. The principal harvest site No. 1 however, was the Stanmore's Road causeway/crossing in the upper tidal reach, approximately 42 km upstream from the mouth of the Logan River (Figure 2.4). The river was approximately 20 m wide at this site, 1.6 m deep at high tide, with a gravel substrate. The site was regularly disturbed during the study due to frequent road works, nearby bridge construction and recreational activity. However the causeway also served as a barrier to fish movement by funnelling flow through nine, 1.2 m diameter concrete culvert pipes. High flow rates through these pipes during ebb tides prohibited glass eels and other fish from moving upstream past the causeway. As such, glass eels tended to accumulate in the deeper pools and riffle areas immediately downstream from the causeway until flood tides greater than 1.65 m in height facilitated their passage through the pipes. Tidal range this distance upstream was generally less than 0.8 m (Table 2.4).

While glass eel nets were trialed in several locations over riffle areas downstream from the causeway, the greatest yields occurred when nets were set over a riffle area directly on the upstream side of the causeway in order to harvest glass eels moving through the pipes on flood tides. Nets were secured by ropes to posts on the causeway and were positioned at low slack water and removed at high slack water. The design of the causeway was such that one large fyke net was used to harvest fish moving through six of the pipes, while a smaller fyke net effectively caught fish moving through the remaining three pipes. Alternatively, sheet-metal barriers placed over the entrance to the three pipes channelled the entire flow through the six pipes, eliminating the need for the second net. To reduce the amount of large debris in the water from clogging the nets, screens were positioned over the entrance to the pipes.

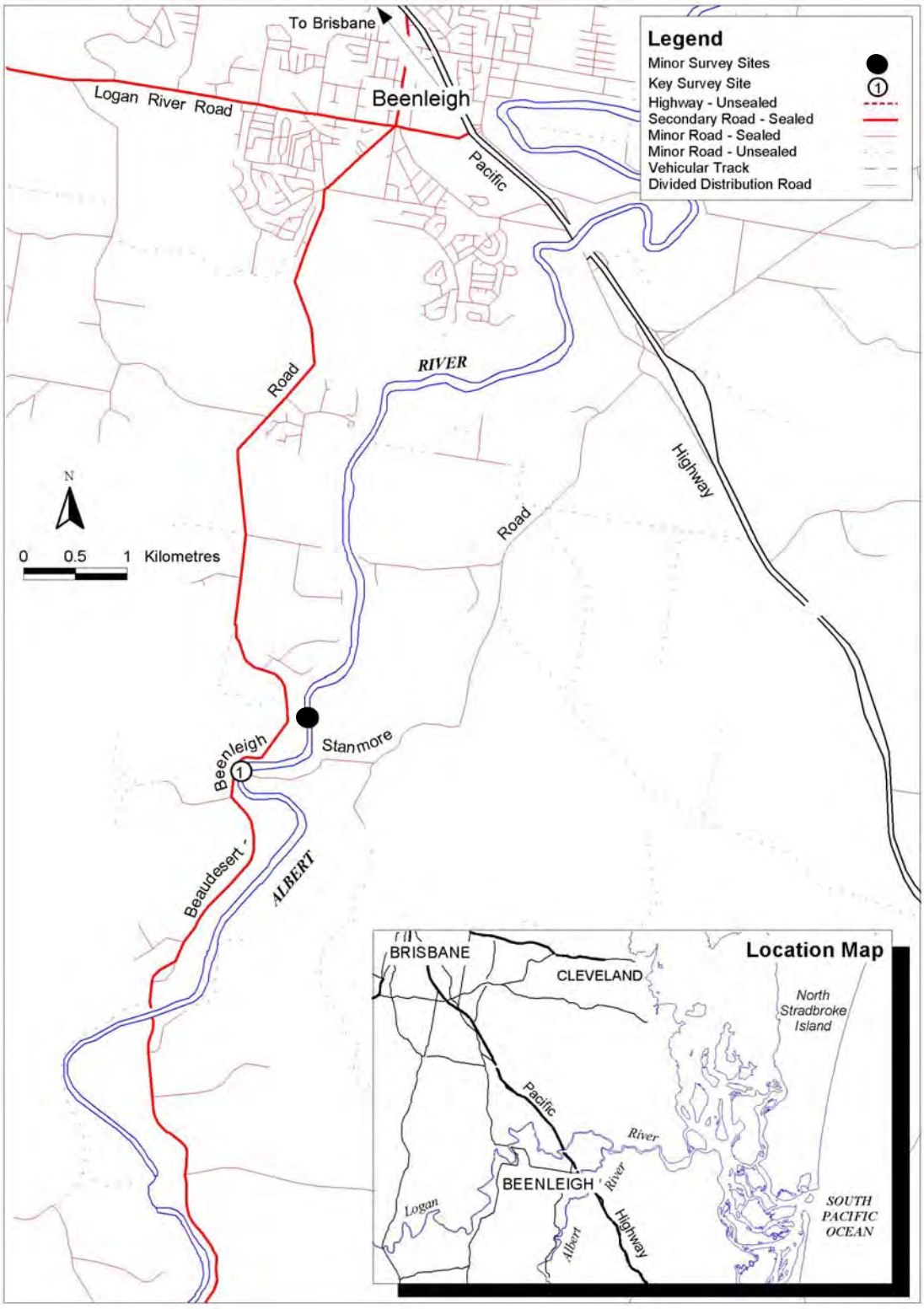


Figure 2.3 Map of Albert River showing the glass eel sampling sites (Source: GIS Digital data – AUSLIG)

Table 2.3 General characteristics of the key river systems.

	Queensland *(Logan / Albert Rivers)*	**New South Wales** *(Port Hacking)*	**Victoria** *(Snowy / Brodribb Rivers)*	**Tasmania** *(Prosser River)*
Catchment Area (km²)	2986 / 754	180	15800[υ]	684
Water Area/Length (km²/km)	175 / 134	11	400 / 95	
Mean annual rainfall (mm)	925A / 268	1200	>800*	695A
Mean annual total discharge (ML)	200,860 / 101,482	69,000,000 m³	1,149,680 / 128,488	103,460
Entrance characteristics	Permanently open	Permanently open	Semi-permanently open	Semi-permanently open
Mean tidal range at site (m)	<0.8	*n/a*	0.25	
Mean spring/*higher* tidal range at entrance (m)	1.68	1.32	1.80	0.61
Estuary type	Drowned river valley	Drowned river valley	Old Embayment	
Latitude	28° 00' S	34° 05' S	37° 47' S	42° 33' S

Source: [*]James 1989; [A] BOM Website; [υ] DWRV 1989

Table 2.4 General characteristics of key sites.

	Queensland	**New South Wales**	**Victoria**	**Tasmania**
Sample Methods	Hell net, Glass eel net, Dip net, Flow trap	Hell net, Glass eel net, Habitat collectors	Hell net, Stow net, Glass eel net	Hell net, Glass eel net
Distance upstream from entrance (km)	42.0	7.0	4.6	0.3
Width of channel (m)	20	50	65	
Maximum depth of channel at LSW* (m)	0.5	5.0	3.5	0.5
Substrate	Gravel	Sand	Muddy sand	Sand
Maximum tidal current recorded (m/s)	3.21	0.73	0.80	0.40
Minimum water temperature recorded (°C)	12.0	13.7	5.5	7.4
Maximum water temperature recorded (°C)	30.2	28.8	19.8	25.3
Minimum salinity recorded (ppt)	0.07	7.4	0.06	8.19
Maximum salinity recorded (ppt)	3.21	35.5	34.8	32.5

* LSW – Low Slack Water

Figure 2.4 The view downstream from the Stanmore Road Crossing, Albert River (Site No 1).

2.2.1.2 Hacking River/Port Hacking Catchment, NSW.

Port Hacking is a relatively small, drowned river valley (Roy 1984) estuary located 24 km south of the Sydney CBD, within the central estuarine bioregion of New South Wales (Pease 1999). The Hacking River and several small streams flow into this marine dominated estuary which has full tidal exchange through a permanently open entrance. The estuary extends 12 km upstream to a causeway across the Hacking River (Figure 2.5). Above the causeway the waters of the Hacking River are always fresh.

Port Hacking forms the northern boundary of the Royal National Park, which also encompasses most of the Hacking River catchment. For this reason the waters of Port Hacking and the Hacking River are considered to be relatively pristine and have been classified 'controlled' (treated discharges permitted by approval into large, well-flushed estuaries) and 'protected' (restricted discharge of effluent into waters used for potable supplies) respectively, by the State Pollution Control Commission of NSW (SPCC 1980) (Table 2.3). The northern side of Port Hacking is bounded by residential suburbs of Sydney and classification of these waters is currently under review by the Environment Protection Authority. Uses, discharges and associated water quality studies in this catchment are summarised in the Hacking River Catchment Management Committee Report (HRCMC 1997) and the Proposed Interim Environmental Objectives for NSW Waters - Sydney, Central Coast and Illawarra Catchments (EPA 1997).

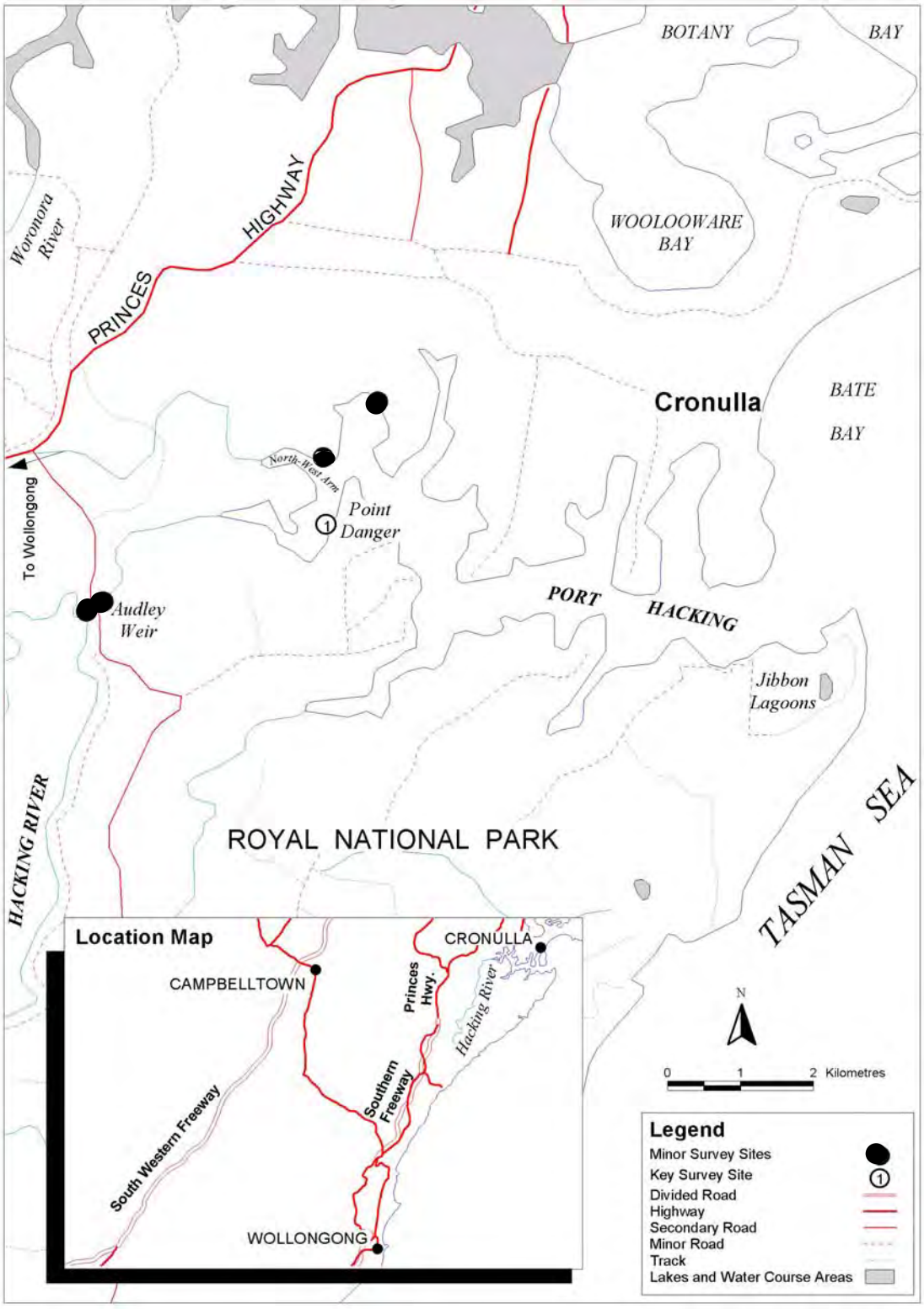


Figure 2.5 Map of Port Hacking and Hacking River showing the glass eel sampling sites (Source: GIS Digital data – AUSLIG**)**

Figure 2.6 View of Pt. Danger site, Port Hacking

All waters of the catchment are closed to commercial fishing. Recreational fishing is very popular in these waters and longfin eels are occasionally caught by recreational fishers in the fresh water above the Audley Causeway.

Port Hacking, Site N°1 (Pt. Danger) is in the channel at the head of the estuary, where the Hacking River previously entered Port Hacking, before the causeway was constructed upstream at Audley (Figure 2.6). It is now a marine dominated area with strong tidal flow and limited freshwater influence from the Hacking River. A hell net is fished at this site by attaching one end of the net to a star picket on the beach at the north side of the channel with the other end attached to an anchor towards the middle of the channel. On the north side of the channel the bottom consists of gradually sloping fine sand. A tide gauge was installed on a navigation pole 50 m downstream from the location where the net was set. A datalogger was also attached to this pole during sampling periods.

2.2.1.3 Snowy River, Victoria

The headwaters of the Snowy River begin on the slopes of Australia's highest mountain, Mt. Kosciusko in south-eastern New South Wales. Passing through cleared highlands used mostly for grazing, it then falls generally south through forested mountains and steep gorge country into eastern Victoria, entering the rich alluvial floodplain flats (James 1989) and estuary of the lower reaches, before finally emptying into eastern Bass Strait. The Brodribb River meets the Snowy River some 4.6 kilometres from the river mouth at the sea, near the coastal town of Marlo.

In the headwaters of Victoria, the mean annual rainfall varies from 600 to 1000mm (James 1989). In the coastal region of the catchment it varies from 700 to 800mm (DWRV 1989). Some 45% of the Snowy River's mean annual flow is now diverted by the Snowy Mountains Hydro-Electric Scheme (James 1989) into the Murray and Tumut Rivers (Table 2.3).

In the Orbost region, water for irrigation is mainly used for pasture and horticulture. Hardwood timber production is a major industry in the Basin, as well as cattle and sheep grazed on the high country and southern hills. Large areas of the catchment have been retained for conservation purposes as part of the Snowy River and Tingaringy National Parks.

Following extensive investigations of potential glass eel survey sites in previous years (Gooley *et al.* 1999) the entrance to the Brodribb River proved to be the most suitable for glass eel collection. The site (No.1) is located at the junction to the Snowy River, 4.6 km upstream from the river mouth (Figure 2.7, Table 2.4). Certain freshwater flows influence and restrict tidal flow reaching this section of river. These freshwater flows subside to a point where the flood tides collide with the Snowy River causing the bulk of the tidal flow to pour into the Brodribb River and ultimately into Lake Curlip further upstream. Under high spring tides, flow up the Brodribb River has been observed for some two hours after high slack water in the Snowy River.

The site (No. 1) that demonstrated the most consistent catch of glass eels was near the point, on the northern bank (Figure 2.8) of this site. The retrieval rope of a plough anchor was attached to a star picket on the edge of the bank. This was to ensure that the anchor did not move through the muddy substrate below the shoulder of the north bank. The opposite end, already attached to an anchor, was lined up with the end of the bank wing and opened towards the middle of the channel.

Nets were generally positioned at low slack water and removed at high slack water. The datalogger that monitored the water quality parameters was sited at the tree adjacent to the south bank, opposite the primary net.

A 2.5 metre gauge, to measure tidal heights, was installed on the northern bank of the site.

2.2.1.4 Prosser River, Tasmania

Originating on the southern slopes of Mount Hobbs (elevation 823m) and the north-east slopes of Brown Mountain (792m), the Prosser River traverses easterly towards the South East Coast of Tasmania where it drains into Prosser Bay at the coastal town of Orford. Most of the catchment is gentle undulating hills, apart from the plains near the main but small townships of Buckland and Runnymede. The major land uses within the catchment are forestry and grazing.

The total area of the catchment is 686 km^2 and is surrounded by the Little Swanport River to the north, the Coal River to the west, and mainly by Sorrel Rivulet, Iron Creek and Carlton River catchments to the south. The major tributaries of the Prosser River are the Back River, Sand River, Tea Tree Rivulet, Bluff River, and the Brushy Plains Rivulet.

The natural flow of the Prosser River has been altered by a large weir located 4 km upstream from the mouth, which was built to supply water to the township of Orford.

The survey site used on the Prosser River (No. 1) is located at the coastal town of Orford, situated approximately 120km from Hobart, on the south-east coast of Tasmania. The sampling area was less than 300m from the mouth of the river (Figure 2.9 and Figure 2.10, Table 2.3 and Table 2.4).

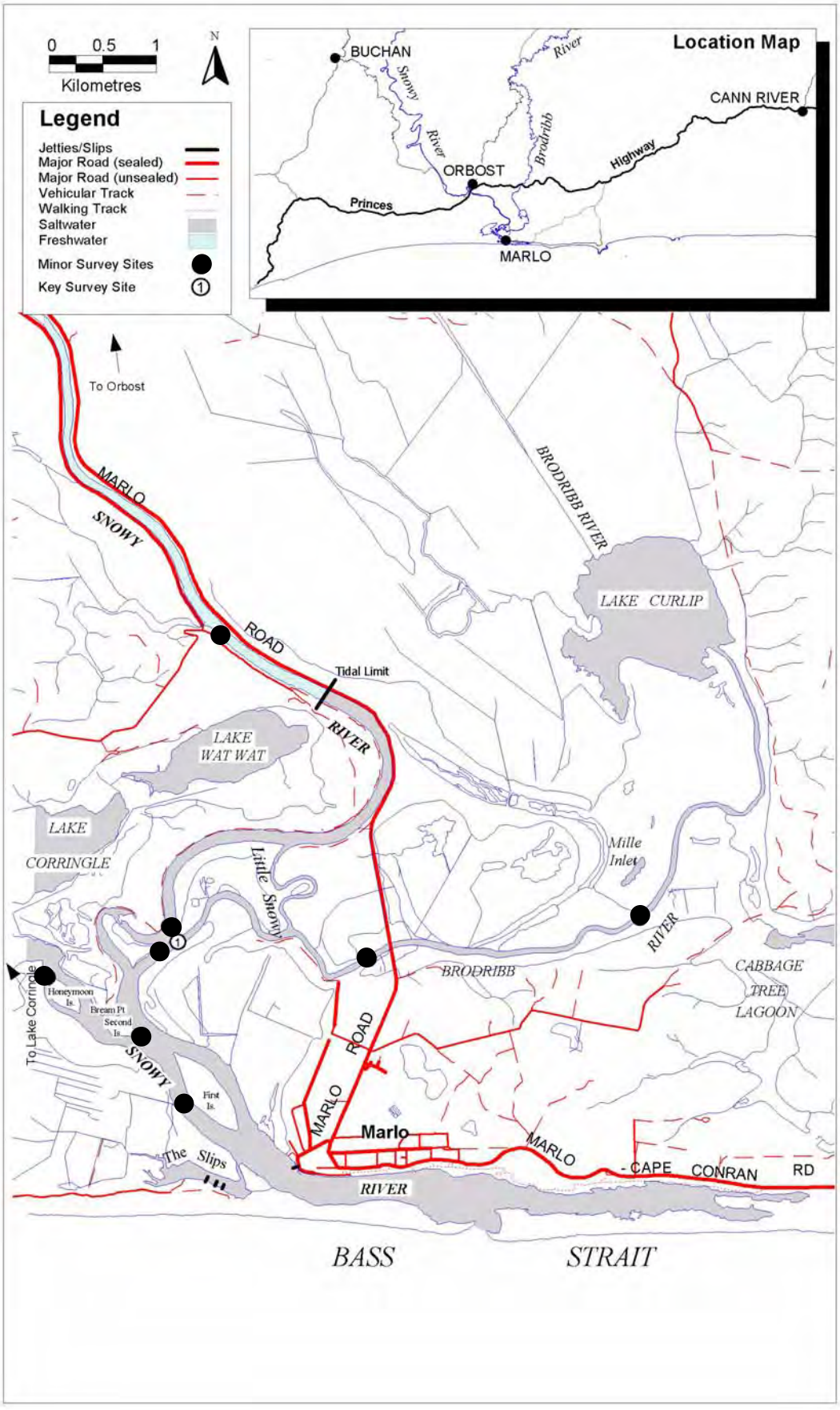


Figure 2.7 Map of the Snowy River indicating sites sampled.

Figure 2.8 View of the junction of the Brodribb and Snowy Rivers (Site N°1). Northern bank is on the right**.**

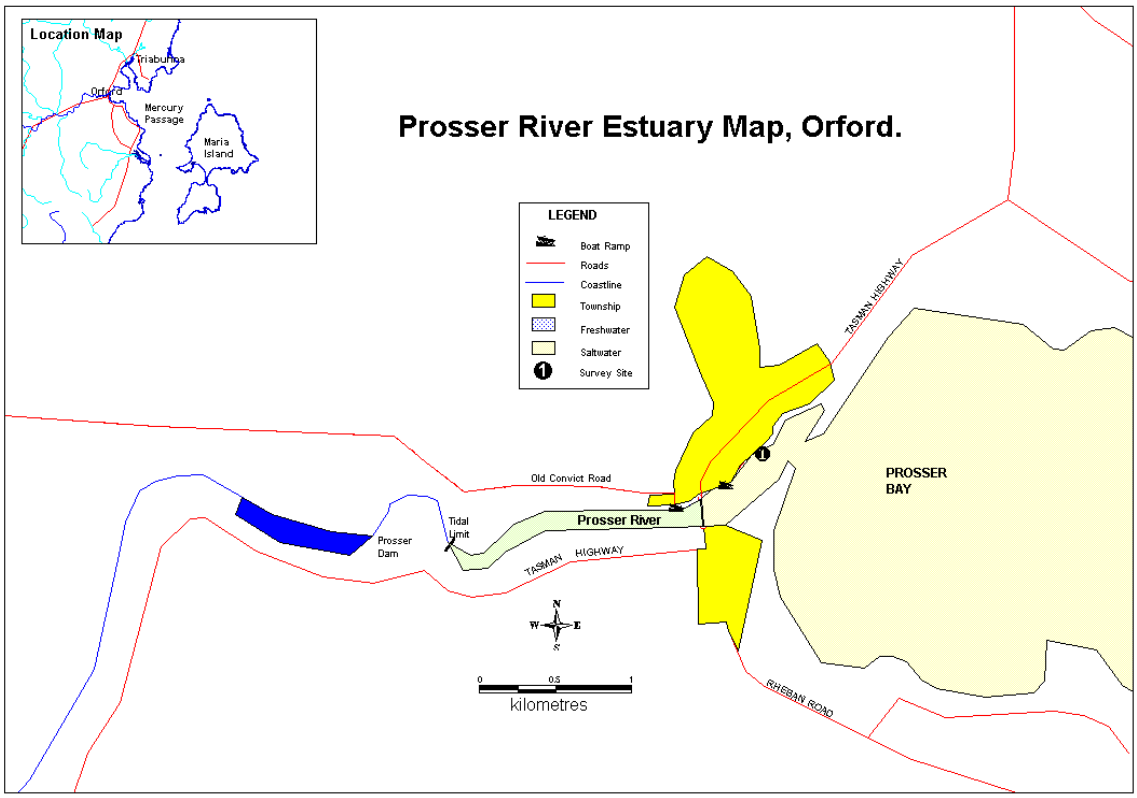


Figure 2.9 The Prosser River estuary showing the glass eel sampling sites**.**

Figure 2.10 Seaward view of the Prosser River sampling site.

2.2.2 Sample collection

Surveys at key sites in Queensland, New South Wales, and Tasmanian estuaries were undertaken throughout the whole year from July 1997 - January 2000, March 1998 - May 2000, and September 1997 - October 1999, respectively. Due in part to the geographically isolated nature of the key Victorian site, and in order to specifically target the main period of shortfin glass eel migration, the assessment surveys were mainly concentrated during June to October, 1997 to 1999, although a number of preceding investigations were carried out from late March to June 1998. These early surveys were carried out to ascertain whether the main part of the season might commence earlier in Victoria.

All waters were predominantly sampled with glass eel nets and hell nets, however in some cases, a stow net, or 'hamennet' (Weber 1986), dip nets and flow traps were used. The data from these latter three gear types are not included in these analyses in detail.

Glass eel nets were 10m in length, had two, 3.5m wings of 1.4m drop attached, and were constructed of 2mm (stretched) nylon mesh. A detachable cod-end, constructed of 1.0mm or <0.5mm mesh, was fitted to an 8cm PVC pipe attached to the end of each net (Figure 2.11). Hell nets were approximately 16m in length, had two, 11m wings of 4.4m centre drop attached, and were constructed of 2mm (stretched) nylon mesh with a detachable funnelled extension, and a cod-end, constructed of 2.0 and 1.0mm mesh, respectively (Figure 2.12). Stow nets, also constructed of 2mm mesh, were as described by Weber (1986), with the exception that a 6.9m cod-end was attached (Figure 2.13).

An aluminium Nordmøre grid (800 mm x 400 mm) (Isaksen *et al.* 1992), as used in the prawn industry in New South Wales (Broadhurst *et al.* 1997) was inserted in the hell net used in Port

Hacking in 1998. This grid had a gap width of 10 mm between the bars and was installed in the bunt of the net at an operational angle of 25 degrees (M. Broadhurst, personal communication). A triangular exit opening 40 cm wide and 15 cm long was cut in the netting behind the top edge of the grid. The Nordmøre grid was replaced in May 1998 with a new grid having the same external dimensions, but a grid gap width of only 5mm between the bars.

The 1999 sampling surveys in Victoria incorporated a preliminary trial utilising a By-catch Reduction Device (BRD) installed in the bunt of one hell net, and based on the Nordmøre-grid (Isaksen *et al.* 1992; Broadhurst *et al.* 1997). The normal detachable extension on a hell net was replaced with an extended version (Nordmøre-grid) integrating a top escape hatch. The triangular hatchway was placed directly above an in-built 45° sloping grid made of 12mm stainless steel rod spaced 3mm apart. A detachable cod-end was also fastened to the escape hatch to determine the efficiency of the BRD by sampling the size and quantity of discarded catch.

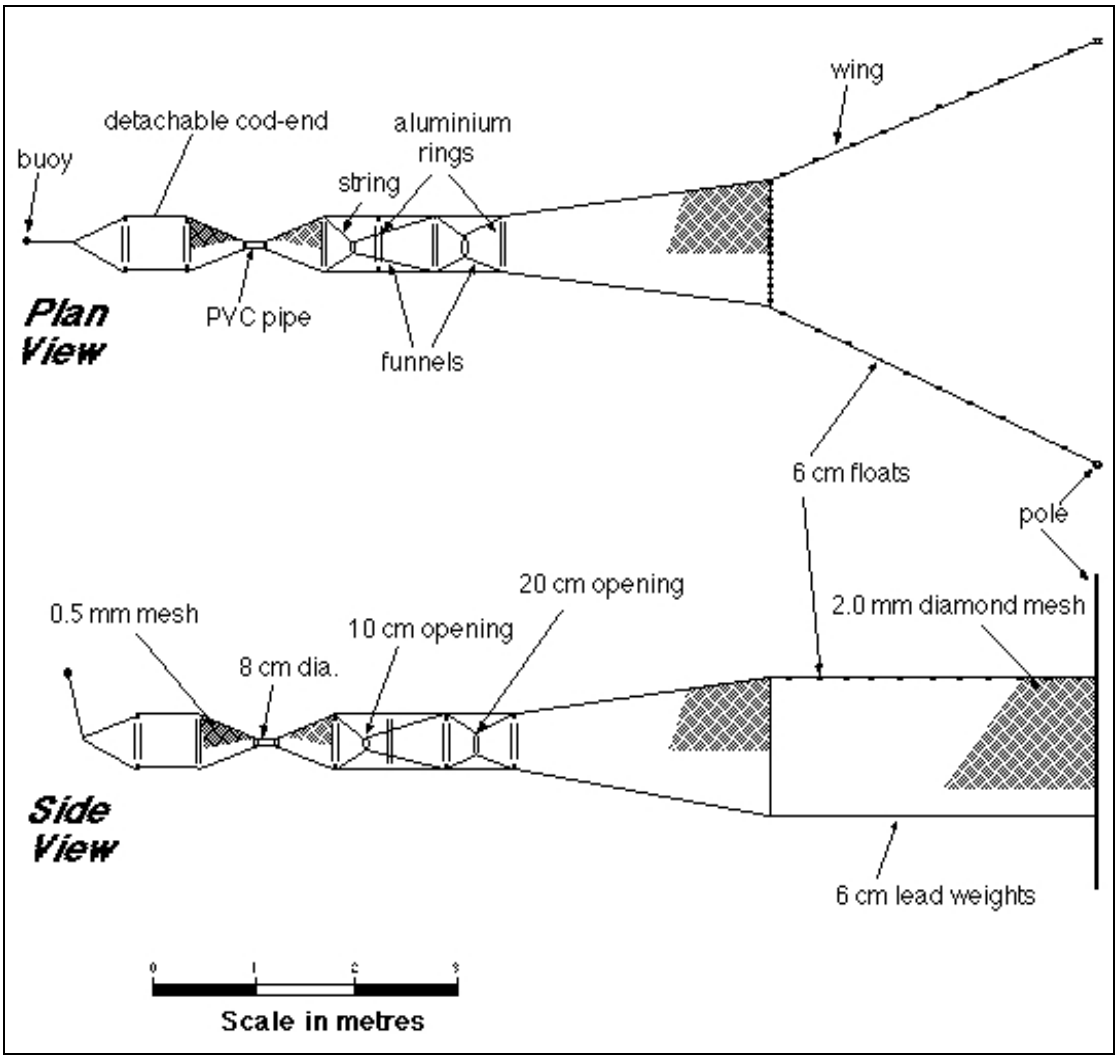


Figure 2.11 Schematic diagram of a glass eel net used in study

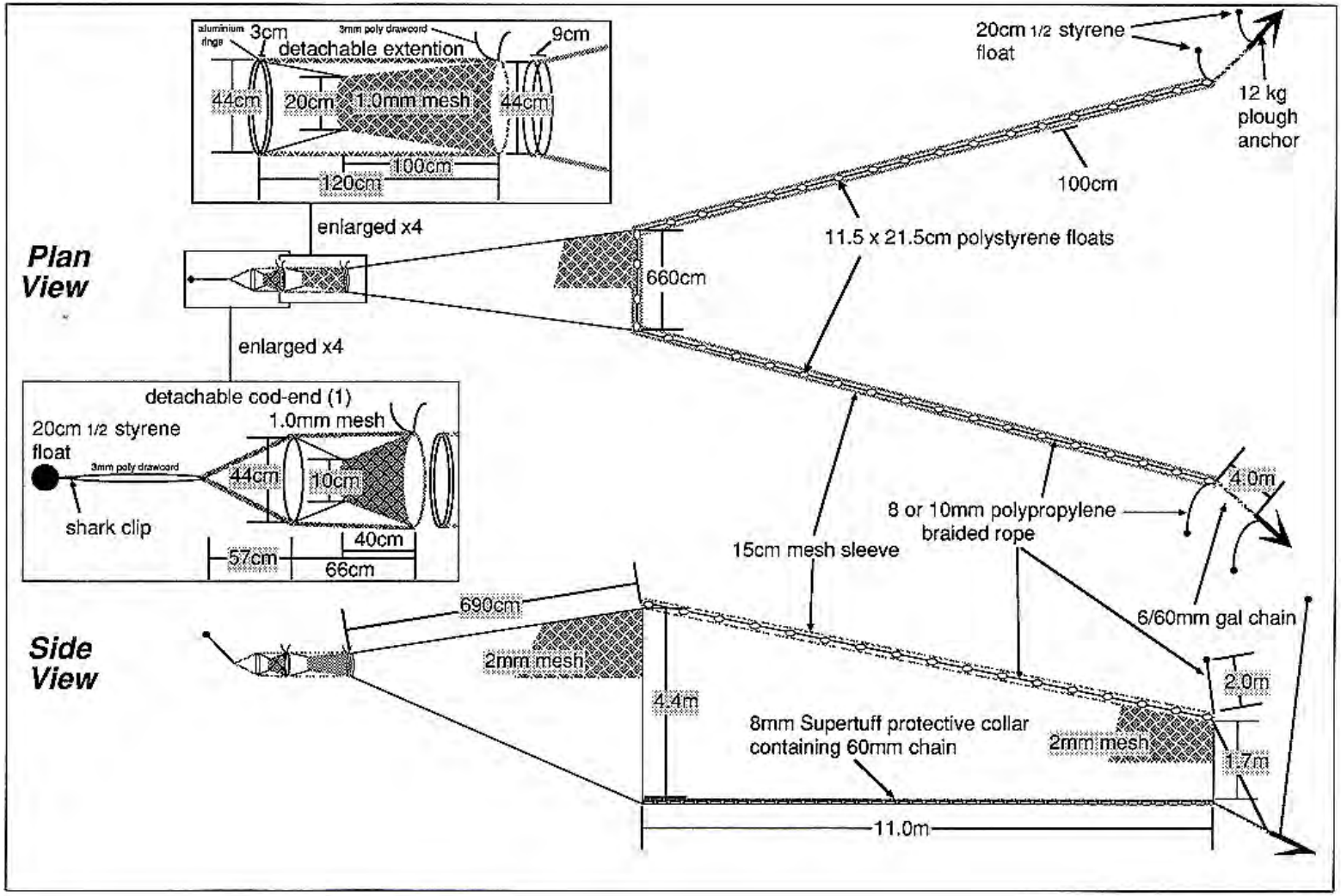


Figure 2.12 Schematic diagram of a hell net used in the study

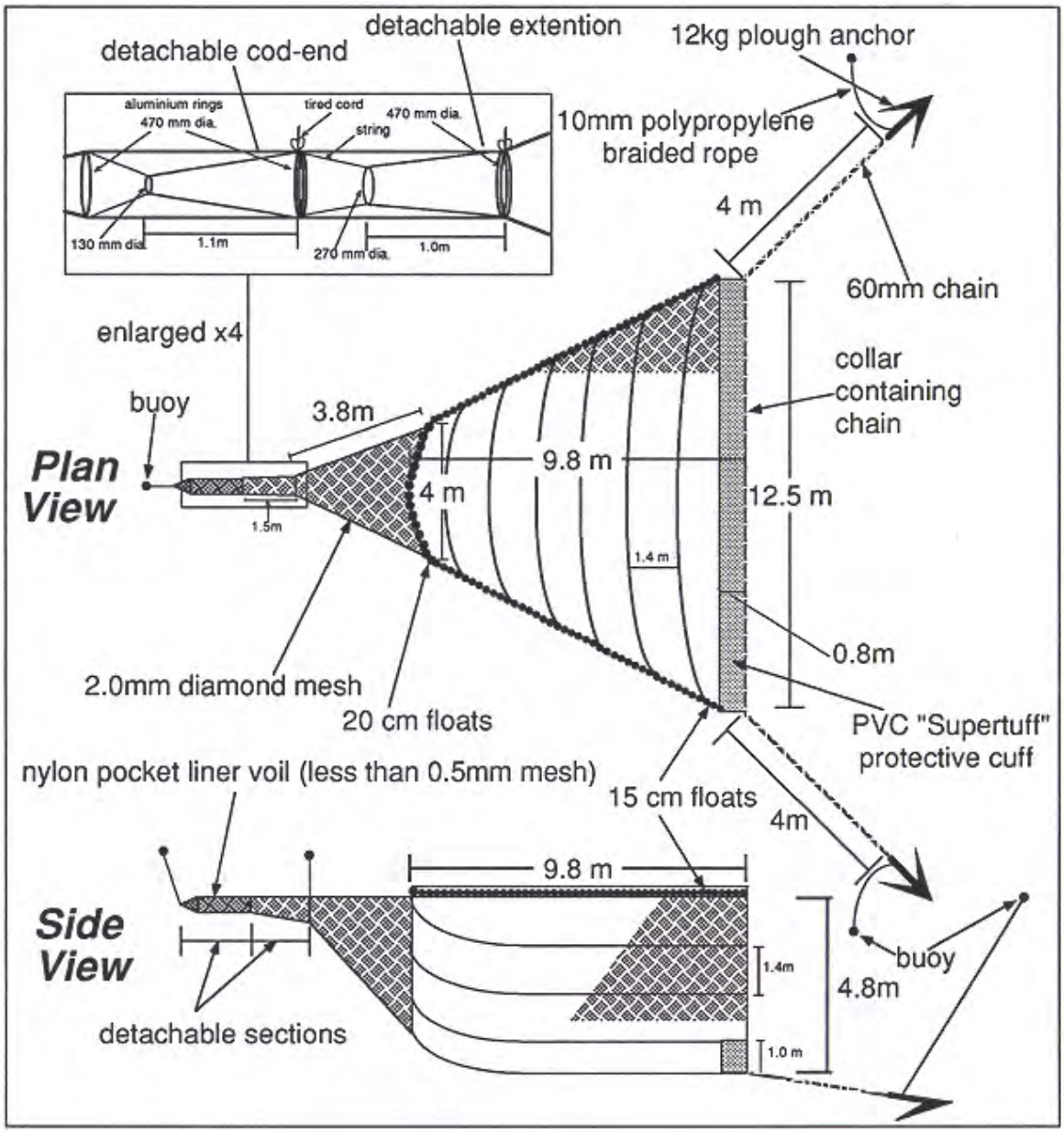


Figure 2.13 Schematic diagram of a stow eel net used in the study.

2.2.3 Fishing Methods and Data Collected

Fishing generally commenced within 2 days after a new and full moon and continued for 2-4 nights or until there was a significant reduction in glass eel capture rates. Glass eel nets were ideally set in estuaries adjacent to the banks, whereas stow nets were generally used in the main channel of the estuary. Hell nets could easily be used in either situation, or a combination of both, running from the bank out into the main channel. All gear types were mostly set at low slack water occurring at or after dusk. Catch was cleared at regular intervals, usually hourly, and fished until the end of the third hour or when high slack water occurred. All site details, catch and effort, length and weight details of glass eels, as well as general conditions were recorded in the field.

Catch was initially sorted using stacked plastic crates (530mm long x 350mm wide x 185mm deep) fitted with a screen mesh base graduated in size from largest (at the top) to smallest (10mm plastic, 3.25 mm woven stainless steel, and 0.5mm nylon mesh size). Glass eels typically sieved through the by-catch and screens, collecting in the bottom tray. Both glass eels and individual by-catch species were then counted or weighed separately (see Appendices). When large numbers of by-catch were attained, a sub-sample of 5 or 10% was counted and identified to species level where possible.

During 1999, detailed analysis of bycatch was undertaken to determine whether any association of particular bycatch species occurred with periods of major glass eel migration in the Snowy River. Subsamples of the 12 most common bycatch species were retained for analysis of stomach contents. Individual dietary items were identified to the lowest possible taxonomic group, and frequency of occurrence of prey items was recorded.

In Victoria, during the 1999 season, a woven stainless steel basket (450mm dia. x 340mm deep) design (Figure 2.14) was successfully used to sort the glass eels from the by-catch. This allowed the catch to settle in a pre-filled 100 litre round (600mm dia. x 435mm deep) polyethylene tank and enabled the glass eels to be quickly sorted whist still in water, creating less handling and therefore greater glass eel and by-catch survival. In some instances, when large numbers of small by-catch (eg. oppossum shrimp) were found, both a woven stainless steel basket and a plastic sorting crate, with a 2.5mm stainless steel mesh insert, were employed to further clean and extract the glass eels.

A subsample of 50 glass eels from each sampling period at each site was taken and individual length, weight and pigmentation stage were recorded. This sample was also used for ageing of glass eels. A further 60 individuals were frozen and kept from each sampling trip, to determine their genetic makeup using electrophoretic techniques. Results from genetic analyses are detailed in a later section of this report.

Methods for glass eel fishing, holding, transportation and weaning and early rearing, have been detailed in a technical report for industry development (McKinnon *et al.* 2001) (see Appendix I).

Figure 2.14 Woven stainless steel basket design (12mm gauge frame with 3.25mm mesh).

A datalogger measured water quality variables water temperature and electrical conductivity (salinity) at each of the key sampling sites. Data was generally recorded at 10 minute intervals throughout the sampling period. In some cases only spot readings were taken before the sampling gear was set and/or after each consecutive haul.

Other environmental data such as predicted and observed times and heights of low and high water and tidal range were entered or collected directly before and after sampling. Other tidal influences such as wind direction and strength were also recorded at the commencement of each night fished. Tidal flow was normally recorded hourly (within 15 minutes of haul) using a flowmeter at the entrance of the key sampling net.

2.2.4 Data Analysis

Detailed analyses were conducted on data from all key sites, collected over the three years of the project, and for the Snowy River alone from 1994-1999, as an extensive dataset has been now established for this river over the last 6 years (Gooley *et al.* 1999). Data was analysed as described in McKinnon and Gooley (1998) and Gooley *et al.* (1999), whereby glass eel abundance for both shortfin and longfin glass eels, quantified as catch per unit effort (CPUE) was correlated with selected environmental variables classified into several categories which were typically encountered during glass eel surveys. These were: electrical conductivity (salinity), 'low', 'medium' and 'high'; temperature, 'low', 'medium' and 'high'; moon phase, 'low', 'medium' and 'high' and stream discharge, 'low', 'medium' and 'high' (Table 2.5). General Linear Modelling (GLM) Procedure (SAS/STAT Release 6.12 Edition) was used to determine relationships between environmental variables and overall catch per unit effort (CPUE) of glass eels (mass (g) of glass eels/net/hour) by site and by season. For the purposes of the analysis, season is defined by financial year (1 July - 30 June) so that the bulk of the data for any one sequence of migrations for each species was approporiately pooled. This is due to the timing of the main periods of migration of both species ie. longfin glass eels generally from spring to autumn, and shortfin glass eels generally from winter to spring.

The dependent variable, CPUE, was taken as an index of relative glass eel abundance. Analysis of variance using GLM procedure was undertaken for all environmental variables as major effects. Significant difference of CPUE at $P < 0.05$ showed dependence. Tukey's Studentized Range Test (SAS/STAT Release 6.12 Edition) was used to compare means of significant effects. The variables tested were: mean salinity (measured as electrical conductivity), mean temperature, moon phase (as age in days) and stream discharge, lagged up to seven days. Table 2.5 summarises the categories assigned to the variables for each year. The model: CPUE = Salinity + Temperature + Moon Phase + Discharge + Error was then tested for each year and for each gear type.

Mean length, weight and condition of glass eel samples were also analysed using GLM procedure with the main effects; sites (spatially) and over time at individual sites (temporally) as well as between years. Condition (K) was calculated from $K = 1000W.L^{-3}$ where W is mean weight (g) and L is mean length (mm). Pigmentation staging was undertaken on glass eel samples from each sampling trip. Different pigmentation stages were classified according to Strubberg (1913) and are summarised in Table 2.6.

Table 2.5 Values of tested class levels applied to environmental/climatic variables for analysis using General Linear Modelling for each year of the project for the Snowy River only. 'OTHER' Moon Phase refers to First and Last Quarters of the moon.

Level	Classes			
	Mean salinity ($x10^3$µs/cm)	Mean temperature (^oC)	Discharge (ml/day)	Moon phase
Low	0-8	<9	800-1400	New (28-7 days)
Medium	8-20	9-11	1400-2200	Other (8-14 & 22-27 days)
High	>20	>11	>2200	Full (15-21 days)

Table 2.6 Pigmentation stages in glass eels, from Strubberg (1913), used in the project.

Stage	Progression of pigmentation
VA	Only on extreme tip of tail and along spinal cord
VB	Only on head and rostrum
VIAI	In formation along dorsal ridge
VIAII (1)	Progress of medio-lateral pigment in rear half of tail
VIAII (2)	Medio-lateral pigment reaches middle of tail
VIAII (3)	Medio-lateral pigment advances, but not over anus
VIAII (4)	Medio-lateral pigment reaches over anus
VIAIII (1)	Medio-lateral pigment reaches below front edge of dorsal fin
VIAIII (2)	Medio-lateral pigment reaches out over liver
VIAIII (3)	Medio-lateral pigment reaches out over pectoral fins. Little or no pre-anal ventro-lateral pigment
VIAIV (1)	Scattered ventro-lateral pigment present pre-anally
VIAIV (2)	Ventro-lateral pigment more distinct pre-anally
VIAIV (3)	Ventro-lateral pigment developed along myosepta pre-anally. No inter-myoseptal pigment present
VIAIV (4)	Development of inter-myoseptal pigment
VIB	Myoseptal pigment arrangement, both dorsally and ventrally, becomes indistinct

2.2.5 Glass Eel Ageing

Ageing of glass eel otoliths was undertaken by the Central Ageing Facility at MAFRI, Queenscliff. Samples of shortfin glass eels were collected for ageing purposes from each key site from an Early, Mid and Late period from the shortfin glass eel migration season in 1998. Samples of longfin glass eels were collected for ageing purposes from the key sites in Queensland, NSW in February, 1999, and Victoria in February, 2001. All samples were preserved in 95% ethanol. Collection dates for each period and state are shown in Table 2.7. Total length of glass eels sampled for ageing purposes was also recorded.

The sagitta was removed from the prootic bullae using needle forceps. Otoliths were placed on numbered slides and left to air dry overnight. Once dry, a small amount of Crystal Bond (thermoplastic glue) was used to adhere the otoliths to glass slides. Ten otoliths from ten different samples were aligned on a single slide and ground down using a fine grade lapping film. Once the primordium had been reached, the ground surface was polished using 0.05 micron aluminium oxide powder. A sonic bath was used to clean the preparations before etching. Otoliths were immersed in a solution of 0.05M HCl for between 12 and 15 sec. Samples were rinsed in distilled water, left to air dry and then coated with gold and viewed under a scanning electron microscope (SEM) at 20kV. Magnification varied depending on the size of the otolith section (1500x-2000x). Serial digital images were saved from the primordium to the edge, along a transect of greatest increment clarity. Images were opened using the image analysis software Optimate® (Media Cybernetics). A medium pass filter was used on some images to enhance the increment clarity. Putative daily ages were determined from otoliths by counting growth increments from the hatch mark to the onset of the metamorphic mark, and then to the edge. GLM and Tukey's Studentized Range test were used to compare ages of glass eels between sites in each period, and over time at each site.

Table 2.7 Collection dates of glass eel ageing samples.

Species	Period	Date	State
Shortfin eel	Early	11/6/98	NSW
Shortfin eel	Early	13/6/98	Victoria
Shortfin eel	Early	21/6/98	Queensland
Shortfin eel	Mid	12/7/98	Tasmania
Shortfin eel	Mid	17/7/98	Queensland
Shortfin eel	Mid	18/7/98	Victoria
Shortfin eel	Mid	26/7/98	NSW
Shortfin eel	Late	10/8/98	Victoria
Shortfin eel	Late	10/8/98	Tasmania
Shortfin eel	Late	10/8/98	NSW
Shortfin eel	Late	17/8/98	Queensland
Longfin eel		19/2/99	NSW
Longfin eel		26/2/99	Queensland
Longfin eel		26/2/01	Victoria

2.2.6 Temporal and Geographical Distribution

Reverse simulation with the numerical hydrodynamic dispersal models 3DD (Black 1995) and POL3DD (Black 1996) was undertaken for a 100 day period prior to sampling dates in the Snowy River in 1996, 1997 and 1998 respectively, to determine the positions of shortfin glass eels prior to collection in each year. These models have various applications including the prediction of current speed and direction, sea levels, the transport of sediment, effluent dispersal and larval dispersal, including the determination of advection pathways for King George whiting in southeastern Australia and their transport through Bass Strait (Jenkins *et al.* 2000). The hydrodynamic model 3DD was used to determine the current speed and direction in Bass strait 100 days prior to sampling, and the dispersal and transport model POL3DD was used to determine the positions of glass eels 100 days prior to sampling, and throughout the 100 day period. The model assumed fully passive transportation and random distribution of glass eels throughout the water column. Similar modelling tools were not available for other areas of the present study.

2.2.7 Mark Recapture Trials

A glass eel mark-recapture program was developed using oxytetracycline (OTC) as a chemical marker in order to obtain more accurate estimates of glass eel abundance, catch efficiency and to assess the rates of upstream migration. Initial laboratory trials tested the uptake of OTC into bony bodily parts over a range of concentrations and salinities to determine shortest exposure time to yield consistently reliable and easily detectable marks (Adrian Collins, QDPI, unpublished data). Good quality marks were apparent on 100% of glass eels immersed in an OTC solution at a concentration of 1500 mg l^{-1}, for 20 min in freshwater buffered with Tris (hydroxymethyl methylamine) to a pH of 7. Marks formed using this method appeared as bright yellow stains in the vertebrae, skull and mandible when exposed to UV light excitation at a wavelength of 540 nm. Lower OTC concentrations, shorter exposure periods and higher salinities yielded marks of lesser quality.

The marking procedure was applied to glass eels harvested at Site 1, Albert River, Queensland (Stanmore Crossing) and in the Snowy River, Victoria. Pre-weighed quantities of glass eels were immersed in the OTC solution en-masse using mesh inserts in 60 L containers supplied with supplemental oxygenation. After 20 mins, the glass eels were removed from solution and placed into clean water prior to release or transportation to the laboratory. A sub-sample was retained to validate marker quality and glass eel survival in either instance. A number of release strategies were trialed in order to define the best release times. These included:

a) one hour after high slack water on night of catch
b) low slack water the following morning
c) on dusk prior to the following evening's flood tide.

Eels were released at a number of locations 0.1, 1 and 12 km downstream of the harvest site in the Albert River and 0.5-1.0km downstream of the harvest site in the Snowy River.

Recapturing marked eels was undertaken by Project staff and/or commercial fishers on successive evening flood tides after release. For each night at liberty, the total catch of all eel fishers at each harvest site was recorded and a sub-sample of each fisher's total catch was taken for analysis. The number of marked individuals in each sample was then used to calculate the total number of marked glass eels recaptured. This figure was then used in

conjunction with the total harvest data to calculate the total abundance of glass eels according to the Petersen method.

Mark and recapture activities were conducted on 11 occasions in the Albert River during both the *A. reinhardtii* and *A. australis* seasons of 1997 and 1998 and on three occasions during the *A. australis* season in 1998 and 1999 in the Snowy River.

2.3 RESULTS

2.3.1 Catch-Effort

Although sampling was undertaken at several sites in each state, and at a number of locations within a particular river, the results presented are largely those from sampling undertaken in each of the key sites (one river per state) (Figure 2.2). Catch of glass eels often varied considerably through the duration of the flood tide, with CPUE generally greater in the first 3-4 hours of the flood tide at each site. CPUE is however presented as mean hourly CPUE (total catch/total effort in net hours per night fished). Results of the GLM and Tukey's Studentized Range test indicate that CPUE of both species of glass eel by season and site showed very large variability (Figure 2.15 and Figure 2.16), with greatest catches occurring in the Albert (both species) and Snowy Rivers (shortfin glass eels only) in each year, but with limited consistency among variables.

In the Albert River, shortfin glass eels were generally present from March to November each year with CPUE often around 200-400g/net/hour, and maximum CPUE of 1600g/net/hour being recorded in July 1998. Longfin glass eels were generally present in the Albert River throughout the year, with CPUE reaching 5kg/net/hour in March 1997, and catches were often in the order of 2-3 kg/net/hour. At Port Hacking, shortfin glass eels were present from May to September inclusive, and a maximum CPUE of 573g/net/hour was recorded in June 1998. However, CPUE of shortfin glass eels was generally less than 100g/net/hour. Longfin glass eels were generally present throughout the year in Port Hacking, with CPUE peaking at 67g/net/hour in June 1998, although CPUE was often less than 1g/net/hour, and generally less than 20g/net/hour. Total catch of shortfin glass eels recorded at site 2 at Port Hacking (on the downstream side of Audley Weir, Figure 2.5) was much lower than at site 1, however different methods were used at each of these sites. Less than 150 shortfin glass eels were collected in each year of the project at this site, however total numbers of longfin glass eels collected at Audley Weir were of the same magnitude as those collected at the key site (site 1) in Port Hacking. Shortfin glass eels were present in the Snowy River throughout the sampling period each year (June-October), with CPUE often in the order of 1-3kg/net/hour during July and August, and with a maximum of almost 7kg/net/hour being recorded in July 1998. Longfin glass eels were recorded in the Snowy River from July-October in 1997 and 1999 but at very low levels (less than 12g/net/hour). No longfin glass eels were recorded from the Prosser River, and shortfin glass eels were recorded from March to September in 1998, and June to September in 1999. CPUE of shortfin glass eels reached a maximum of 7.6g/net/hour, but was usually less than 2g/net/hour in the Prosser River.

In the Albert River, CPUE of shortfin glass eels in Hell Nets was significantly greater during the new moon phase in all seasons ($F_{2,141} = 4.05$, $P = 0.0197$, $R^2 = 0.2$) but was not affected by the other environmental/climatic variables (season, salinity, temperature and river

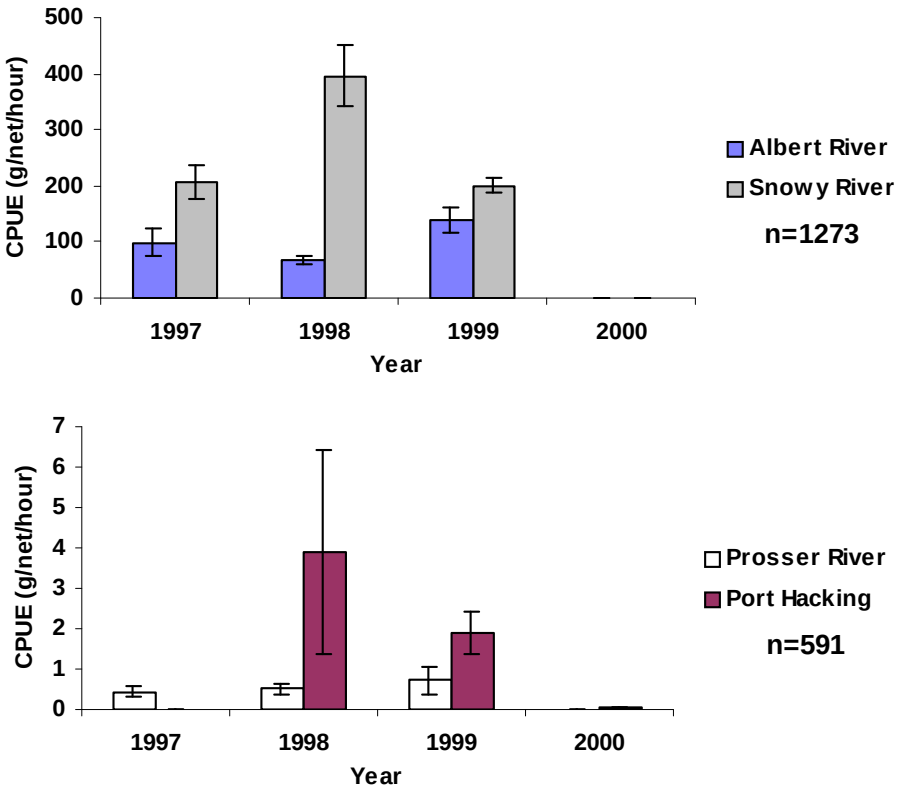


Figure 2.15 Catch per unit effort (± SE) of shortfin glass eels in hell nets.

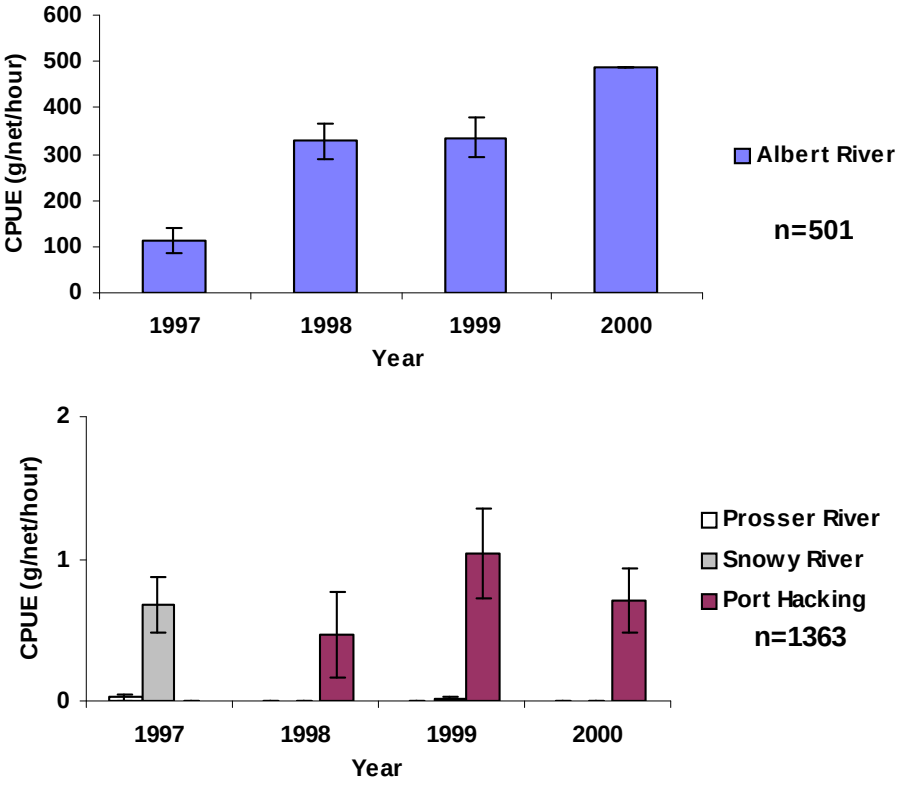


Figure 2.16 Catch per unit effort (± SE) of longfin glass eels in hell nets.

discharge). CPUE of longfin glass eels was much greater in the Albert River than at other sites throughout the study (Figure 2.16) and CPUE was significantly affected by season ($F_{2,141}$ = 7.49, P = 0.0008, R^2 = 0.145), but environmental/climatic variables had no effect on catch. Catches of glass eels of either species were generally low in Port Hacking and no significant effect on CPUE of either species was observed for any gear type used at this site. Catches of glass eels of either species were also generally low in the Prosser River, and no significant effect of any environmental/climatic variables on CPUE of shortfin glass eels was observed for any gear type used at this site. CPUE of longfin glass eels in the Prosser River was significantly affected by lunar phase ($F_{1,24}$ = 5.53, P = 0.028, R^2 = 0.21), with CPUE greater during the new moon phase in glass eel nets. In the Snowy River during the current project, CPUE of shortfin glass eels was significantly affected by salinity ($F_{3,110}$ = 2.95, P = 0.037, R^2 = 0.37), temperature ($F_{3,110}$ = 7.20, P = 0.0012, R^2 = 0.37) and lunar phase ($F_{3,110}$ = 5.28, P = 0.0067, R^2 = 0.37), but no effect of river discharge was observed. Tukey's Studentized Range test indicated that CPUE of shortfin glass eels was greatest at medium salinity than at low or high salinity, low temperature than at medium or high temperature, and during the new moon phase rather than during other moon phases. When lagging of river discharge was undertaken in the analyses for both the Albert and Snowy Rivers, only a significant effect on CPUE was observed with a 5 day lag in the Snowy River, suggesting a delayed effect of freshwater discharge on shortfin glass eel recruitment.

Considerable overlap was observed during the main periods of migration of shortfin and longfin glass eels at Port Hacking and in the Albert River in most years. Between 32-79% and 35-82% of the glass eel catch comprised longfin eels during the expected main period of shortfin glass eel migration (nominally May-September) in Port Hacking and the Albert River respectively. Conversely, very little of the catch comprised shortfin glass eels during summer and autumn, when longfin glass eel migration occurs extensively.

When data collected from the Snowy River over the six years encompassing the two glass eel assessment projects (1994-1999) was analysed, CPUE of shortfin glass eels in glass eel nets was significantly greater at low mean salinity ($F_{1,28}$ = 8.38, P = 0.01, R^2 = 0.76), and in stow nets was greatest at medium temperature ($F_{1,60}$ = 23.63, P < 0.0001, R^2 = 0.53).

2.3.2 Length, Weight and Condition

Length, weight and condition of glass eels varied considerably between sites and over time. Despite many statistically significant differences in each of these variables between sites and over time, few consistent patterns emerged which could explain these differences. In addition, the coefficient of determination (R^2) values were often very small, indicating that other factors than those measured influence length, weight and condition of shortfin and longfin glass eels, both spatially and temporally.

For longfin glass eels, the only consistent pattern emerging from the data was consistently larger, in terms of length and weight, and better conditioned longfin glass eels in the Albert River, compared with those from Port Hacking from January to May inclusive in 1998 (P<0.0001, R^2 = 0.07 - 0.47) (Figure 2.17, Figure 2.18 and Figure 2.19). Length, weight and condition of Albert River longfin glass eels were generally greater than those for Port Hacking longfin glass eels in November 1998 and January 1999 (P<0.05), and in August and October 1999 for weight and condition only (P<0.0001). At all other times there was either no consistent significant differences in length, weight or condition of longfin glass eels between sites over time, or any significant differences in length, weight or condition observed were inconsistent between sites and over time.

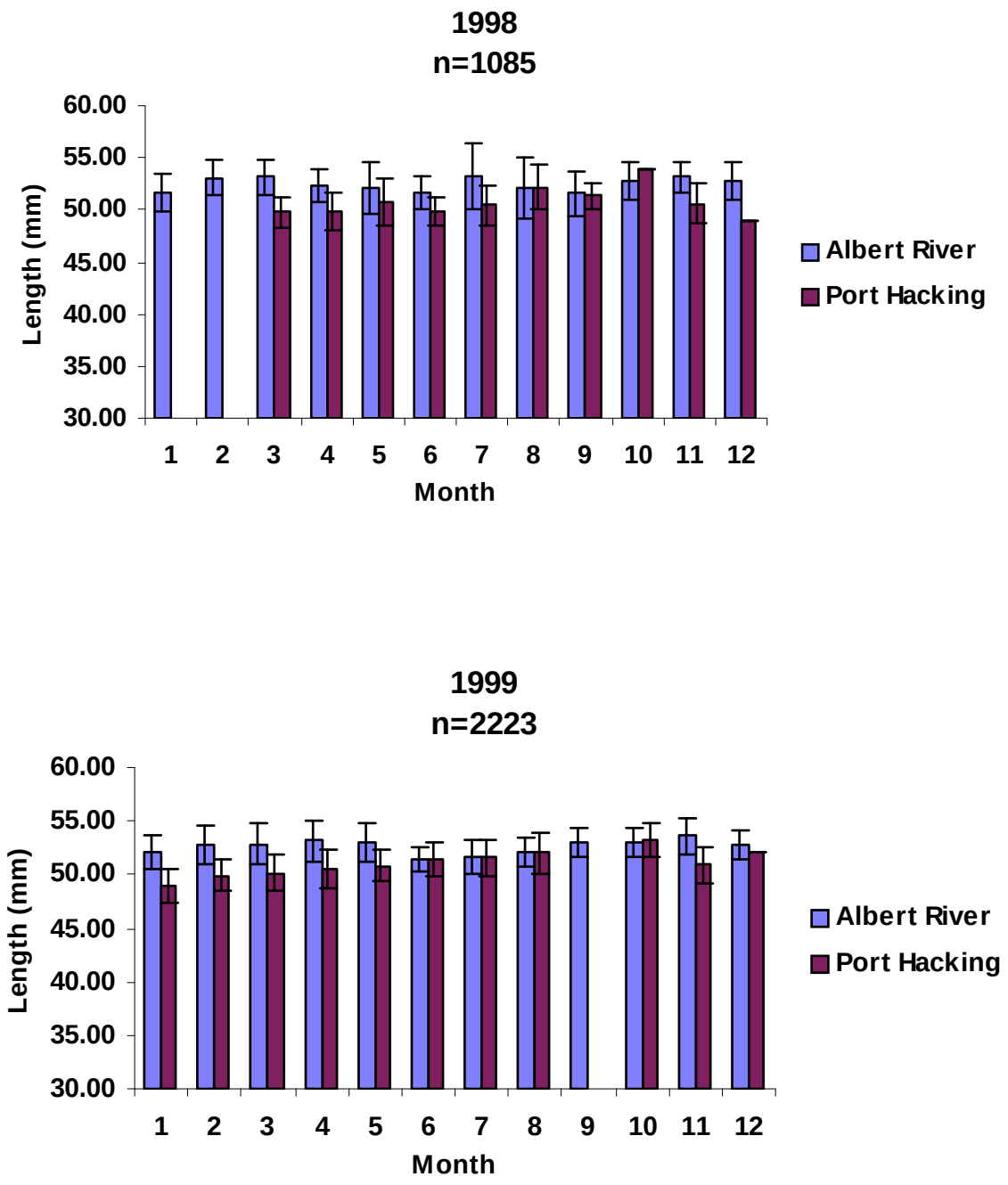


Figure 2.17 Mean length (±SD) of longfin glass eels in 1998 and 1999 (month 1 = January).

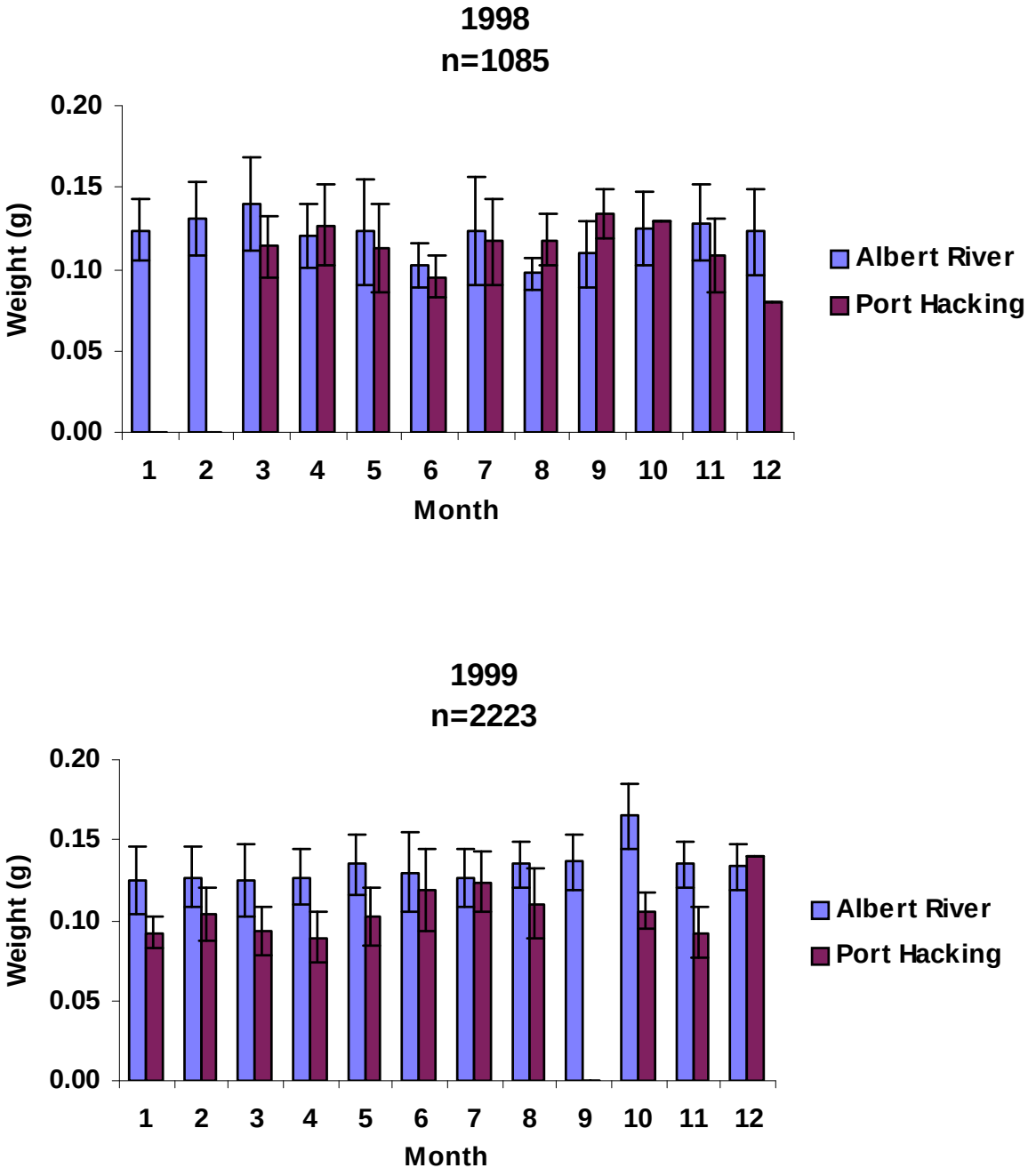


Figure 2.18 Mean weight (±SD) of longfin glass eels in 1998 and 1999 (month 1 = January).

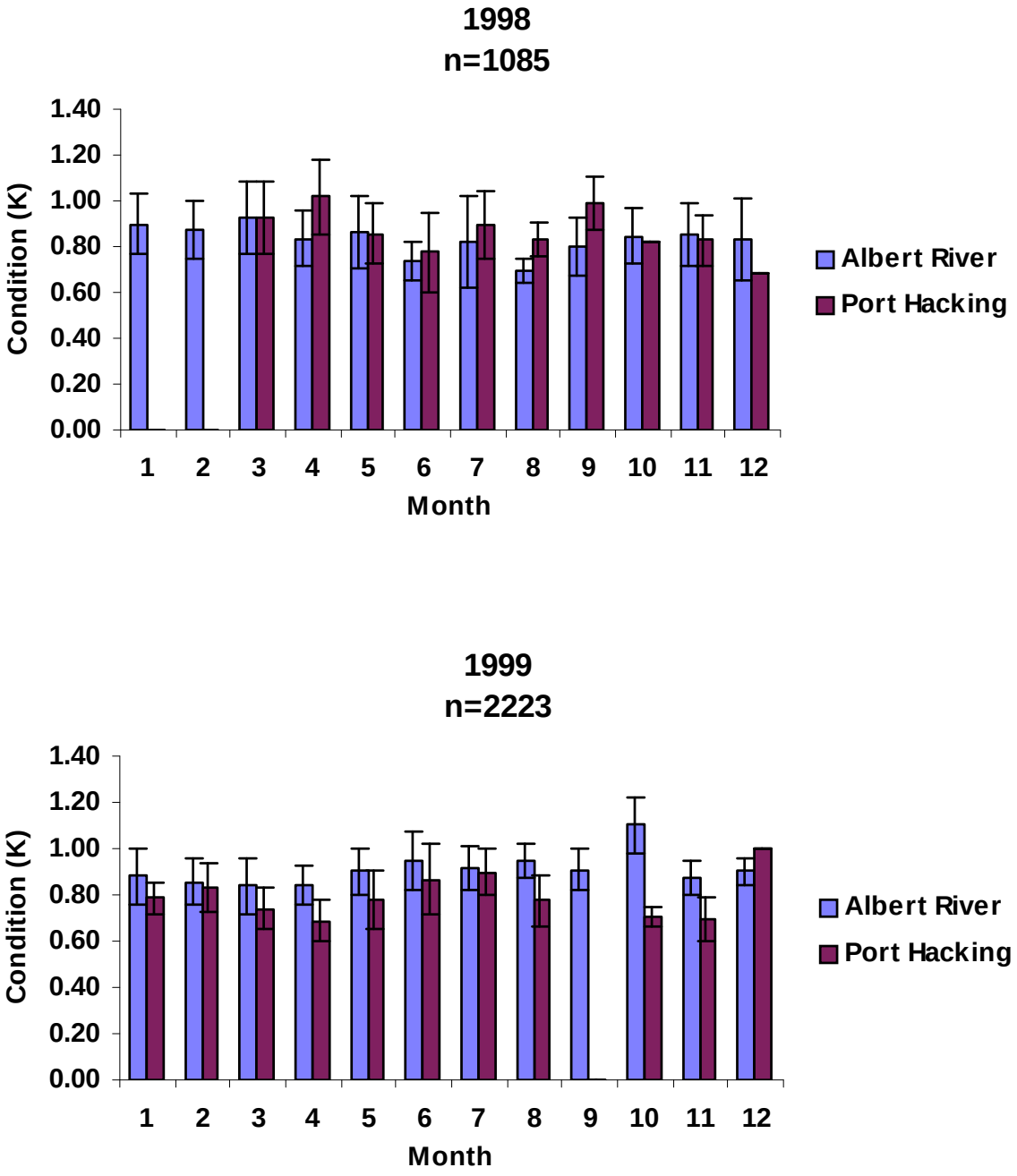


Figure 2.19 Mean condition (± SD) of longfin glass eels in 1998 and 1999 (month 1 = January).

For shortfin glass eels, length, weight and condition were generally greater at the southern sites than in the northern sites over time in each year of the study (Figure 2.20 and Figure 2.21), in the order:

Prosser River > Snowy River > Port Hacking > Albert River (P<0.0001).

Although not statistically significant, the trend for condition of shortfin glass eels suggests that northern sites, particularly the Albert River, produced better conditioned fish than the southern sites over the course of the study (Figure 2.22).

Condition of both shortfin and longfin glass eels was described by the models $W=0.9L^3/10^3$ for Albert River longfin glass eels (N=2774, R^2 = 0.98), $W=0.8L^3/10^3$ for Albert River shortfin glass eels, Port Hacking longfin and shortfin glass eels, and Prosser River shortfin glass eels (N=1561, R^2 = 0.97; N=1464, R^2 = 0.94; N=2182, R^2 = 0.97; N=499, R^2 = 0.94 respectively), and by $W=0.7L^3/10^3$ for Snowy River shortfin glass eels (N=1498, R^2 = 0.98). Overall, condition was represented by $W=0.9L^3/10^3$ for longfin glass eels, and $W=0.8L^3/10^3$ for shortfin glass eels (N=4244, R^2 = 0.97; N=5740, R^2 = 0.97 respectively).

For aquaculture purposes, the number of individual glass eels per kg, also referred to as 'pieces (pcs)/kg', is a useful parameter to assist development of production scenarios and associated cost-benefit analyses. Based on mean weights of all sampled glass eels in the present study, shortfin glass eels numbered approximately 8,300 pcs/kg (mean weight 0.12g/pc) from the Albert River and 5,900 pcs/kg (mean weight 0.17g/pc) from the Snowy River, with an overall mean of approximately 7,100 pcs/kg (mean weight 0.14g/pc) for all shortfin glass eels combined for all sites. Likewise, longfin glass eels numbered approximately 7,700 pcs/kg (mean weight 0.13g/pc) from the Albert River, and 9,100 pcs/kg (mean weight 0.11g/pc) from Port Hacking, with an overall mean of 8,300 pcs/kg (mean weight 0.12g/pc) for all longfin glass eels combined for all sites.

2.3.3 Pigmentation

Pigmentation stage of both shortfin and longfin glass eels varied considerably throughout each respective migration season at all sites in all years, with no clear pattern depicting any progression of pigmentation of either species. When the percentage frequency of each pigmentation stage was compared by month for each river using a chi-square test, month showed a significant (P<0.0001) effect. However little consistency between sites was observed. The only similar pattern observed between sites over all years was a decrease in the frequency of Stage VA shortfin glass eels, and a concurrent increase in frequency of Stage VB shortfin glass eels in the Albert and Snowy Rivers from June to August inclusive. The frequency of both shortfin and longfin glass eels at all pigmentation stages fluctuated between sites and over time, indicating a wide variation in the classification of pigment in glass eels. For longfin and shortfin glass eels, most stages from VB to VIAIV(4) were observed throughout the sampling period at both the Albert River and at Port Hacking, while very few Stage VA glass eels of either species were observed in Port Hacking. Overall, fewer stages were generally observed in shortfin glass eels in the Snowy and Prosser Rivers.

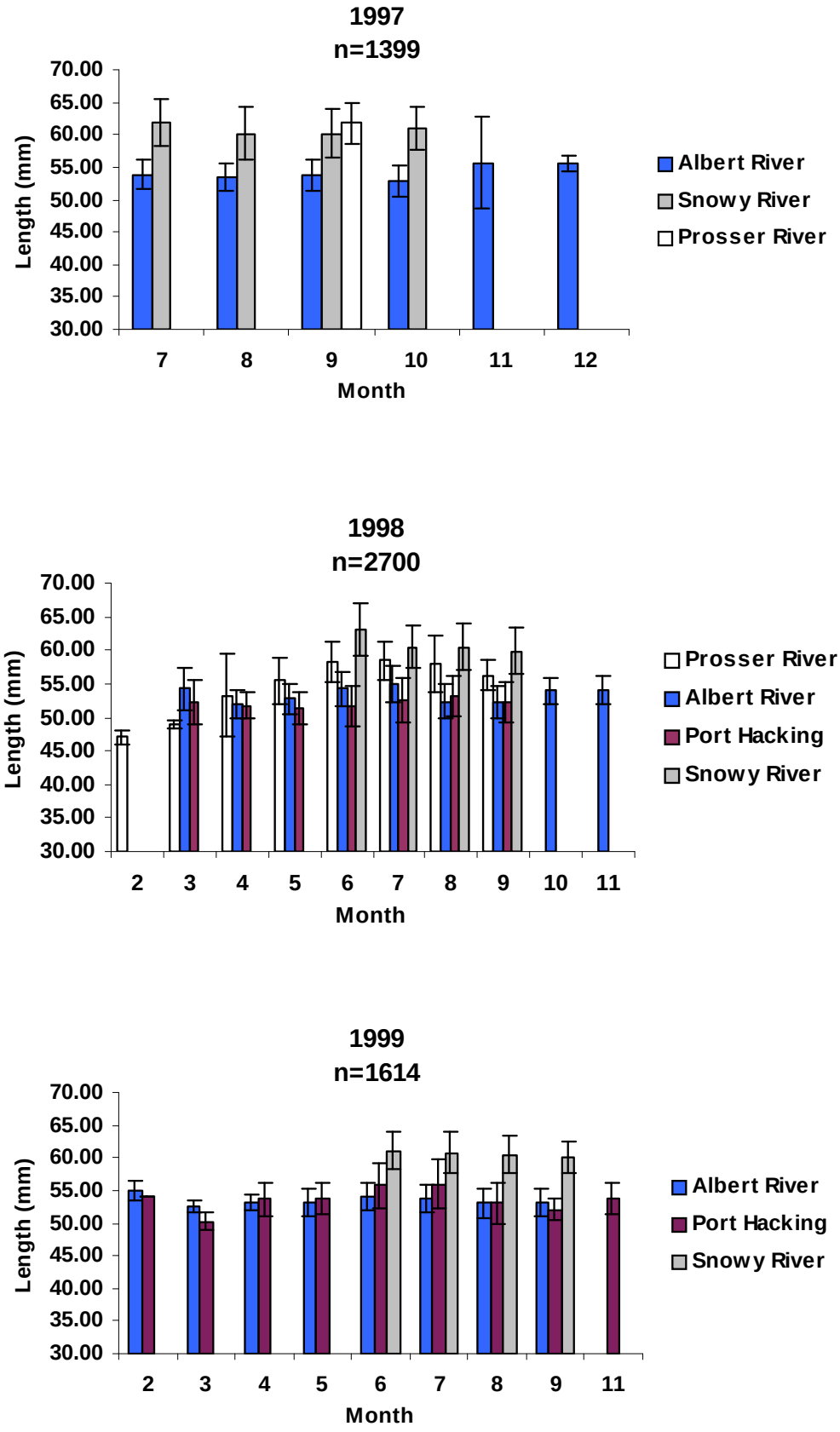


Figure 2.20 Mean length (±SD) of shortfin glass eels in 1997, 1998 and 1999 (month 2 = February and month 7 = July).

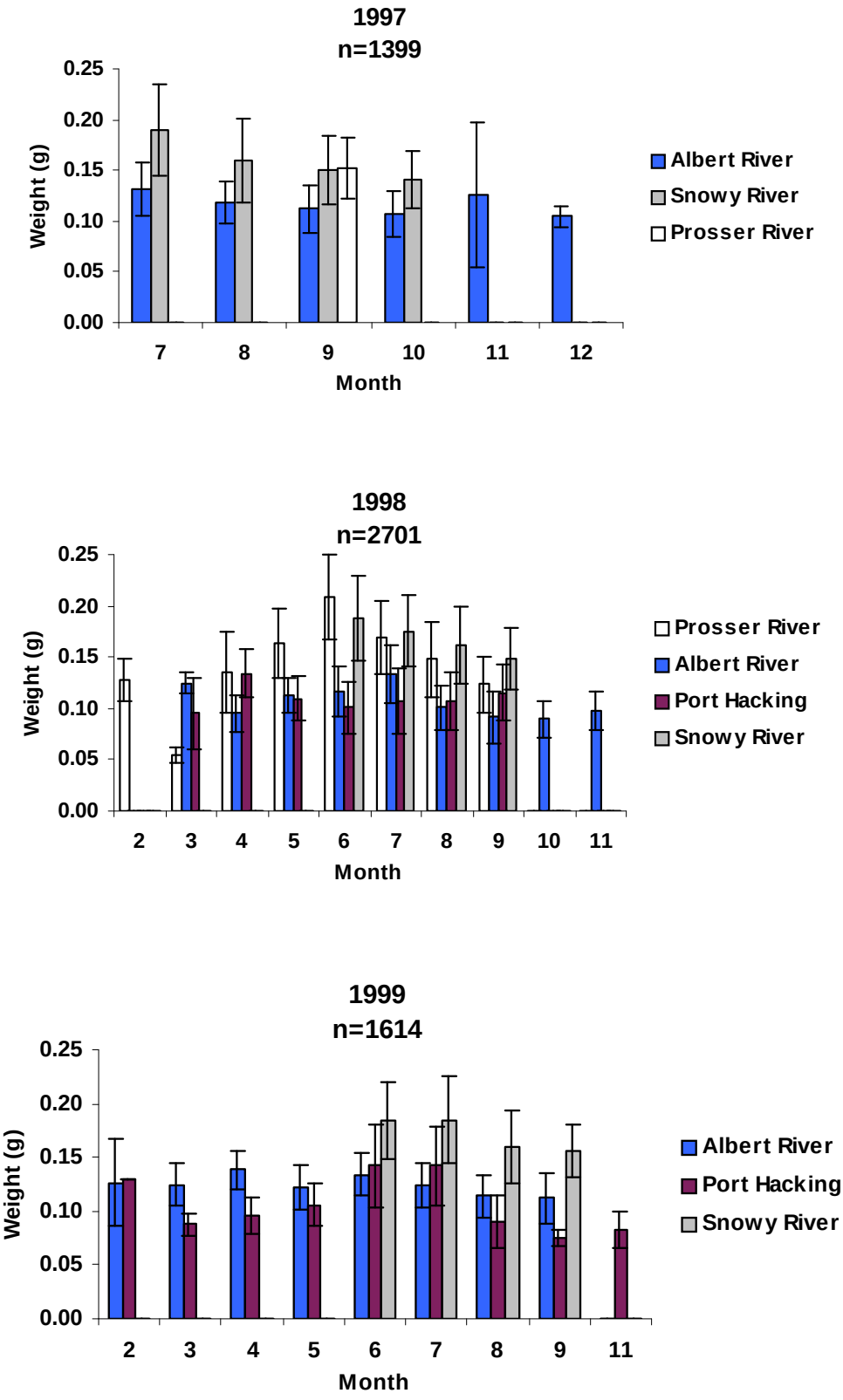


Figure 2.21 Mean weight (±SD) of shortfin glass eels in 1997, 1998 and 1999 (month 2 = February and month 7 = July).

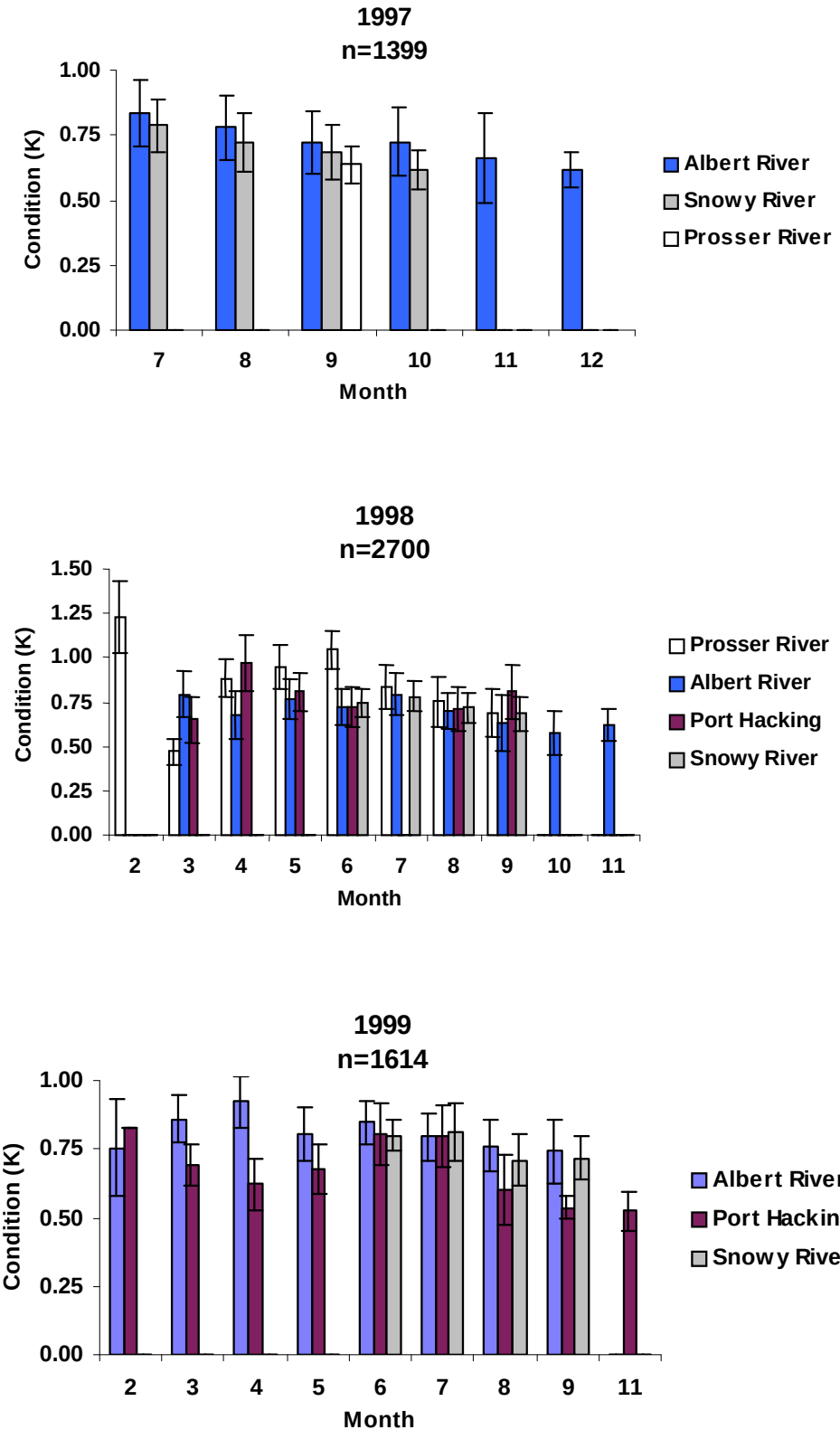


Figure 2.22 Mean condition (±SD) of shortfin glass eels in 1997, 1998 and 1999 (month 2 = February and month 7 = July).

2.3.4 Ageing

Estimates were made of daily age at onset of metamorphosis, total age (age at sample date) and for the time between onset of metamorphosis and total age (post-larval sea life) for both shortfin and longfin glass eels collected from each key site (Figure 2.23). The exact point of recruitment to the estuary was found to be difficult to determine from otolith microstructure. In some otoliths, up to four checks were observed near the otolith edge, which may indicate the point of recruitment to freshwater. In others, no checks at all were observed near the otolith edge. For the purposes of this study, total age of glass eels at the point of collection is therefore referred to, rather than age at recruitment.

Age estimates for shortfin glass eels were made from three seasonal stages (early, mid, late) during the major shortfin glass eel migration period in 1998, while age estimates for longfin glass eels were made from single samples from each site, excluding the Prosser River, Tasmania.

2.3.4.1 Shortfin Glass Eels

Mean putative daily ages for shortfin glass eels from each site and at each stage are shown in Figure 2.24. Mean total age of shortfin glass eels (at point of capture in each estuary) varied from 142.6 ± 17.2 days for early arriving glass eels in the Snowy River, to 218.9 ± 24.4 days for late arriving glass eels in the Albert River (Table 2.8). Overall, total age ranged from 108-259 days. Age at onset of metamorphosis varied from 105.4 ± 13.8 days for early arriving glass eels in the Snowy River, to 175.7 ± 13.1 days for mid-season glass eels in the Prosser River (Table 2.8). Post-larval sea life ranged between 32.2 ± 6.5 days for late arriving glass eels in Port Hacking, to 50.3 ± 8.5 days for late arriving glass eels in the Albert River (Table 2.8). Post-larval sea life was greater in late arriving glass eels at the Albert River ($F_{2,26}$ = 6.56, P<0.005, R^2 = 0.34) than for glass eels arriving earlier, and for late-arriving glass eels at other sites ($F_{3,37}$ = 3.78, P<0.05, R^2 = 0.24) (Figure 2.24). No other differences in age of post-larval sea life were observed. Total age of glass eels in the Snowy River was significantly (between 27.9 and 35.0 days) lower than at the other sites ($F_{3,119}$ = 16.83, P<0.0001, R^2 = 0.45), and total age of early arriving glass eels was significantly lower by 23.2-24.1 days than those arriving later ($F_{2,119}$ = 14.34, P<0.0001, R^2 = 0.45) (Figure 2.24). Age at onset of metamorphosis was also lower for glass eels arriving at the Snowy River by 28.0-35.7 days ($F_{3,117}$ = 20.59, P<0.0001, R^2 = 0.48), and age at onset of metamorphosis of glass eels arriving earlier was 20.9-24.1 days lower than that of glass eels arriving later ($F_{2,117}$ = 15.12, P<0.0001, R^2 = 0.48) (Figure 2.24). By contrast, total age of mid-arriving glass eels in the Prosser River was greater than that of those arriving later ($F_{1,14}$ = 6.53, P<0.05, R^2 = 0.32) (Figure 2.24).

Shortfin glass eels arriving at the Snowy River are younger, and commence metamorphosis at an earlier age, than those arriving at the Albert River, Port Hacking and the Prosser River at the same point in time. In addition, glass eels arriving earlier in the season are younger, and commence metamorphosis at an earlier age, than those arriving later in the season. For shortfin glass eels the period of post-larval sea life as glass eels is generally no different between sites or over time, and differences in age at onset of metamorphosis are reflected in differences in total age. Thus, age of shortfin glass eels recruiting to the estuary is determined predominantly by the duration of the larval phase.

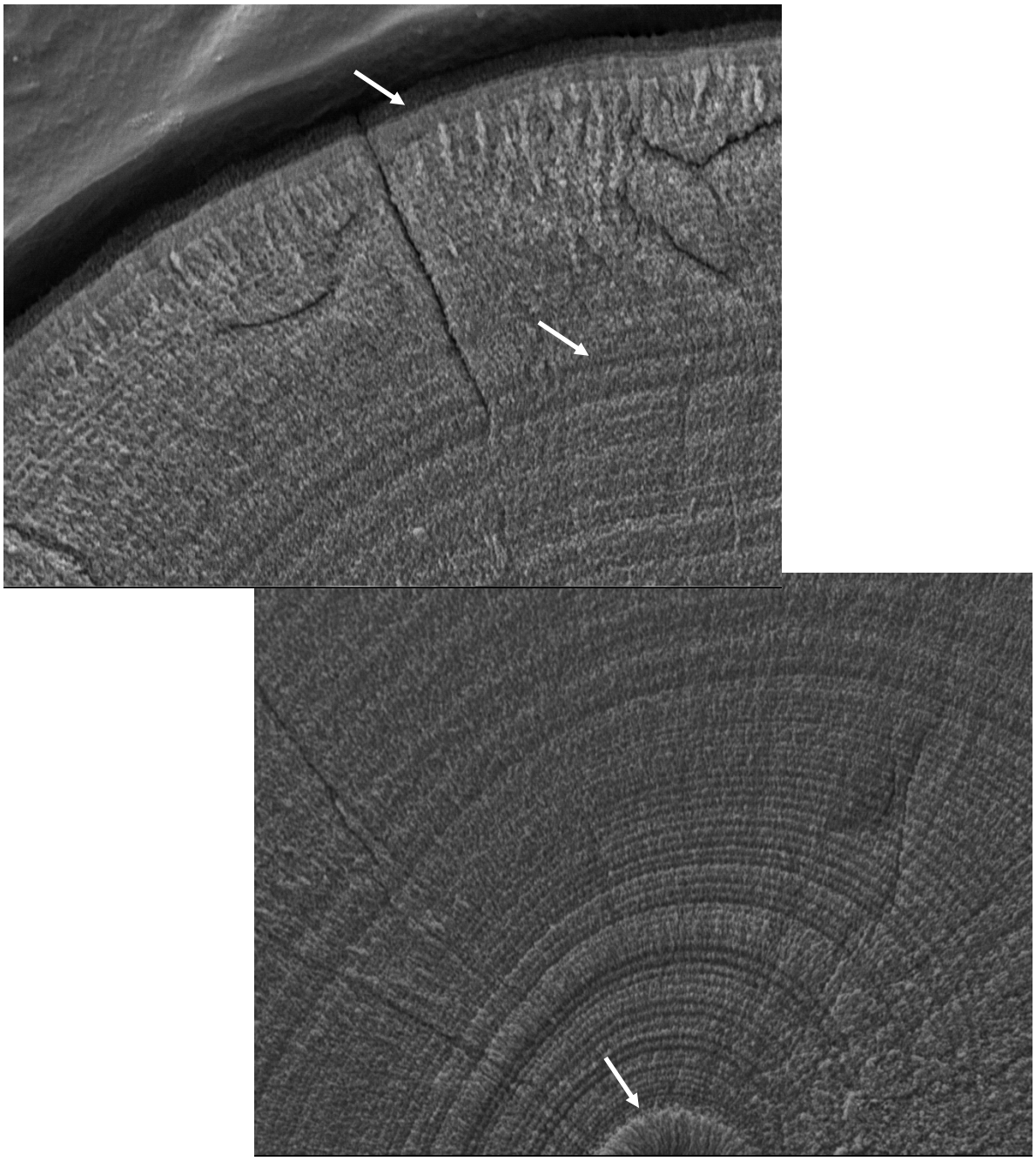


Figure 2.23 Scanning electron microscope image of a shortfin glass eel sagittal otolith, sampled Albert River 21/6/98, 52mmTL. Fish was estimated to be 151 days old. Upper arrow indicates otolith edge, central arrow indicates metamorphosis check and lower arrow indicates hatching mark.

Table 2.8 Mean putative daily ages for shortfin glass eels

River	Period	Age Type	No. Days	SD
Albert	Early	Onset of Metamorphosis	153.4	16.8
		Post-Larval	40.8	7.8
		Total Age	194.2	22.8
	Mid	Onset of Metamorphosis	164.8	28.4
		Post-Larval	37.8	7.0
		Total Age	202.5	29.0
	Late	Onset of Metamorphosis	168.6	19.5
		Post-Larval	50.3	8.5
		Total Age	218.9	24.4
Port Hacking	Early	Onset of Metamorphosis	156.1	21.6
		Post-Larval	41.3	9.0
		Total Age	197.3	22.4
	Mid	Onset of Metamorphosis	167.6	17.3
		Post-Larval	37.6	8.0
		Total Age	205.3	20.0
	Late	Onset of Metamorphosis	169.7	26.9
		Post-Larval	32.2	6.5
		Total Age	208.3	27.2
Snowy	Early	Onset of Metamorphosis	105.4	13.8
		Post-Larval	37.3	8.9
		Total Age	142.6	17.2
	Mid	Onset of Metamorphosis	149.4	17.5
		Post-Larval	41.2	9.3
		Total Age	189.9	20.4
	Late	Onset of Metamorphosis	143.2	18.4
		Post-Larval	45.4	11.0
		Total Age	188.6	18.1
Prosser	Mid	Onset of Metamorphosis	175.7	13.1
		Post-Larval	41.7	11.2
		Total Age	212.4	11.5
	Late	Onset of Metamorphosis	160.3	8.3
		Post-Larval	39.5	14.3
		Total Age	199.8	13.9

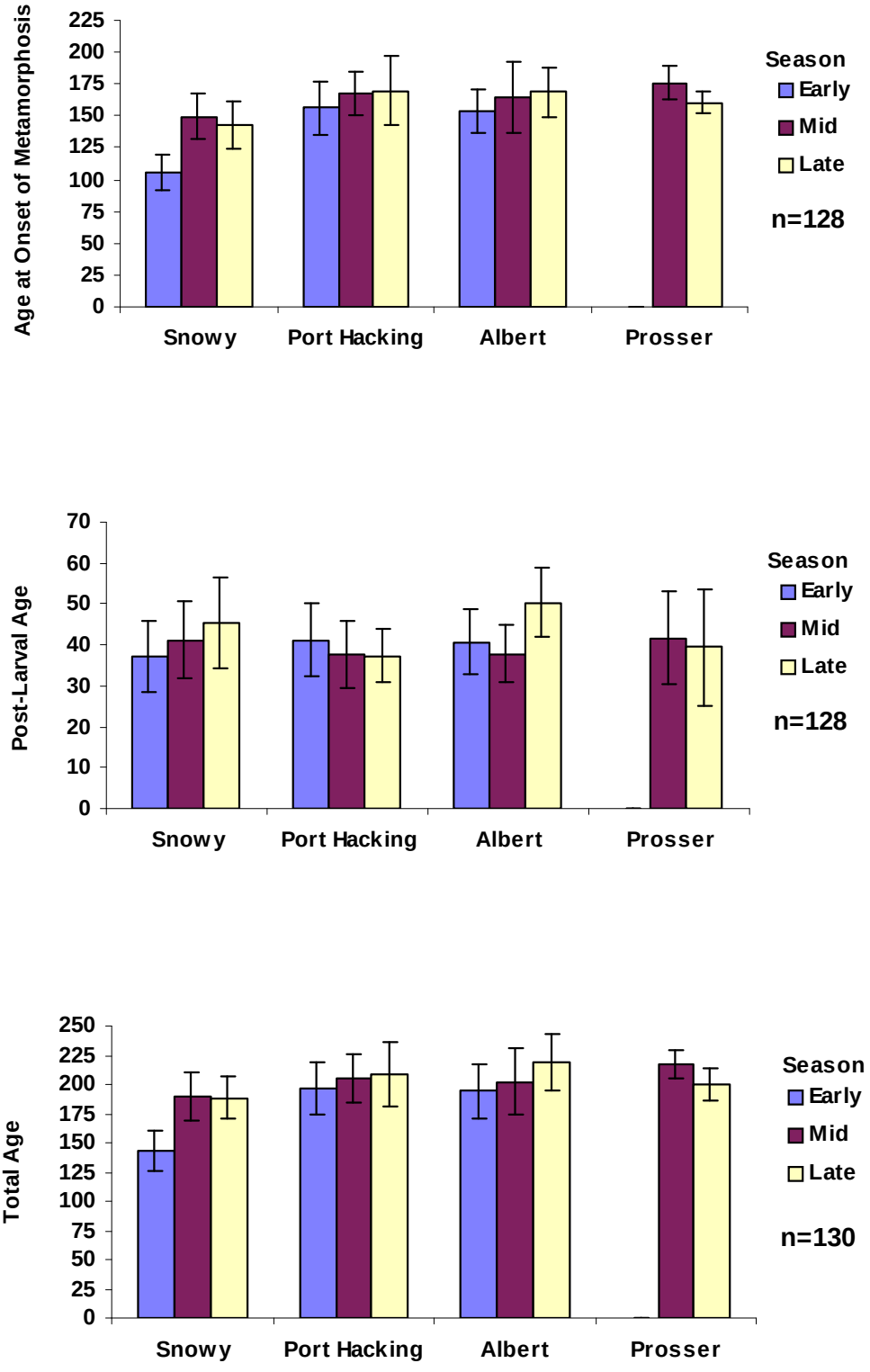


Figure 2.24 Putative daily ages (± SD) of shortfin glass eels from key sites in 1998.

Total length of shortfin glass eels sampled for ageing purposes is summarised in Figure 2.25. Early-arriving shortfin glass eels sampled from the Snowy River were greater in length than those arriving later ($F_{2,72}$ = 5.58, P<0.01, R^2 = 0.13), and than those from the other rivers ($F_{2,72}$ = 99.28, P<0.0001, R^2 = 0.74) (Figure 2.25). Shortfin glass eels arriving at the Snowy and Prosser Rivers during the mid-sampling period were greater in length than those arriving at the same time at the Albert River and at Port Hacking ($F_{3,96}$ = 40.35, P<0.0001, R^2 = 0.56), and shortfin glass eels arriving at the Prosser River during the late sampling period were greater in length than those arriving at the Snowy River, which were in turn, greater in length than those arriving at the Albert River and at Port Hacking during the same period ($F_{3,96}$ = 85.65, P<0.0001, R^2 = 0.73) (Figure 2.25). This strongly suggests that larger glass eels may travel further and arrive at their destination sooner than their smaller counterparts.

In summary, for shortfin glass eels, faster growing animals commence metamorphosis at an earlier age, are larger at recruitment, recruit to estuaries more distant from the spawning area, and do so sooner than their slower growing, later-recruiting, and smaller counterparts.

2.3.4.2 Longfin Glass Eels

Mean putative age at onset of metamorphosis of longfin glass eels ranged from 117.9 ± 12.9 days in samples taken from Port Hacking, to 126.3 ± 13.2 days in samples taken from the Snowy River (Table 2.9). The time between onset of metamorphosis and recruitment varied from 39.8 ± 5.6 days in samples taken from the Albert River, to 71.1 ± 13.9 days in samples taken from the Snowy River (Table 2.9). Total age varied from 164.1 ± 14.8 days in samples taken from the Albert River, to 197.4 ± 21.8 days in samples taken from the Snowy River (Table 2.9). No significant differences in age at onset of metamorphosis were observed between sites, however the post-larval period of sea life was greater in longfin glass eels from the Snowy River than for glass eels from the Albert River or Port Hacking ($F_{2,48}$ = 26.98, P<0.0001, R^2 = 0.53) (Figure 2.26). Consequently, total age of longfin glass eels from the Snowy River was also greater than that of longfin glass eels from the Albert River or Port Hacking ($F_{2,48}$ = 17.01, P<0.0001, R^2 = 0.42) (Figure 2.26), suggesting that, in contrast to shortfin eels, age of longfin glass eels at recruitment is determined predominantly by length of post-larval sea life, which may be determined in part by distance travelled during the post-larval phase. No significant differences in length of longfin glass eels were observed between sites in the samples used for ageing.

Overall, shortfin glass eels had a longer larval phase than longfin glass eels ($F_{1,177}$ = 35.3, P<0.0001), shorter post metamorphic oceanic phase ($F_{1,177}$ = 72.8, P<0.0001) and a greater total age at sampling ($F_{1,179}$ = 320.4, P<<0.0001). Comparing each species by site, total age of shortfin glass eels was greater than that of longfin glass eels from the Albert River ($F_{1,44}$ = 32.5, P<0.0001) due to differences in length of the larval phase ($F_{1,44}$ = 36.1, P<0.0001), whereas total age of shortfin glass eels from the Snowy River was less than that of longfin glass eels ($F_{1,52}$ = 7.5, P<0.01) due to differences in duration of post-larval sea life ($F_{1,51}$ = 77.1, P<0.0001). Shortfin glass eels sampled from Port Hacking were older at onset of metamorphosis than longfin glass eels ($F_{1,62}$ = 69.1, P<0.0001), and had a shorter post-larval sea life than longfin glass eels ($F_{1,62}$ = 11.5, P<0.01). Overall, total age of shortfin glass eels from Port Hacking was greater than that of longfin glass eels ($F_{1,63}$ = 37.2, P<0.0001). In longfin glass eels, the period of post-larval sea life appears to increase from north to south.

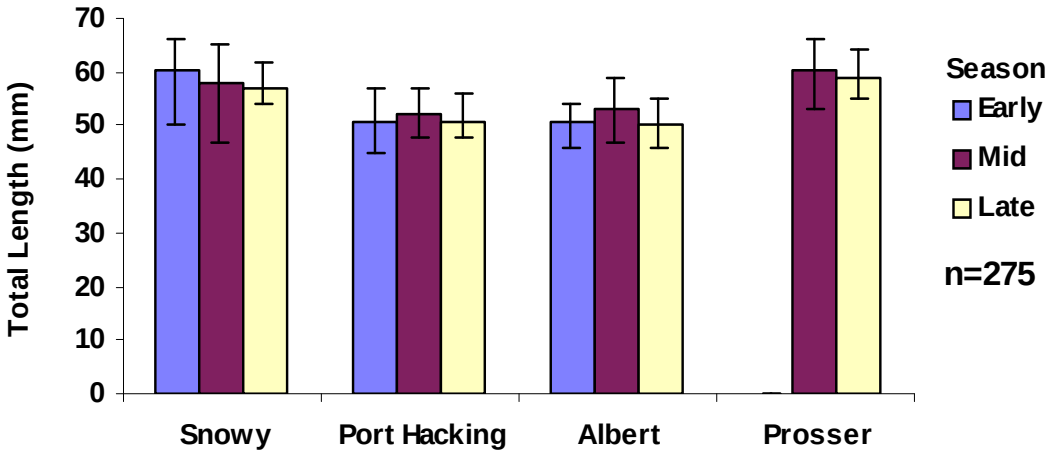


Figure 2.25 Total length (± SD) of shortfin glass eels from key sites in 1998

Table 2.9 Mean putative daily ages of longfin glass eels.

River	Age Type	No. Days	SD
Albert	Onset of Metamorphosis	124.3	15.8
	Post-Larval	39.8	5.6
	Total Age	164.1	14.8
Port Hacking	Onset of Metamorphosis	117.9	12.9
	Post-Larval	48.7	15.7
	Total Age	166.6	17.7
Snowy	Onset of Metamorphosis	126.3	13.2
	Post-Larval	71.1	13.9
	Total Age	197.4	21.8

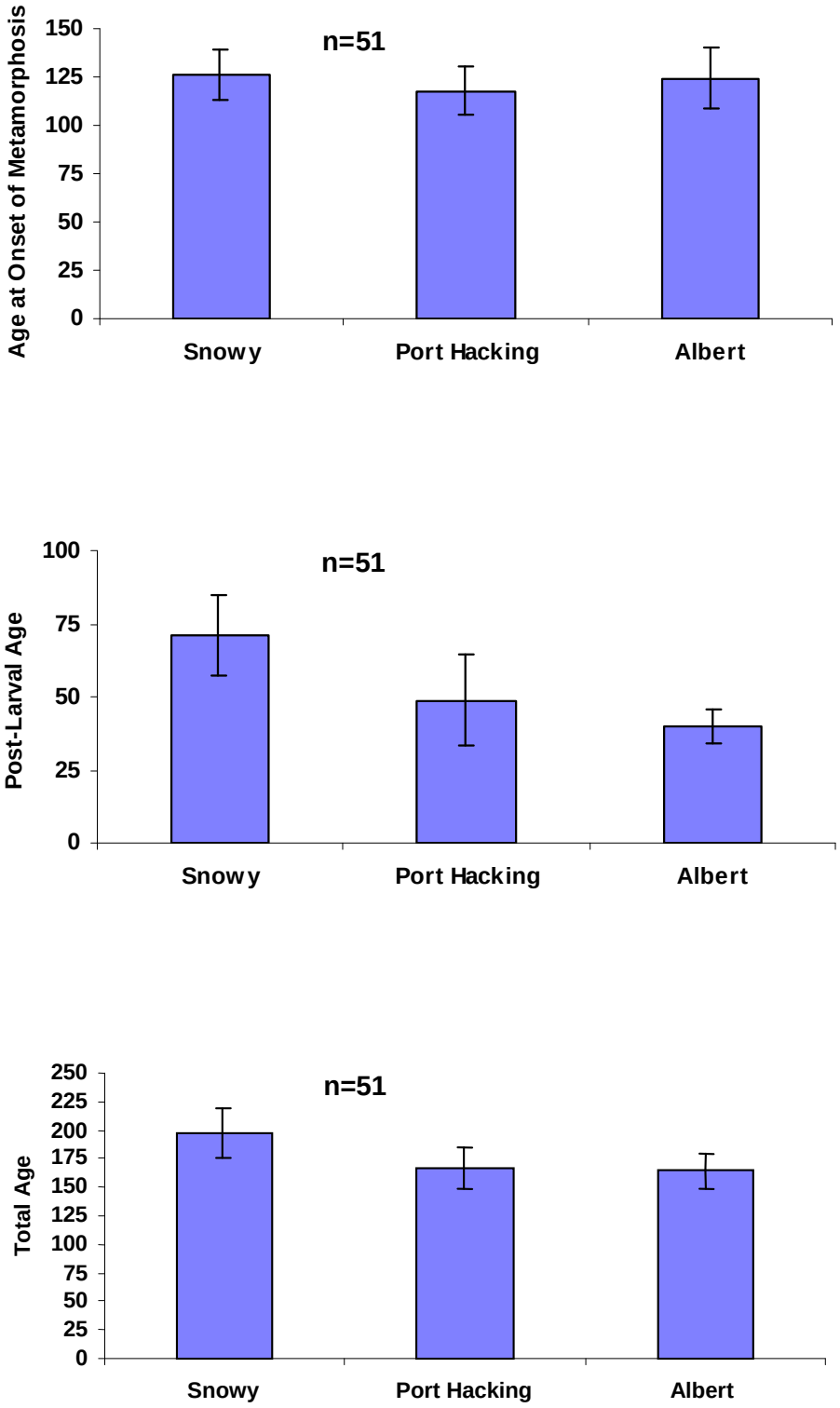


Figure 2.26 Putative daily ages (± SD) of longfin glass eels sampled from key sites during the present study.

2.3.4.3 Hatching date

The estimated hatching dates of shortfin and longfin glass eels are summarised in Table 2.10. Hatching dates of shortfin glass eels ranged from 20 October, 1997 for early season glass eels arriving at Port Hacking in 1998, to 7 March, 1998 for late season glass eels arriving at the Snowy River the same year (Table 2.10). Estimated hatching dates therefore reflect the different sampling dates. For longfin glass eels, the estimated hatching dates ranged from 5 July, 2000 for glass eels arriving at the Snowy River in February 2001, to 11 October, 1998 for glass eels arriving at the Albert River in February, 1999 (Table 2.10).

2.3.5 Temporal and Geographical Distribution

The numerical hydrodynamic dispersal model POL3DD (Black 1996; Jenkins *et al.* 2000) was run in reverse for 100 days prior to sampling dates in the Snowy River in 1996, 1997 and 1998 respectively, to determine the likely positions of shortfin glass eels prior to collection in each year. In each case, assuming passive transportation and random movement of particles (glass eels) through the water column, the model indicated that shortfin glass eels were predominantly west of the Snowy River, between Lakes Entrance and Cape Otway, 100 days before sampling (Figure 2.27). Within the 100 day period, the model predicted that glass eels traversed across much of the area encompassed by Bass Strait, from Point Hicks to Cape Otway and northern Tasmania (Figure 2.27).

The results of the model run tend to contradict the generally held belief that glass eels arrive in Australian estuaries, including the estuaries in Bass Strait, from the east. Indeed, the model suggests that if glass eels rely on passive transport, then shortfin glass eels must enter Bass Strait from the opposite direction. However, in practice it is more likely that glass eels enter Bass Strait from the east and employ active swimming, with support from favourable coastal currents and tidal flows when available, to migrate toward and into estuaries. Such migration patterns, for both shortfin and longfin eel, as leptocephali and glass eels, are depicted in Figure 2.28.

2.3.6 Mark-Recapture Trials

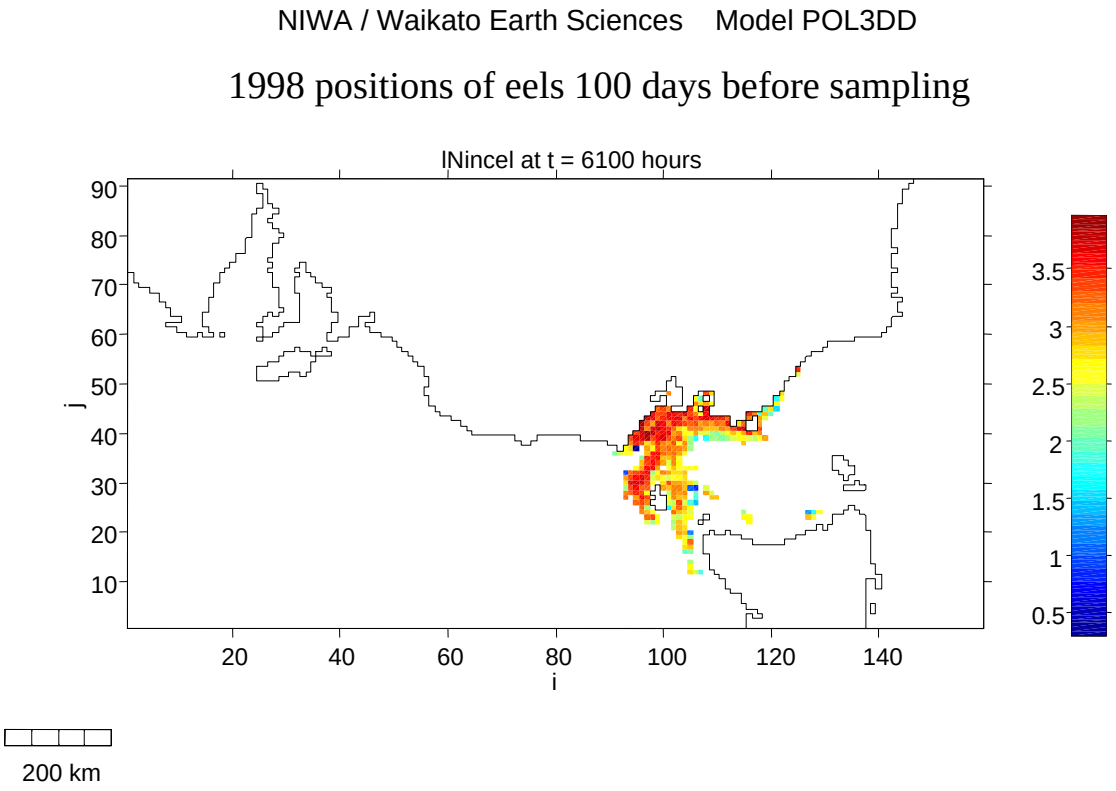
The average total number of recaptures and pattern of recaptures of marked fish varied in accordance with the distance of the respective release sites from the recapture site. In the Albert R, an average of 36 ± 9 % of all marked animals released 0.1 km downstream of the harvest site were recaptured within a period of 4 days at liberty. The majority of recaptured animals, approximately 78 ± 13 % of all recaptures, were recovered within 24 hrs of their release. Similarly, an average of 39 ± 17 % of all marked glass eels released 1 km downstream of the harvest site were recaptured also after 4 days at liberty. However, the majority of recaptured animals, an average of 75 ± 10 %, were recaptured on the second night as opposed to the first night of liberty. A total of 19 ± 5 % of the animals released 12 km downstream were recovered over a period of five days. In this instance, the majority of recaptures were obtained on the second and third nights of liberty and represented an average of 64 ± 12 % and 25 ± 17 % respectively of all recaptured eels. Conversely, recapture rates in the Snowy River were extremely low with less than 5% of marked glass eels recaptured in 1998, and less than 0.2% of marked glass eels recaptured after two releases in 1999 (Table 2.11). Mortality of OTC marked glass eels, retained as controls, was negligible.

Table 2.10 Estimated hatching dates for shortfin (SF) and longfin (LF) glass eels by key site and season (SF only).

Site	Species	Collection Date	Season	Earliest Hatching Date	Latest Hatching Date
Albert River	SF	21/06/1998	Early	11/11/1997	21/01/1998
	SF	17/07/1998	Mid	23/11/1997	11/02/1998
	SF	17/08/1998	Late	01/12/1997	04/02/1998
	LF	26/02/1999		10/08/1998	11/10/1998
Port Hacking	SF	11/06/1998	Early	20/10/1997	18/01/1998
	SF	26/07/1998	Mid	02/12/1997	24/02/1998
	SF	10/08/1998	Late	27/11/1997	26/02/1998
	LF	19/02/1999		30/07/1998	26/09/1998
Snowy River	SF	13/06/1998	Early	28/12/1997	25/02/1998
	SF	18/07/1998	Mid	14/12/1997	18/02/1998
	SF	10/08/1998	Late	03/01/1998	07/03/1998
	LF	26/02/2001		05/07/2000	24/09/2000
Prosser River	SF	12/07/1998	Mid	22/11/1997	23/12/1997
	SF	10/08/1998	Late	06/01/1998	14/02/1998

Table 2.11 Releases and recaptures of OTC marked glass eels at key sites during the present study.

Site/Year	Mean Quantity Released (kg)	Recapture rate (%)
Snowy River 1998	4.0	<5.0
Snowy River 1999	4.5	0.13
	5.0	0.19
Albert River 1998	1.5	16.0
	1.5	37.0
	1.5	57.5
	1.5	37.0
	1.5	26.0
	1.5	21.0
	1.5	22.0



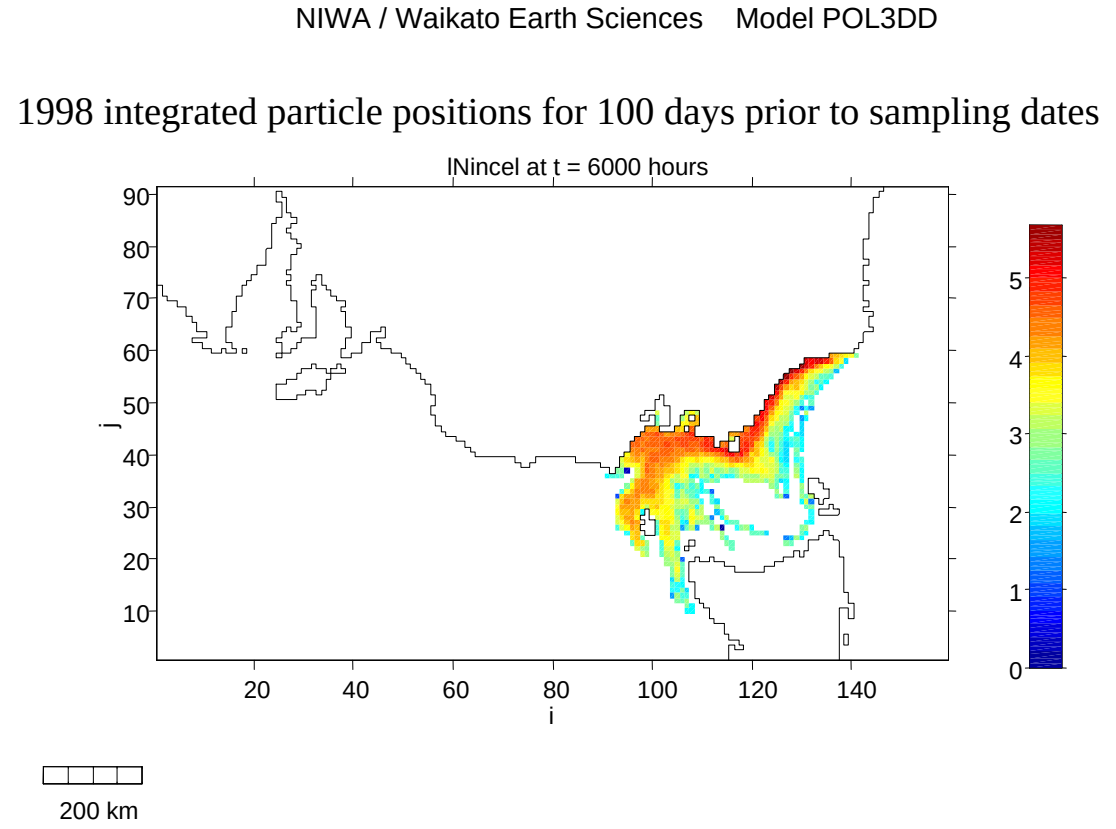


Figure 2.27 Results of numerical hydrodynamic model indicating positions of glass eels 100 days before sampling in 1998, assuming passive drift**.**

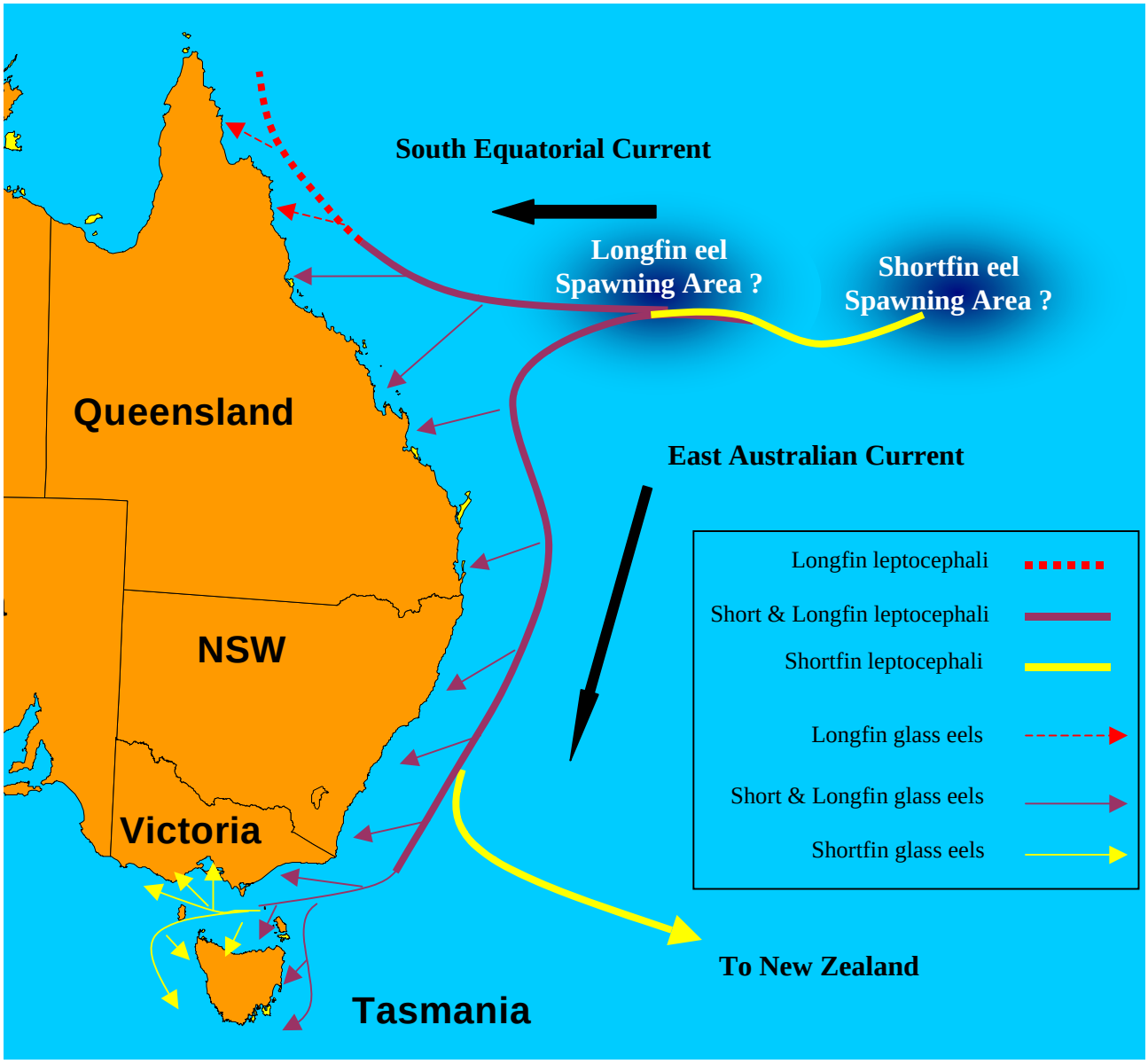


Figure 2.28 Suggested migration routes of shortfin and longfin leptocephali and glass eels from the supposed spawning areas to coastal waters.

2.3.7 Bycatch

Summaries of bycatch caught at each site of the three years of the project are presented in the Appendices. The composition of the bycatch was very diverse at each site over the three years of the project. The bycatch over the three years of the project comprised 40 species from the Albert River, including 5 crustacean and 35 fish species, 47 species from Port Hacking, including 2 mollusc, 2 crustacean and 43 fish species, 76 species from the Snowy River, including 12 crustacean, 3 mollusc and 54 fish species, and 33 species from the Prosser River, including 7 crustaceans, 1 mollusc and 25 fish species, many of which were caught repeatedly over the life of the project. In general, the majority of bycatch, in terms of quantity and diversity, comprised small species, such as glassfish (*Ambassis* spp.) at the Albert River and Port Hacking, galaxiids at the Snowy River and Prosser River, sandy sprat (*Hyperlophus vittatus*) at Port Hacking and the Snowy River, hardyheads (Atherinidae) at the Prosser River, and shrimp (*Macrobrachium* spp., *Haplostylus dakini*) at all sites. Often juveniles of larger species were observed in the bycatch, including catfish (*Plotosus lineatus*) at the Albert River and Port Hacking, tailor (*Pomatomus saltatrix*) and black bream (*Acanthopagrus butcheri*) at the Snowy River, and Australian salmon (*Arripis trutta*) and yellow eye mullet (*Aldrichetta forsteri*) at the Prosser River. In general, the fishing methods used resulted in high bycatch mortality, even when nets were cleared at frequent intervals (hourly, or more frequently).

Bycatch reduction devices (BRDs), both based on the Nordmøre grid design, employed at the Snowy River and Port Hacking returned differing results. The BRD used at Port Hacking was designed primarily for the purpose of deflecting the large quantities of jellyfish which would otherwise quickly fill and block the net, requiring constant clearing and resulting in decreased fishing efficiency. Spacing between the bars on the grid was consequently large enough (10mm) to permit the passage of most other smaller species, including glass eels, whilst being sufficiently narrow to reduce the entry of jellyfish into the net. When the spacing was reduced to 5mm, bycatch of jellyfish and other species was further reduced but the more narrow grid spacing could result in the grid being jammed with small fish. The BRD used in the Snowy River was designed using narrower spaced bars (3mm spacing) to deflect smaller bycatch species while still allowing the passage of glass eels into the codend of the net.

The BRD used at the Port Hacking site proved to be very useful in dealing with the problem of jellyfish entering the net, but the bar spacing was too great to prevent smaller species from entering the net, whilst that used in the Snowy River, although effectively deflecting bycatch, tended to result in the deflection of significant quantities (up to half the total catch) of glass eels as well.

CPUE of bycatch (kg/net/hr) was observed to decrease in the latter part of the 1999 shortfin glass eel migration season (Figure 2.29). This coincided with higher CPUE of glass eels, although no correlation between the two was observed. In addition, no correlation between CPUE of total bycatch and any environmental criteria measured was observed.

Stomach contents of the smaller bycatch fish species comprised mainly copepods and the opossum shrimp (*Haplostylus dakini*), as well as amphipods and plant material. Larger bycatch species such as tailor contained small fish (sprat, anchovies, gobies) and opossum shrimp. One glass eel was recorded in the stomach contents of a smooth toadfish (*Tetractenos glaber*), indicating that predation of glass eels by other fish species in the estuary may be limited.

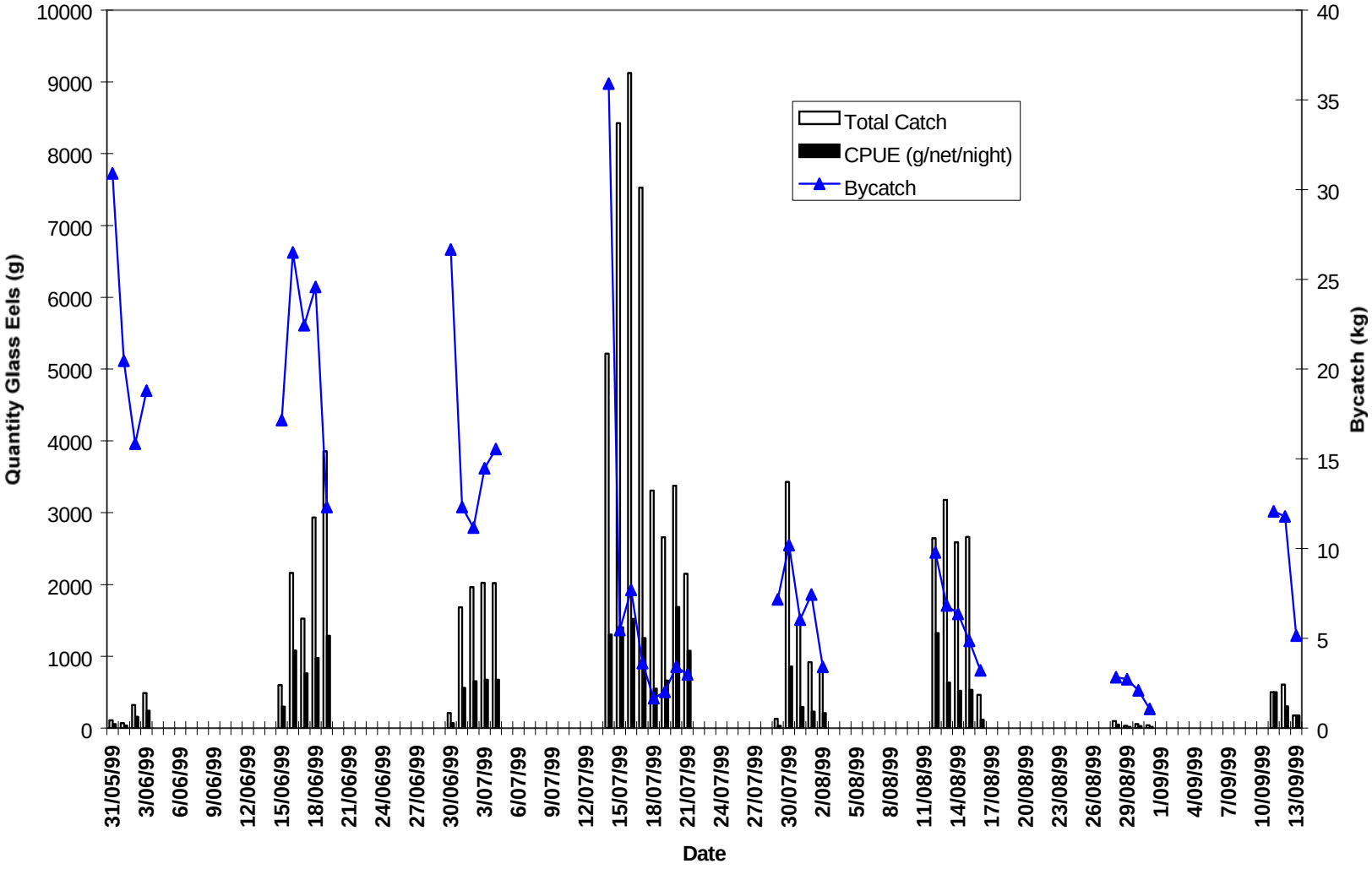


Figure 2.29 CPUE of bycatch and shortfin glass eels in the Snowy River, 1999**.**

2.4 DISCUSSION

2.4.1 Glass Eel Abundance

CPUE of both species of glass eels is highly variable between sites and seasons. The greatest potential for the commercial development of glass eel fisheries, of all sites studied, appears to be in the Albert and Snowy Rivers with up to 100kg caught annually at each site. However local climatic conditions may severely affect access to these fishing sites. On several occasions, high river flows in both the Albert and Snowy Rivers prevented fishing access, often under otherwise optimal fishing conditions, ie. season, lunar/tidal phase. Such events, occurring in 1999 in the Albert River and in both 1997 and 1998 in the Snowy River, prohibited sampling at predetermined times, thus adding to the high degree of variability in the data. In addition, high recapture rates of glass eels in the Albert River suggest that fishing mortality of glass eels is very high, and stocks may be expected to be at risk of overfishing under commercial harvesting conditions. Conversely, it appears that fishing mortality of shortfin glass eels in the Snowy River is relatively low, thus this resource could potentially better support sustainable commercial glass eel harvesting.

Abundance of glass eels of both species was comparatively low in Port Hacking and the Prosser River, with a maximum of about 67g/net/hour of longfin glass eels (Figure 2.16) and 570g/net/hour of shortfin glass eels caught in Port Hacking, and a maximum of only 7.6g/net/hour of shortfin glass eels caught in the Prosser River (Figure 2.15). It is possible that site selection may not have been ideal to maximise glass eel catch at these sites, although in the case of Port Hacking, the sampling site at Point Danger (Site 1, Figure 2.5) was at a natural constriction in the river channel and it is considered that this would have provided one of the best available opportunities for glass eel fishing in the general area. Audley Weir (Sites 2 & 4, Figure 2.5) also provides a potentially viable glass eel harvesting site, although the abundance of either species of glass eel does not appear to be of commercial scale, in comparison with the Albert and Snowy Rivers. It may be that the location and/or orientation of the estuary itself may not be conducive to high natural eel recruitment from the ocean, or that low river flows in the years when sampling was undertaken may have provided insufficient cues for glass eel recruitment to Port Hacking. Recruitment of shortfin glass eels in the Port Hacking estuary was greater than that for longfin glass eels overall, however numbers of shortfin glass eels arriving upstream at the point of entry to freshwater (Audley Weir) was an order of magnitude lower than that for longfin glass eels. Longfin eels dominate the Hacking River catchment, indicating the process of upstream migration of glass eels of both species of eels has important implications for ecological interactions between shortfin and longfin eels (Pease *et al.* 2000). In contrast, the abundance of both shortfin and longfin glass eels in the Albert River, some 42km upstream from the sea, was generally of the same magnitude for both species in each year of the study.

The sampling site in the Prosser River was less than 300m from the river mouth which would be expected to maximise catch of glass eels during estuarine invasion. However, the methodology employed at this site differed on the majority of sampling occasions, for various reasons, from the standard sampling protocol employed at the key sites in the other states. Specifically, fishing at the Prosser River often occurred on diurnal flood tides (flood tides commencing before sunset) in place of nocturnal flood tides for glass eel fishing ie. flood tides commencing at or after sunset. It is likely that this fishing strategy contributed to comparatively low catches of glass eels in the Prosser River.

The high rate of glass eel recapture during mark-release activities on the Albert River indicates that the efficiency of glass eel harvesting methods at this site is prohibitive for further industry development and resource sustainability. The high average recapture rates of almost 39, 36 and 21 % for marked animals released within 0.1, 1 and 12 km downstream of the recapture site respectively, indicates that CPUE data is likely to be highly indicative of total glass eel abundance. Combined with the relatively low annual total catch of 110, 99.8, and 35.1 kg for the Albert River in 1997, 1998 and 1999 respectively (QFMA and DPI returns), it is questionable as to what extent this river can continue to be used as a primary source of glass eels for an emerging aquaculture industry. Indeed, the impact of such highly efficient harvesting practices on resource sustainability needs to be investigated. A high degree of exploitation of glass eel stocks from a particular river may ultimately affect the standing crop of eels in that river. Such exploitation however, would be unlikely to affect the population of either species as a whole, or the future recruitment of glass eels to that river, given the supposed panmictic nature of each species. If the eel aquaculture industry is to develop in Australia, the risks of potential over-exploitation of eel recruitment to certain productive rivers will need to be assessed in light of the potential benefits of such industry development.

The observed rate of upstream movement by marked glass eels and the associated dispersal pattern observed during recapture clearly demonstrated that incoming flood tides are utilised by both species to facilitate upstream riverine migration. While most animals released within 0.1 km of the harvest site on the Albert River were recaptured during the subsequent flood tide, it took an additional tidal cycle for the majority of marked animals released 1 km downstream to reach the recapture site. However, despite the additional time taken to reach the recapture site this arrival was directly associated with the arrival of the next flood tide. Releases conducted even further downstream (12 km) also demonstrate that while the flood tide is actively utilised to assist migration, some glass eels appear likely to continue to push upstream despite its absence. Marked animals were recaptured within 24 hrs of their release during the next available flood tide. Consequently, either flood tide was sufficient in velocity and duration to assist faster or more active glass eels to negotiate this distance within a few hours, or some glass eels continue to migrate upstream during the day or during nightly ebb tides. The possibility of glass eels remaining active during the day in estuarine areas is likely to increase as turbidity increases and reduces light intensity. Glass eels were observed in this study, attempting to negotiate many tidally influenced structures such as weirs and fishways during the day when turbidity was high. The movement of glass eels under conditions other than those associated with the nightly flood tide is understandable given these animals will quite rapidly move past the tidally influenced zone of the estuary and enter more stable hydrological conditions.

Assuming marked glass eels resumed their normal behaviour upon release, the low recapture rate of glass eels in the Snowy River suggests that fishing mortality of glass eels is extremely low at this site. This further indicates that the glass eel resource has the potential to sustain some degree of fishing pressure, at least at the level imposed during the present study, without affecting recruitment of glass eels to the catchment. Conversely, recapture rates of both shortfin and longfin glass eels in the Albert River were continuously high, suggesting a high degree of fishing efficiency/mortality. The clear differences in recapture rate of glass eels at the respective sites is indicative of the nature of each river. The Snowy River at the sampling site is a relatively open system, with glass eels potentially able to migrate along four separate major routes in the lower Snowy system between the point of release and the point of capture. In addition, the sampling equipment used is only able to ‘block off’ less than one-third of the width of the river at the sampling site on the Snowy River, potentially allowing a high degree of net avoidance. Conversely, glass eels in the Albert River may only migrate along one

major route between the release site(s) and the sampling location, and the river can be completely and effectively blocked off with fishing gear at the point of capture. The negligible mortality observed among retained tagged glass eels indicates little trauma due to the tagging treatment. Other impacts on recapture rates may have included predation and/or immobility of tagged glass eels on return to the wild, neither of which were able to be assessed within the scope of this work.

The high degree of inconsistency observed between the effects of the various environmental/climatic variables on both shortfin and longfin glass eel abundance, again is compounded by the high degree of variability in the data. However, lunar phase exhibits the most consistent effect on CPUE, with greater catches of shortfin glass eels, in particular, in the Albert and Snowy Rivers, occurring during a new moon phase. Significant effects of salinity and temperature on shortfin glass eel abundance were repeatedly observed in the Snowy River for both the three year (present study) and six year (present plus previous glass eel study) periods. However, the range of each of these variables which affects glass eel abundance is variable, with both low and medium salinity and low and medium temperature found to significantly affect CPUE independently of one another. From this it appears that both high salinity (>20μS/cm) and high temperature (>11^{o}C) ranges do not affect shortfin glass eel abundance. These observations are consistent with those of earlier studies of shortfin glass eel migration in south-eastern Australia, where temperature, salinity and lunar phase were each found to affect glass eel abundance (McKinnon and Gooley 1998; Gooley *et al.* 1999). These results also agree with studies on the responses of *A. anguilla* and *A. japonica* glass eels to changes in salinity and temperature (Tosi *et al.* 1990; Domingos 1992; Chen *et al.* 1994).

Despite the analyses not suggesting a significant effect of river discharge on glass eel abundance, it is suspected that CPUE of glass eels is likely to be positively affected by high freshwater flows, provided otherwise optimal conditions for glass eel fishing occur immediately following high flow events. Such conditions include new (or to a lesser extent, full) moon phase, and season. High river flows discharge geosmins and other 'earthy odorants' which are known to attract glass eels (Tosi *et al.* 1990; Tosi and Sola 1993; Sola 1995) and resultant decreases in salinity may attract glass eels toward estuaries (Tosi *et al.* 1989). High river flows also clear river mouths and increase primary production in the estuary. All these factors are conducive to promoting high levels of successful recruitment of glass eels to estuaries.

2.4.2 Oceanic and coastal migration of glass eels

The East Australian Current flows southward along the continental margin of the eastern Australian coast to a point between 28^{o} and 36^{o} S where it separates from the coast (Tomczak 1981). Water from the Coral Sea, characterised by an intermediate salinity medium, is entrained in the East Australian Current which transports it southward along the continental margin, at least as far south as Sydney (Rochford 1968). The predominant flow in Bass Strait during winter is from west to east (Baines *et al.* 1991). Bass Strait water, characterised by its temperature-salinity signature, has been found to flow northwards along the continental shelf on the eastern Australian coastline (Tomczak 1985), penetrating into the Tasman Sea and reaching as far as the Coral Sea, over 1000km from the east of Bass Strait (Boland 1971; Tomczak 1981). Thus if spawning of anguillid eels occurs in the region of the Coral Sea, eel leptocephali may be passively transported by the South Equatorial Current toward the north-eastern coast of Australia, then southward by the East Australian Current along the continental shelf. At any point along the continental shelf leptocephali may metamorphose, following which active swimming in glass eels may occur. It may be feasible that water from

Bass Strait, reaching as far north as the Coral Sea, attracts actively swimming glass eels which then orient themselves and swim in the direction of prevailing Bass Strait flows.

Currents along the Queensland coast are far more complex. However, it is known that the East Australian current divides at between 14-18^{o}S, with a southwards flow forming the East Australian Current proper, and the northwards flow eventually feeding the equatorial currents, and flowing through the Indonesian Archipelago (Church 1987). In the rivers and impoundments of Queensland and northern NSW, longfin eels tend to predominate, and shortfin eels appear to suffer significant recruitment failure. It is proposed that the South Equatorial Current transports anguillid leptocephali from their South Pacific spawning area toward the eastern Australian coast, at which point the East Australian Current then bifurcates and directs glass eels of both shortfin and longfin eels into estuaries northwards along the northern Queensland coast, and southwards along the southern Queensland and northern NSW coasts (Figure 2.28). Longfin eels, which are better adapted to tropical, subtropical and warm temperature climates, proliferate in these waters, while the more temperate shortfin eels do not recruit as well. Consequently standing crop of shortfin eels in these catchments is depleted. Other, perhaps bigger and fitter shortfin glass eels and/or larvae, remain entrained in the East Australian Current and its eddies, and/or employ active swimming and migrate southwards, moving into the more optimal, cooler estuaries of southern NSW, Victoria and Tasmania (Figure 2.28).

It is unlikely that shortfin glass eels rely solely on passive transport through their oceanic and coastal migration. The results of available numerical hydrodynamic modelling suggest that passive shortfin glass eel migration in Bass Strait would require glass eels to enter Bass Strait from the west, as the predominant flow direction in Bass Strait is from the west during April/May-November (Baines *et al.* 1991), the period of major shortfin glass eel recruitment. Assuming spawning occurs in the Coral Sea, and essentially passive migration transports leptocephali westwards and southwards off the Australian coast prior to metamorphosis, such a mode of transport through Bass Strait and into Victorian, southern NSW and Tasmanian estuaries seems highly unlikely. It is more probable that glass eels enter Bass Strait from the east and employ active swimming, with support from favourable coastal currents and tidal flows where available, to migrate toward and into estuaries. It is not known at what depth within the water column glass eels undertake their oceanic and coastal migration, although glass eels tend to predominate in mid water during flow-assisted migration within estuaries (McCleave and Kleckner 1982). Flow in Bass Strait is reduced near the sea floor (Neira *et al.* 1998) which may provide less resistance for active glass eel migration against the prevailing currents.

The putative daily age data suggest also that it is extremely unlikely that, 100 days prior to sampling, shortfin glass eels collected in the Snowy River were in the western part of Bass Strait, as predicted by the hydrodynamic model, assuming passive drift of glass eels. Glass eel ages range from approximately 143-190 days post hatching, when entering the Snowy River, and spend between 37-45 days post-metamorphosis before entering the estuary. Assuming spawning of eels occurs somewhere in the South-Pacific Ocean and that metamorphosis from the leptocephalus to the glass eel occurs on or near the Continental Shelf as proposed for other species of anguillid eels (Deelder 1970; Tesch 1977), glass eels destined for Victoria and Tasmania could not have metamorphosed 100 days before sampling but would be expected to be still undergoing oceanic migration off the continental shelf, presumably somewhere in the Tasman Sea. In addition, the distance required to be covered by the leptocephalus/glass eel from the supposed spawning area to south-eastern Australia may be 2000km or greater, requiring a mean travel speed of at least 10-11 km/day. Such travel would be expected to require some form of active migration, thus it would seem unlikely that

glass eels would revert to fully passive migration on entering Bass Strait, if flow assisted active migration in oceanic and/or coastal waters had been previously undertaken (Figure 2.28).

During summer and autumn, the flow in Bass Strait tends to predominate from the east (Neira *et al.* 1998). This may provide increased opportunities for passive, and/or flow-assisted active migration of longfin glass eels at that time of year. Indeed, longfin glass eels may not have the same requirement as shortfin glass eels for active swimming in the oceanic and coastal migration phases, given that the major area of distribution of this species is nearer the supposed spawning area than that of shortfin glass eels. The passive distribution of longfin glass eels at the extremes of the species' natural range is also facilitated by favourable coastal currents during the major periods of longfin glass eel migration.

2.4.3 Spatial and temporal variability in age and size of glass eels

For shortfin glass eels, the bio-physical data collected indicate a high degree of variability in length, weight and condition of glass eels within and between sites over time and over the entire geographical distribution of the species. The trend of increasing size and condition of glass eels from the northern to southern reaches of the species' range at any given time and age, poses interesting conjecture. Coupled with the data indicating that early arriving shortfin glass eels are younger and of larger size, and metamorphose at an earlier age than those arriving later, such distribution of 'superior' animals, which appear to move faster and further than their smaller counterparts, may infer a selective advantage for the species. Geographical distributions of different age-size classes of glass eel have been seen in other anguillid species (Guerault *et al.* 1992; Jessop 1998; Wang and Tzeng 1998), and in *A. australis* previously (Shiao *et al.* 2001). As was found in the present study, Shiao *et al.* (2001) found that glass eels recruiting to southern Australian estuaries were larger than those recruiting to northern estuaries, but that faster-growing and earlier-metamorphosed leptocephali recruited to northern Australia and slow-growing and late-metamorphosed leptocephali recruited to southern Australia. This is in contrast to the results of the present study.

The greater distance travelled by some animals may be associated with an increased risk of recruitment failure due to predation or other environmental or climatic influences, but this may be offset by the inherent increased vigour of these glass eels, due to their larger size and more substantial energy reserves. In addition, the recruitment of larger, more vigorous shortfin glass eels to catchments which are more distant from the spawning area, may be a selective advantage resulting in ultimately stronger adult eels in those catchments. An associated increased propensity for survival may be of ultimate benefit to adult eels from such distant areas on their return spawning migration, given the greater distance required to be covered, compared with eels in areas closer to the spawning area. Likewise, some variation in the quality of glass eels for aquaculture purposes may be apparent with the larger, younger shortfin glass eels arriving earlier in the season. Growth variability and depensation is known to be characteristic of glass eel aquaculture (Heinsbroek 1989; Gooley *et al.* 1999).

The results for longfin glass eel ageing indicate that, conversely to shortfin glass eels, the period of post-metamorphic sea life is greater for glass eels travelling further from the supposed spawning area before recruitment to estuaries, whereas no difference in age at onset of metamorphosis was observed for longfin glass eels sampled from across the species' range. Thus longfin glass eels metamorphose at the same age, but differences in the duration of the post-metamorphic sea life may be observed in glass eels recruiting to spatially distant areas. In contrast, shortfin glass eels recruiting to geographically distant parts of the species' range do not metamorphose at the same age, but experience the same extent of post-metamorphic

sea life, regardless of where recruitment occurs in relation to the spawning area. Longfin glass eels generally had a shorter larval phase than shortfin glass eels, and the duration of post-larval sea life increases progressively in longfin glass eels recruiting to more distant areas. In samples from the Albert River and Port Hacking, longfin glass eels recruiting to the estuaries were younger than shortfin glass eels, however longfin glass eels recruiting to the Snowy River were older than shortfin glass eels at that site, indicating that age of longfin glass eels increases with distance from the spawning area.

For shortfin glass eels, faster growing animals metamorphose at an earlier age, are larger at recruitment, recruit to estuaries more distant from the spawning area, and do so sooner than their slower growing, later-recruiting, and smaller counterparts. For longfin glass eels, age at recruitment may increase with distance from the spawning area due to increasing duration of the post-metamorphic sea life, but no relationship between glass eel size and recruitment appears to exist for longfin glass eels.

Inherent difficulties arise when comparing estimates of total age of glass eels between key sampling sites, due to vastly different characteristics of each of the sites. The major site characteristics which may affect total age of glass eels at the time of sampling include geographic location of each site within each species' distribution, the distance upstream of the sampling site from the river mouth, and the facility with which glass eels may migrate upstream. The latter is in turn affected by individual characteristics of the river, including stream morphology and hydrology, tidal range and velocity, and degree of river discharge, all of which vary seasonally, and may even vary significantly on a daily basis. In the present study, distance from the river mouth to the key sampling location ranged from 300m (Prosser River, Tasmania) to 42km (Albert River, Queensland). As described above, key sampling locations were chosen based on the anticipated ability to maximise glass eel production, which is not necessarily related to proximity to the river mouth.

Glass eels may undergo rapid migration upstream upon entering estuaries, and predominant migrations are known to occur during flood tides where flow-assisted migration occurs (Jellyman 1977b, 1979; McCleave and Kleckner 1982; Gascuel 1986; McKinnon and Gooley 1998). Maximum sustained swimming speeds for *A. australis* and *A. reinhardtii* have been determined at 29 cms^{-1} and 32cms^{-1} respectively (Langdon and Collins 2000). Mark-recapture experiments undertaken as part of this study indicate that glass eels can migrate large distances upstream in estuaries in relatively short periods of time, with marked glass eels found to migrate 12km within 2-3 days of release in the Albert River. Thus, in the present study it may be assumed that any effect of sampling location, relative to river mouth, on the total age of sampled glass eels would be relatively small.

The exact point of time of recruitment to the estuary is difficult to determine from otolith microstructure due to the presence of multiple checks near the edge of a large number of otoliths, any of which could indicate the point of recruitment to freshwater. In some otoliths, no checks at all were observed near the otolith edge, possibly indicating these particular animals were captured immediately upon entering the estuary from the sea. Such variation in the presence, absence and/or number of possible freshwater checks in otoliths occurred in both species at all sites. The total age of glass eels at the point of collection therefore provides an indication only of age at recruitment.

The estimates of hatching dates suggest discrete spawning periods for *A. australis* and *A. reinhardtii*, with hatching of shortfin eels occurring between late October and early March, and that of longfin eels occurring between early July and mid October. The hatching dates proposed for shortfin eel overlap those found for glass eels of the same species sampled from

the North Island of New Zealand in 1996 (2 October, 1995 to 9 January, 1996) (Marui *et al.* 2001) and encompass those estimated for *A. australis* sampled from south-east Queensland and New Zealand in 1996 by Arai *et al.* (1999a) (mid-November, 1995 to early January, 1996, and late November, 1995 to late January, 1996 respectively). For shortfin eels, hatching occurs 42-45 hours after fertilisation (Lokman and Young 2000). In other anguillids, hatching occurs within a similar period of time (36-48 hrs for *A. japonica* (Satoh *et al.* 1992); 46-48 hrs for *A. anguilla* (Prokhorchik 1986). It is reasonably assumed therefore, that hatching in *A. reinhardtii* occurs within a similar timeframe. Consequently, the estimated hatching dates for shortfin and longfin eels closely approximate the spawning period for these species.

The results of this study indicate that longfin eels may spawn in an area closer to the Australian coast than shortfin eels (Figure 2.28). Firstly, longfin glass eels undergo a shorter larval phase than shortfin glass eels. Secondly, shortfin and longfin eels undertake spawning migrations at the same time of year (Beumer 1978), but longfin eels appear to spawn up to 5 months earlier than shortfin eels. The generally larger size of longfin eels at the point of seaward migration (Beumer 1996) may also indicate faster oceanic migration to the spawning area. Separate spawning areas may also partly explain the more limited distribution of longfin eels.

Mean age at recruitment of *A. australis* glass eels in New Zealand has been found to be from 232-268 days (Arai *et al.* 1999a; Marui *et al.* 2001). Age at recruitment of *A. australis* glass eels from the Albert River, Queensland has previously been found to be between 186-239 (mean 208) days (Arai *et al.* 1999a), which is in close agreement with the results of the present study (total age for *A. australis* glass eels from the Albert River sampled in the present study ranged from 150-259 days (mean 202 ± 23.9 days)).

Compared with overall total age of 108-259 days (mean 143 ± 17.2-219 ± 24.4 days) found in the present study for shortfin glass eels migrating to the east coast of Australia, the period of oceanic migration of shortfin glass eels may be considerably greater for those arriving in New Zealand. The larval phase for *A. australis* glass eels arriving in eastern Australia is shorter than that for glass eels arriving in New Zealand, with mean age at onset of metamorphosis of Australian glass eels 156 ± 26.4 days (range 79-215 days) compared with that of shortfin glass eels from the North Island of New Zealand (mean 204 days, range 151-265 days (Marui *et al.* 2001). The shorter larval phase for *A. australis* glass eels arriving in eastern Australia may indicate closer proximity of the *A. australis* spawning area to Australia than New Zealand, and the subsequent greater duration of larval migration of shortfin glass eels destined for New Zealand. Overall mean total length of Australian shortfin glass eels (54.8 ± 4.8mm) is lower than that of shortfin glass eels arriving in New Zealand (60.3 ± 2.2mm), further indicating a longer larval phase for shortfin glass eels destined for New Zealand.

The interpretation of the results from the present study is based on the assumption that panmictic stocks exist for both shortfin eel and longfin eel respectively. In the absence of an alternative genetic hypothesis for these species, it is suggested that commercial harvesting of glass eels for aquaculture should result in little impact on biodiversity, at least at the species level. It is expected that this is particularly the case where a high degree of recruitment failure appears to occur, such as for shortfin eels in south-east Queensland. Conversely, the apparently larger and younger (faster growing) shortfin glass eels in southern Australia may be selectively targeted by the aquaculture industry due to potentially better performance in intensive aquaculture.

The glass eel resource identification undertaken during the course of this project has added greatly to the knowledge base of biological information on both shortfin and longfin glass eels. By contrast, the information collected on the staging of pigmentation in both shortfin and longfin glass eels, reveals very little in terms of glass eel development, abundance or spatial and temporal distribution. Despite pigmentation stage progression in shortfin glass eels having been observed in other studies (Jellyman 1977a, 1979; Sloane 1984; Gooley *et al.* 1999), little consistent evidence of temporal progression of pigmentation within or between sites was observed for either shortfin or longfin glass eels in this study. Only at two sites was a concurrent decrease in stage VA shortfin glass eels observed with an increase in stage VB glass eels, and glass eel samples often comprised several pigmentation stages throughout each year. The subjective nature with which pigmentation stages are judged may render data recorded by different observers unable to be compared effectively, unless some form of validation is employed.

The use of pigmentation staging as an indicator of glass eel development may be limited in its use to determining newly arriving glass eels from late-season glass eels, or those which have not moved out of the estuary into fresh water. Newly arriving glass eels are generally unpigmented or show little pigmentation, while those arriving at the extreme end of the season, or remain in the estuary may be well pigmented. Based on the results of the study, pigmentation of glass eels *per se* is therefore not considered a reliable means of monitoring and assessment of shortfin or longfin glass eels. Consequently the use of pigmentation stage as a measure of the development of glass eels throughout their migration is limited, and is unlikely to provide useful information for glass eel resource management.

2.4.4 Bycatch

At all sites the quantities of bycatch were significant and the diversity of species in the bycatch was high over the length of the project. The majority of bycatch comprised small fish species and juveniles of larger fish species, some of which are of commercial importance. Mortality of bycatch was generally high at all sites and it is clear that, if the glass eel fishery in Australia is to develop, the potential impact on bycatch species and biodiversity may be quite significant unless the issue is addressed.

The problem of bycatch reduction using hell nets and other passive fishing devices remains an issue in glass eel collection. The use of Nordmøre grids in hell nets was effective in reducing the catch of jellyfish in Port Hacking, allowing clear passage of glass eels through the BRD but also that of other bycatch species. Reducing the grid spacing of the BRD to a width which would be expected to deflect the bulk of the bycatch species, also reduced the catch of glass eels in the Snowy River. Due to the narrow body width of glass eels (<3mm) and the general small size of the species comprising the bycatch, spacing of BRD bars would need to be narrow to have any useful effect on bycatch reduction. Although both shortfin and longfin glass eels may pass through a 3mm bar spacing, the cumulative effect of the narrow bar spacing, the presence of other bycatch, and the associated backflow of water, may result in some glass eels being diverted away from the BRD and out of the net with the bycatch. The optimum spacing of BRD grids would therefore be expected to be between 3mm, to allow passage of glass eels, and 10 mm to ensure effective diversion of significant quantities of bycatch. Optimum spacing of BRD grids may vary between fishing locations, depending on the type and quantity of bycatch, water flow and possibly glass eel abundance and species targeted.

In the absence of effective BRDs for hell nets and other non-selective glass eel fishing gear such as glass eel nets, trawls and stow nets, including tela nets and hamennets, other selective

gear such as dipnets and flow traps should be further investigated. Under some conditions, hand held dipnets may return excellent catches of glass eels. For example, in areas where upstream migration of glass eels is restricted by weirs and causeways, dipnetting may be a very effective means of collecting congregating glass eels. Under such conditions, flow traps may also provide a means of collecting glass eels while minimising bycatch. A number of glass eel fisheries around the world are based solely or partly on the use of dipnets eg. Severn and Wye Rivers in the UK, and the Canadian and US glass eel fisheries (Jessop 2000). The reduction of bycatch through the development of effective BRDs for the glass eel fishery, as well as the selection of appropriate gear and its effective management is an area which will require further development by industry. The location within the estuary at which glass eel harvesting occurs can also impact the extent of bycatch, as species diversity tends to decrease with distance upstream. Site selection for glass eel harvesting may consequently play an important role in ensuring the ecologically sustainable development of the industry. The reduction and/or utilisation of bycatch in all commercial fisheries, including the glass eel fishery, is a major issue at both the state and national levels.

2.4.5 Management Implications

The abundance of both shortfin and longfin glass eels varies widely between season and over a wide geographical range and there are few clear patterns or relationships between abundance or migration of glass eels, and quantifiable environmental criteria, as measured in the present study. The spatial and temporal scaling of the present study certainly imposed a significant constraint on the collection of data which may provide some useful scientific basis for the management of the Australian glass eel resource. However, it is clear that the inherently variable nature of the anguillid life history further compounds this problem.

Although largely predictable, anticipating the major periods of glass eel migration is limited to time of year (season) and location, combined with certain criteria such as nocturnal flood tides during new and full moon periods, and immediately following periods of high river flows. Two of the four key sites examined in this study exhibited potential for commercial exploitation of either or both shortfin and longfin glass eels. It is expected however, that a number of other waters could produce commercial quantities of each species of glass eels across each species' range. At this stage it appears that there is enough information to suggest that commercial glass eel harvesting, albeit perhaps in smaller quantities than seen elsewhere in the world, may be a reality for the Australian eel fishing and aquaculture industries.

Shortfin and longfin eels are relatively long lived fish, maturing at 10 to 20 years of age (Beumer 1996). It is thought that eels sustain high natural mortality in the early life stages, and this becomes progressively lower in later life stages. Thus in principle, and from an ESD perspective, exploitation of glass eels could potentially be undertaken to a relatively high degree without affecting recruitment to the fishery. The populations of both shortfin and longfin eel are apparently of single genetic stocks respectively, and recruitment to freshwater habitats is random (Gooley *et al.* 1999). Thus the recruitment potential to any and all parts of each species' range is large, with the distribution of shortfin eel ranging from subtropical Queensland to western Victoria, Tasmania and throughout New Zealand, and that of longfin eel from tropical Queensland to eastern Victoria and Tasmania, with recent reports from the North Island of New Zealand (Jellyman *et al.* 1996; McDowall *et al.* 1998). In practice therefore, harvesting of glass eels from any one catchment may not affect the standing crop of eels in either the catchment being fished, or over the respective ranges of each species. The assumed panmictic nature of eel populations in Australia will however, require a national approach to management.

As previously stated, it is presupposed that where a disproportionate ratio of migration of shortfin and longfin glass eels into estuaries occurs, compared with recruitment into the catchment proper, then it may be possible to commercially harvest glass eels with minimal environmental impact. This appears to be the case for shortfin glass eels in estuaries in south-east Queensland, and may also be the case for longfin glass eels in estuaries at the extreme of the natural range in south-east Australia. However, to be certain of this, it will be necessary to quantify within an appropriate temporal and spatial scale, the standing crop of eel species within their respective natural range. It will also be necessary to confirm that indeed both stocks of eels do display panmixia, as has been assumed to the present time. If this is not the case, and discrete stocks of either species are identified, then an alternative management strategy may be required.

It should also be noted that the opportunity to target apparently faster growing shortfin glass eels from more southerly waters, purely on the basis that these are more suited as seedstock for intensive aquaculture production, may also be worth considering. Either way the challenge for fisheries managers and industry will be to achieve an appropriate management balance between the sometimes competing 'productivity v biodiversity' needs of the respective state agencies in Australia, and also what might best be achieved at an industry-wide level through adopting a more national approach. Again, clear management guidelines at both state and national level are required.

It is noted that commercial glass eel harvesting operations have commenced in the Albert River, Queensland, and the Snowy River, Victoria. In the Albert River, harvesting permits have been issued and a total of 126.9kg of both species have been retained commercially over the period 1997/98-1999/00 (Lobegeiger 2001). In the Snowy River, a consortium from the Victorian Eel Fishers' Association (VEFA) has undertaken commercial glass eel harvesting under permit since the completion of the project, with more than 30kg of shortfin glass eels and 20kg of longfin glass eels caught during 2001 (VEFA, unpublished data). In addition, a number of Victorian waters allocated to licensed fishers, have recently been fished commercially for glass eels, with catches of up to 10kg of shortfin glass eels from each of these waters.

The knowledge and understanding of the glass eel resource in the Snowy River, and the commercial interest in this resource, has contributed to the preparation of a management plan for the eel fishery in Victoria (McKinnon 2001), in which the sustainable use of glass eels will be accommodated within an ESD framework. Such an approach is considered appropriate for national adoption also. It is worth noting that the decline in recruitment of glass eels in Europe, which was thought to be due primarily to overfishing and habitat loss etc., is now being attributed largely to oceanic perturbations affecting migration and food supply to larvae (Knights In prep.). Management of the European eel is now focussing largely on providing for escapement of spawning stock (EIFAC/ICES 2001).

Environment Australia requires commercial export fisheries to demonstrate ecological sustainability in order to obtain export permits. It is suggested that commercial glass eel fishing can be undertaken sustainably, and that CPUE may be used as an index of recruitment to assist in the monitoring process. The glass eel database developed as part of this project should form the basis for a comprehensive, national glass eel database which will provide a long term management tool for the developing glass eel fishery and eel aquaculture industry. The maintenance of this database, and the overall monitoring of glass eel resources and their sustainable exploitation, may be undertaken by the Australia and New Zealand Eel Reference Group (ANZERG) on behalf of the state fisheries agencies. The use of such a database would facilitate accurate and timely supervision of the industry, and ensure ESD is observed in the

developing glass eel fishery and eel aquaculture industry. Indeed, the comprehensive monitoring database that developed in the course of this project provides a unique tool for management of glass eel resources on a national, and possibly international, basis. It should be noted however that the full benefit of such a database may only be realised over a minimum 10-20 year timeframe to take account of the natural life history variability of the species. Accordingly, this database needs to be considered as only one management tool along with many others to be considered to ensure the sustainability of these valuable glass eel resources in Australia.

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2.6 REFERENCES

Allan, K. (1995). *Relation between length, weight, stomach contents and pigmentation stage in glass-eels of Anguilla australis and Anguilla reinhardtii in south-eastern Australian estuaries*. Graduate Diploma in Fisheries Report. Australian Maritime College, Tasmania. Launceston. 65 pp.

Antunes, C. (1994). The Seasonal Occurrence of Glass Eels (*Anguilla anguilla* L) in the Rio-Minho Between 1991 and 1993 (North of Portugal). *Int. Rev. Gesamten. Hydrobiol.* 79(2): 287-294.

Antunes, C. and Tesch, F.W. (1997). A critical consideration of the metamorphosis zone when identifying daily rings in otoliths of European eel, *Anguilla anguilla* (L). *Ecology of Freshwater Fish* 6(2): 102-107.

Aoyama, J., Mochioka, N., Otake, T., Ishikawa, S., Kawakami, Y., Castle, P., Nishida, M. and Tsukamoto, K. (1999). Distribution and dispersal of anguillid leptocephali in the western Pacific Ocean revealed by molecular analysis. *Marine Ecology Progress Series* 188: 193-200.

Arai, T., Limbong, D. and Tsukamoto, K. (2000). Validation of otolith daily increments in the tropical eel *Anguilla celebesensis*. *Canadian Journal of Zoology* 78(6): 1078-1084.

Arai, T., Otake, T., Jellyman, D.J. and Tsukamoto, K. (1999a). Differences in the early life history of the Australasian shortfinned eel *Anguilla australis* from Australia and New Zealand, as revealed by otolith microstructure and microchemistry. *Marine Biology* 135: 381-389.

Arai, T., Otake, T., Limbong, D. and Tsukamoto, K. (1999b). Early life history and recruitment of the tropical eel *Anguilla bicolor pacifica*, as revealed by otolith microstructure and microchemistry. *Marine Biology* 133: 319-326.

Arai, T., Otake, T. and Tsukamoto, K. (1997). Drastic changes in otolith microstructure and microchemistry accompanying the onset of metamorphosis in the Japanese eel *Anguilla japonica*. *Marine Ecology Progress Series* 161: 17-22.

Baines, P.G., Hubbert, G. and Power, S. (1991). Fluid transport through Bass Strait. *Continental Shelf Research* 11(3): 269-293.

Beumer, J. and Sloane, R. (1990). Distribution and abundance of glass-eels *Anguilla* spp. in East Australian waters. *Int. Rev. Gesamt. Hydrobiol.* 75(6): 721-736.

Beumer, J.P. (1978). *Eels*. Fish of Victoria No 3. Fisheries and Wildlife Division, Victoria. Melbourne. 4 pp.

Beumer, J.P. (1983a). Eels. *Victorian Naturalist* 100(4): 168-171.

Beumer, J.P. (1983b). Suitability of *Anguilla australis* for intensive culture. *Aust. Aquacult.* 4(2): 13-18.

Beumer, J.P. (1996). Freshwater eels. In: *Freshwater Fishes of South-Eastern Australia* (ed. by R. McDowall), pp 39-43. Reed Books, Sydney.

Beumer, J.P. and Harrington, D.J. (1980). Techniques for Collecting Glass-Eels and Brown Elvers. *Aust. Fish.* 39(8): 16-22.

Black, K.P. (1995). *The hydrodynamic model 3DD and support software*. Occasional Report No. 19. Department of Earth Sciences, University of Waikato. Hamilton. 53 pp.

Black, K.P. (1996). *POL3DD langrangian dispersal and sediment transport model and support software*. Occasional Report No. 20. Department of Earth Sciences, University of Waikato.

Boland, F.M. (1971). Temperature-salinity anomalies at depths between 200m and 800m in the Tasman Sea. *Australian Journal of Marine and Freshwater Research* 22: 55-62.

Broadhurst, M.K., Kennelly, S.J. and O'Doherty, G. (1997). Specifications for the construction and installation of two by-catch reducing devices (BRDs) used in the New South Wales prawn trawl fisheries. *Marine and Freshwater Research* 48: 485-489.

Cairns, D. (1941). Life-history of the two species of New Zealand fresh-water eel. Part I. Taxonomy, age and growth, migration, and distribution. *The New Zealand Journal of Science and Technology* 23(3B): 53-72.

Castle, P.H.J. (1963). Anguillid leptocephali in the southwest Pacific. *Zoology Publications from Victoria University of Wellington* 33: 1-14.

Chen, Y.L.L., Chen, H.Y. and Tzeng, W.N. (1994). Reappraisal of the Importance of Rainfall in Affecting Catches of *Anguilla japonica* Elvers in Taiwan. *Australian Journal of Marine and Freshwater Research* 45(2): 185-190.

Cheng, P.W. and Tzeng, W.N. (1996). Timing of metamorphosis and estuarine arrival across the dispersal range of the Japanese eel *Anguilla japonica*. *Mar. Ecol. Progr. Ser.* 131: 87-96.

Church, J.A. (1987). East Australian Current adjacent to the Great Barrier Reef. *Australian Journal of Marine and Freshwater Research* 38(6): 671-683.

Creutzberg, F. (1961). On the orientation of migrating elvers (*Anguilla anguilla* Turt.) in a tidal area. *Netherlands Journal of Sea Research* 1: 257-338.

de Casamajor, M.N., Bru, N. and Prouzet, P. (1996). Influence of environmental conditions on glass-eel (*Anguilla anguilla* L.) catchability on the Ardour estuary. *EIFAC/ICES Working Party on Eel, IJmuiden, the Netherlands, 23-27 September, 1996.*

Deelder, C.L. (1970). *Synopsis of biological data on the eel Anguilla anguilla (Linnaeus) 1758*. Fisheries Synopsis No. 80. FAO.

Domingos, I.M. (1992). Fluctuation of glass eel migration in the Mondego estuary (Portugal) in 1988 and 1989. *Irish Fisheries Investigations Series A (Freshwater)* 36: 1-4.

DWRV. (1989). *Water Victoria. An Environmental Handbook.* Department of Water Resources, Melbourne. 352 pp.

EIFAC/ICES. (2001). *Report of the EIFAC/ICES Working Group on Eels.* ICES CM 2002/ACFM:03. International Council for the Exploration of the Sea. Copenhagen. 59 pp.

EPA. (1997). *Proposed Interim Environmental Objectives for NSW Waters - Sydney, Central Coast and Illawarra Catchments. Public Discussion Paper*. Environment Protection Authority, Sydney. 33 pp.

Gascuel, D. (1986). Flow-carried and active swimming migration of the glass eel (*Anguilla anguilla*) in the tidal area of a small estuary on the French Atlantic coast. *Helgolander Meeresunters* 40: 321-326.

Gooley, G.J., McKinnon, L.J., Ingram, B.A., Larkin, B., Collins, R.O. and de Silva, S.S. (1999). *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production. Final Report FRDC Project No 94/067*. Marine and Freshwater Resources Institute, Alexandra, Australia. 124 pp.

Guerault, D., Lecomte-Finiger, R., D,saunay, Y., Biagianti-Risbourg, S., Beillois, P. and Grellier, P. (1992). Glass eel arrivals in the Vilaine estuary (northern Bay of Biscay) in 1990: Demographic features and early life history. *Irish Fisheries Investigations Series A (Freshwater)* 36: 5-14.

Heinsbroek, L.T.N. (1989). Preliminary investigations on husbandry, nutrition and growth of glass eels and elvers, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 20: 119-127.

HRCMC. (1997). *Hacking River Management - A Pollution Source Inventory*. Internal Report. Hacking River Catchment Management Committee. Sydney. 102 pp.

Isaksen, B., Valdemarsen, J.W., Larsen, R.B. and Karlsen, L. (1992). Reduction of fish by-catch in shrimp trawl using a rigid separator grid in the aft belly. *Fisheries Research (Amsterdam)* 13: 335-352.

James, B. (1989). *South East Water Management Strategy Snowy Mountains Scheme Effects on Flow Regime of Lower Snowy River, 1989.*

Jellyman, D.J. (1977a). Invasion of a New Zealand freshwater stream by glass-eels of two *Anguilla* spp. *New Zealand Journal of Marine and Freshwater Research* 11(2): 193-2209.

Jellyman, D.J. (1977b). Summer upstream migration of juvenile freshwater eels in New Zealand. *New Zealand Journal of Marine & Freshwater Research* 11(1): 61-71.

Jellyman, D.J. (1979). Upstream migration of glass-eels (*Anguilla*- spp.) in the Waikato River. *New Zealand Journal of Marine and Freshwater Research* 13(1): 13-22.

Jellyman, D.J. (1987). Review of the marine life history of Australasian temperate species of *Anguilla*. In: *Common Strategies of Anadromous and Catadromous Fishes. Proceedings of an International Symposium held in Boston, Massachusetts, USA, March 9-13,1986* (ed. by M.J. Dadswell, R.J. Klauda, C.M. Moffitt, R.L. Saunders, R.A. Rulifson and J.E. Cooper), pp 276-285. American Fisheries Society, Bethesda.

Jellyman, D.J., Chisnall, B.L., Bonnett, M.L. and Sykes, J.R.E. (1999). Seasonal arrival patterns of juvenile freshwater eels (*Anguilla* spp.) in New Zealand. *New Zealand Journal of Marine & Freshwater Research.* 33(2): 249-261.

Jellyman, D.J., Chisnall, B.L., Dijkstra, L.H. and Boubee, J.A.T. (1996). First record of the Australian longfinned eel, *Anguilla reinhardtii*, in New Zealand. *Marine and Freshwater Research* 47(8): 1037-1040.

Jenkins, G.P., Black, K.P. and Hamer, P.A. (2000). Determination of spawning areas and larval advection pathways for King George whiting in southeastern Australia using otolith microstructure and hydrodynamic modelling. I. Victoria. *Marine Ecology Progress Series* 199: 231-242.

Jespersen, P. (1942). Indo-Pacific leptocephalids of the genus *Anguilla*. Systematic and biological studies. *Dana Report* 4 (22): 1-132.

Jessop, B.M. (1998). Geographic and seasonal variation in biological characteristics of American eel elvers in the Bay of Fundy area and on the Atlantic coast of Nova Scotia. *Canadian Journal of Zoology* 76: 2172-2185.

Jessop, B.M. (2000). Size, and exploitation rate by dip net fishery, of the run of American eel, *Anguilla rostrata* (Le Sueur), elvers in the East River, Nova Scotia. *Dana* 12: 43-47.

Kimura, S., Tsukamoto, K. and Sugimoto, T. (1994). A model for the larval migration of the Japanese eel: Roles of the trade winds and salinity front. *Mar. Biol.* 119(2): 185-190.

Knights, B. (In prep.). Speculations on adaptive life strategies of Northern Hemisphere anguillids and the causes of decadal variations in recruitment.

Langdon, S.A. and Collins, A.L. (2000). Quantification of the maximal swimming performance of Australasian glass eels, *Anguilla australis* and *Anguilla reinhardtii*, using a hydraulic flume swimming chamber. *New Zealand Journal of Marine & Freshwater Research* 34(4): 629-636.

Lobegeiger, R. (2001). *Report to Farmers: Queensland Aquaculture Production Survey 1999-2000*. Information Series QI 01019. Department of Primary Industries, Queensland. Brisbane. 24 pp.

Lokman, P.M. and Young, G. (2000). Induced spawning and early ontogeny of New Zealand freshwater eels (*Anguilla dieffenbachii* and *A. australis*). *New Zealand Journal of Marine & Freshwater Research* 34(1): 135-145.

Martin, M.H. (1995). Validation of daily growth increments in otoliths of *Anguilla rostrata* (Lesueur) elvers. *Can. J. Zool.* 73(1): 208-211.

Marui, M., Arai, T., Miller, M.J., Jellyman, D.J. and Tsukamoto, K. (2001). Comparison of early life history between New Zealand temperate eels and Pacific tropical eels revealed by otolith microstructure and microchemistry. *Marine Ecology Progress Series* 213: 273-284.

McCleave, J.D. (1993). Physical and behavioural controls on the oceanic distribution and migration of leptocephali. *Journal of Fish Biology* 43(Supplement A): 243-273.

McCleave, J.D. (1996). Do leptocephali of the European eel swim to reach continental waters? Conflicting results from biology and oceanography *EIFAC/ICES Working Party on Eel* IJmuiden, The Netherlands.

McCleave, J.D., Bedaux, J.J.M., Doucet, P.G., Jager, J.C., Jong, J.T.L., van der Steen, W.J. and Voorzanger, B. (1987). Statistical methods for analysis of plankton and nekton distribution, with application to selective tidal stream transport of juvenile American eels (*Anguilla rostrata*). *J. Cons. Ciem.* 44(1): 90-103.

McCleave, J.D. and Kleckner, R.C. (1982). Selective tidal stream transport in the estuarine migration of glass eels of the American eel (*Anguilla rostrata*). *J. Cons. int. Explor. Mer* 40: 262-271.

McCleave, J.D. and Wippelhauser, G.S. (1987). Behavioral aspects of selective tidal stream transport in juvenile American eels. In: *Common Strategies of Anadromous and Catadromous Fishes. Proceedings of an International Symposium held in Boston, Massachusetts, USA, March 9-13,1986* (ed. by M.J. Dadswell, R.J. Klauda, C.M. Moffitt, R.L. Saunders, R.A. Rulifson and J.E. Cooper), pp 138-150. American Fisheries Society, Bethesda.

McDowall, R.M., Jellyman, D.J. and Dijkstra, L.H. (1998). Arrival of an Australian anguillid eel in New Zealand: an example of transoceanic dispersal. *Environmental Biology of Fishes* 51: 1-6.

McKinnon, L. (2001). *Victorian Eel Fishery Management Plan*. Marine and Freshwater Resources Institute. Queenscliff. 37 pp.

McKinnon, L.J. and Gooley, G.J. (1998). Key environmental criteria associated with the invasion of *Anguilla australis* glass eels into estuaries of south-eastern Australia. *Bulletin Français de la Pêche et de la Pisciculture* 349: 117-128.

McKinnon, L.J., Ingram, B.A., Larkin, B. and Gasior, R.J. (2001). *Best Practice Guidelines for Australian Glass Eel Fishing and Aquaculture*. Report No. 48. Marine and Freshwater Resources Institute. Alexandra. 21 pp.

Neira, F.J., Jenkins, G.P. and Longmore, A. (1998). *Spawning and larval recruitment processes of commercially important species in coastal waters off Victoria 1997-1998*. 96/116. Marine and Freshwater Resources Institute. Queenscliff. 150 pp.

Otake, T., Ishii, T., Nakahara, M. and Nakamura, R. (1994). Drastic changes in otolith strontium/calcium ratios in leptocephali and glass eels of Japanese eel *Anguilla japonica*. *Marine Ecology Progress Series* 112: 189-193.

Pease, B., Silberschneider, V. and Walford, T. (2000). Seasonal characteristics of migration into fresh water by glass eels of two *Anguilla* species in the Hacking River, New South Wales, Australia *Eel 2000* St. Louis.

Pease, B.C. (1999). A spatially oriented analysis of estuaries and their associated commercial fisheries in New South Wales, Australia. *Fisheries Research* 42: 67-86.

Prokhorchik, G.A. (1986). Postembryonic development of European eel, *Anguilla anguilla*, under experimental conditions. *Journal of Ichthyology* 26: 121-127.

Rochford, D.J. (1968). The continuity of water masses along the western boundary of the Tasman and Coral Seas. *Australian Journal of Marine and Freshwater Research* 19: 77-90.

Roy, P.S. (1984). New South Wales estuaries: their origin and evolution. In: *Coastal Geomorphology in Australia* (ed. by B.G. Thom). Academic Press, Sydney.

Russell, B.J. (1995). *A survey on the distribution and composition of glass eel populations Anguilla spp. in south-east Queensland 15 April 1995 to 27 August 1995*. Department of Primary Industries. Brisbane. 13 pp.

Satoh, H., Yamamori, K. and Hibiya, T. (1992). Induced spawning of the Japanese eel. *Nippon Suisan Gakkaishi Bull. Jap. Soc. Sci. Fish.* 58(5): 825-832.

Schmidt, J. (1925). The breeding places of the eel. *Smithsonian Report for 1924.*: 279-317.

Shiao, J.C., Tzeng, W.N., Collins, A. and Jellyman, D.J. (2001). Dispersal pattern of glass eel stage of *Anguilla australis* revealed by otolith growth increments. *Marine Ecology Progress Series* 219: 241-250.

Sloane, R.D. (1984). Invasion and upstream migration by glass-eels of *Anguilla australis australis* Richardson and *A. reinhardtii* Steindachner in Tasmanian freshwater streams. *Australian Journal of Marine and Freshwater Research* 35(1): 47-59.

Sola, C. (1995). Chemoattraction of upstream migrating glass eels *Anguilla anguilla* to earthy and green odorants. *Environ. Biol. Fish.* 43(2): 179-185.

Sola, C. and Tongiorgi, P. (1996). The effect of salinity on the chemotaxis of glass eels, *Anguilla anguilla*, to organic earthy and green odorants. *Environmental Biology of Fishes* 47(2): 213-218.

Sorensen, P.W. (1986). Origins of the freshwater attractant(s) of migrating elvers of the American eel, *Anguilla rostrata*. *Environmental Biology of Fishes* 17(3): 185-200.

SPCC. (1980). *An Atlas of Classified Waters in New South Wales*. Internal Report. State Pollution Control Commission. Sydney. 53 pp.

Strubberg, A. (1913). The metamorphosis of elvers as influenced by outward conditions some experiments. *Meddelelser fra Kommissionen for Havundersígelser. Serie: Fiskeri* 4(3): 1-11.

Tesch, F.-W. (1977). *The Eel. Biology and Management of Anguillid Eels*. Chapman and Hall, London. 434 pp.

Tesch, F.-W. (1998). Age and growth rates of North Atlantic eel larvae (*Anguilla* spp.), based on published length data. *Helgolander Meeresuntersuchungen* 52: 75-83.

Tomczak, M.J. (1981). Bass Strait water intrusions in the Tasman Sea and mean temperature-salinity curves. *Australian Journal of Marine and Freshwater Research* 32: 699-708.

Tomczak, M.J. (1985). The Bass Strait water cascade during winter 1981. *Continental Shelf Research* 4(3): 255-278.

Tongiorgi, P., Tosi, L. and Balsamo, M. (1986). Thermal preferences in upstream migrating glass eels of *Anguilla anguilla*. *Journal of Fish Biology* 28: 501-510.

Tosi, L. and Sola, C. (1993). Role of geosmin, a typical inland water odour, in guiding glass eel *Anguilla anguilla* (L.) migration. *Ethology*. 95(3): 177-185.

Tosi, L., Sola, C., Spampanato, A. and Tongiorgi, P. (1989). The behaviour of glass-eels of *Anguilla anguilla* (L.) towards salinity: Discrimination and preferences. *Riv. Ital. Acquacolt.* 24(3): 219-223.

Tosi, L., Spampanato, A., Sola, C. and Tongiorgi, P. (1990). Relation of water odour, salinity and temperature to ascent of glass-eels, *Anguilla anguilla* (L.): A laboratory study. *Journal of Fish Biology* 36(3): 327-340.

Tsukamoto, K. (1992). Discovery of the spawning area for Japanese eel. *Nature* 356: 789-791.

Tsukamoto, K. and Umezawa, A. (1994). Metamorphosis: a key factor of larval migration determining geographic distribution and speciation of eels *Fourth Indo-Pacific Fish Conference*. Faculty of Fisheries, Kasetsart University, Bangkok, Thailand. Pp 231-248.

Tzeng, W.N. (1996). Effects of salinity and ontogenetic movements on strontium:calcium ratios in the otoliths of the Japanese eel, *Anguilla japonica* Temminck and Schlegel. *Journal of Experimental Marine Biology and Ecology* 199: 111-122.

Tzeng, W.-N. (1990). Relationship between growth rate and age at recruitment of *Anguilla japonica* elvers in a Taiwan estuary as inmferred from otolith growth increments. *Marine Biology* 107: 75-81.

Tzeng, W.N. and Tsai, Y.C. (1994). Changes in otolith microchemistry of the Japanese eel, *Anguilla japonica*, during its migration from the ocean to the rivers of Taiwan. *Journal of Fish Biology* 45: 671-683.

Tzeng, W.-N. and Tsai, Y.-C. (1992). Otolith microstructure and daily age of *Anguilla japonica*, Temminck and Schelegel elvers from the estuaries of Taiwan with reference to unit stock and larval migration. *Journal of Fish Biology* 40(6): 845-857.

Umezawa, A. and Tsukamoto, K. (1991). Factors influencing otolith increment formation in Japanese eel, *Anguilla japonica* T. and S., elvers. *Journal of Fish Biology* 39(2): 211-223.

Wang, C.H. and Tzeng, W.N. (2000). The timing of metamorphosis and growth rates of American and European eel leptocephali: A mechanism of larval segregative migration. *Fisheries Research* 46: 191-205.

Wang, C.-H. and Tzeng, W.-N. (1998). Interpretation of geographic variation in size of American eel *Anguilla rostrata* elvers on the Atlantic coast of North America using their life history and otolith ageing. *Marine Ecology Progress Series* 168: 35-43.

Weber, M. (1986). Fishing method and seasonal occurrence of glass eels (*Anguilla anguilla* L.) in the Rio Minho, west coast of the Iberian peninsula. *Vie Milieu* 36(4): 243-250.

2.7 APPENDICES

Map and drainage details of all waters sampled in each state (Key water sites highlighted).

State	Drainage Name (AWRC)	Drain N°	Basin Name	Basin N°	Water	Location	AMG East	AMG North	Map Name	Map N°	Grid Ref.	Site N°	Distance U/S of Mouth
QLD	North-East Coast	I	Burnett River	36	Burnett River	Ben Anderson Barrage	428197	7244735	Bunderberg	9348	281447	1	25900
QLD	North-East Coast	I	Burnett River	36	Burnett River	Splitters	428197	7248929	Bunderberg	9348	281489	3	24900
QLD	North-East Coast	I	Burrum River	37	Burrum River	Burrum Barrage	457576	7198403	Maryborough	9446	575984	1	26500
QLD	North-East Coast	I	Mary River	38	Mary River	Mary River	462083	7170000	Maryborough	9446	620700	1	59300
QLD	North-East Coast	I	Caboolture River	42	Caboolture River	Caboolture Weir	495988	7004012	Caboolture	9443	959040	1	18500
QLD	North-East Coast	I	Logan-Albert Rivers	45	Albert River	Riffle	518945	6928107	Beenleigh	9542	189281	3	40500
QLD	*North-East Coast*	*I*	*Logan-Albert Rivers*	*45*	*Albert River*	*Stanmore Road Crossing*	*518273*	*6927572*	*Beenleigh*	*9542*	*182275*	*1*	*42000*
QLD	North-East Coast	I	Nerang River	46	Nerang River	NERANG	529926	6890000	Tweed Heads	9641	299900	1	27500
NSW	South-East Coast	II	Wollongong Coast	14	Port Hacking	Alkaringa Creek	324300	6230600	Port Hacking	9129	243306	3	6500
NSW	South-East Coast	II	Wollongong Coast	14	Port Hacking	North West Arm	323700	6229800	Port Hacking	9129	237298	20	7500
NSW	*South-East Coast*	*II*	*Wollongong Coast*	*14*	*Port Hacking*	*Point Danger*	*323600*	*6228800*	*Port Hacking*	*9129*	*236288*	*1*	*7000*
NSW	South-East Coast	II	Wollongong Coast	14	Hacking River	Audley Weir (Above)	320610	6227810	Port Hacking	9129	206278	4	12000
NSW	South-East Coast	II	Wollongong Coast	14	Port Hacking	Audley Weir (Below)	320600	6227800	Port Hacking	9129	206278	2	12000
VIC	South-East Coast	II	East Gippsland	21	Mallacoota Inlet	Mallacoota	744800	5839800	Mallacoota	8822	448398	1	1600
VIC	South-East Coast	II	East Gippsland	21	Mallacoota Inlet	Mallacoota	743800	5839000	Mallacoota	8822	438390	2	700
VIC	South-East Coast	II	East Gippsland	21	Mallacoota Inlet	Mallacoota	744200	5838800	Mallacoota	8822	442388	3	300
VIC	South-East Coast	II	Snowy River	22	Snowy River	Lochend	633800	5820300	Marlo	8622	338203	16	9500
VIC	South-East Coast	II	Snowy River	22	Brodribb River	Lake Curlip Game Reserve	637700	5817700	Marlo	8622	377177	6	9600
VIC	South-East Coast	II	Snowy River	22	Snowy River	Marlo	633400	5817600	Marlo	8622	334176	11	4600
VIC	*South-East Coast*	*II*	*Snowy River*	*22*	*Brodribb River*	*Marlo*	*633600*	*5817500*	*Marlo*	*8622*	*336175*	*1*	*4600*
VIC	South-East Coast	II	Snowy River	22	Brodribb River	Marlo	635200	5817300	Marlo	8622	352173	3	6800
VIC	South-East Coast	II	Snowy River	22	Snowy River	Marlo	633300	5817400	Marlo	8622	333174	10	4200
VIC	South-East Coast	II	Snowy River	22	Snowy River	Marlo	632500	5816700	Marlo	8622	325167	9	4000
VIC	South-East Coast	II	Snowy River	22	Snowy River	Marlo	633200	5816700	Marlo	8622	332167	8	3400
VIC	South-East Coast	II	Snowy River	22	Snowy River	Marlo	633400	5815900	Marlo	8622	334159	7	2700
VIC	South-East Coast	II	East Gippsland	23	Lake Tyers	Lake Tyers	595600	5809800	Orbost	8522	956098	1	700
VIC	South-East Coast	II	South Gippsland	27	Bruthen Creek	McLoughlins Beach	491400	5726200	Yarram	8220	914262	2	4200
VIC	South-East Coast	II	South Gippsland	27	Tarwin River	Boongas Gutter	398200	5719000	Anderson Inlet	8020	982190	3	14000
VIC	South-East Coast	II	South Gippsland	27	Tarwin River	Tarwin Lower	399500	5716100	Anderson Inlet	8020	995161	2	17700
TAS	Tasmanian	III	Forth River	15	Forth River	Turners Beach	437000	5443200	Forth	8115	370432	3	300

Albert River, Queensland, Site 1 by-catch species list and abundance.

Scientific Name	Common Name	1997 Total N°	1998 Total N°	1999 Total N°	2000 Total N°
Acanthopagrus australis	Bream, Yellowfin	13	17	6	
Ambassis marianus	Glassfish, Ramsay's	755	22771	3360	20
Anguilla australis	Eel, Shortfin		3	4	
Anguilla reinhardtii	Eel, Longfin		12	8	
Anguilla spp. (Elvers)	Eel, Elver [Unspecified]	280	292	202	
Arenigobius bifrenatus	Goby, Bridled	1	8	2	
Argyrosomus japonicus	Jewfish	2	1		
Arius graeffei	Catfish, Fork-tailed	6	6081	114	
Arrhamphus sclerolepis	Garfish, Snub-nosed		64	2	
Atherinomorus ogilbyi	Hardyhead, Ogilby's		71		
Carassius auratus	Goldfish			2	
Elops hawaiensis	Herring, Giant		18		
Gerres ovatus	Silver Biddy	26	321	36	
Girella tricuspidata	Luderick		2		
Mogurnda australis	Gudgeon, Striped	55	48	4	
Hyporhamphus regularis ardelio	Garfish, Eastern River	1	1		
Hypseleotris compressa	Gudgeon, Empire	16	11	374	
Leipotherapon unicolor	Perch, Spangled	4	1		
Macquaria novemaculeata	Bass, Australian		1	8	
Macrobrachium australiense	Prawn, Southern Freshwater	527	2412	919	1
Marilyna pleurosticta	Toadfish, Banded		6		
Metapenaeus bennettae	Prawn, Greasyback		125	1290	
Monodactylus argenteus	Butter-bream	4	2		
Mugil cephalus	Mullet, Sea	61	8848	8754	8
Muraenesox cinereus	Eel, Pike		25		
Nematolosa erebi	Bream, Bony	2	333	34	
Notesthes robusta	Bullrout	77	57	84	
Paratya australiensis	Shrimp, Common Freshwater	4250	8386	15434	200
Philypnodon grandiceps	Gudgeon, Flat-headed	969	1605	5442	80
Platycephalus fuscus	Flathead, Dusky	1	2		
Polydactlyus spp.	Perch, Putty-nosed		22		
Pseudomugil signifer	Blue-eye			8	
Pseudorhombus arsius	Flounder, Large-toothed		4		
Scatophagus argus	Scat, Spotted	4	116		
Scylla seratta	Crab, Mud		3		
Selenotoca multifasciatus	Butterfish, Striped		15		
Sillago maculata	Whiting, Winter		5		
Suborder Brachyura	Crab, Juvenile [Unspecified]	5	42		
Taenioides cirratus	Goby, Bearded Worm	30			
Thryssa aestuaria	Herring	36	47	42	

Port Hacking, New South Wales, Site 1 by-catch species list and abundance.

Scientific Name	Common Name	1998	1999
		Total N°	Total N°
Acanthopagrus australis	Bream, Yellowfin	1	1
Ambassis jacksoniensis	Glassfish, Port Jackson	54	
Ambassis marianus	Glassfish, Ramsay's	347	
Anguilla australis	Eel, Shortfin	1	
Anguilla spp.	Eel, [Unspecified]	1	2
Anguilla spp. (Leptocephali)	Eel, Leptocephali [Unspecified]	1	4
Atherinosoma microstoma	Hardyhead, Smallmouth	7	1
Cnidoglanis macrocephalus	Catfish, Estuary	3	
Engraulis australis	Anchovy, Australian	43	6
Family Balistidae, Monacanthidae	Triggerfish, Leatherjacket, [Unspecified]	1	14
Family Carangidae	Mackerel, [Unspecified]	3	
Family Centriscidae		6	16
Family Centropomidae/Chandidae	Giant Perch/Glassfish, [Unspecified]	2101	1782
Family Clupeidae	Sprat, [Unspecified]	217	114
Family Diodontidae	Porcupinefishes [Unspecified]	1	
Family Engraulididae	Anchovy, [Unspecified]	26	29
Family Galaxiidae, Lepidogalaxiidae	Galaxias, Salamanderfish, [Unspecified]	1	8
Family Gobiidae	Goby, [Unspecified]	1154	287
Family Hemiramphidae	Garfish, [Unspecified]	4	18
Family Mugilidae	Mullet, [Unspecified]	83	46
Family Mysidaceae	Shrimp, Opossum [Unspecified]	2	372
Family Penaeidae	Prawns, [Unspecified]	109	5
Family Plotosidae	Catfish, Eel-Tail [Unspecified]		1
Family Scorpaenidae	Scorpionfish, [Unspecified]	7	
Family Scorpididae, Kyphosidae	Sweep, Drummer, [Unspecified]	5	1
Family Sepiidae	Cuttlefish, [Unspecified]	14	1
Family Siganidae	Rabbitfish, [Unspecified]		1
Family Sillanginidae	Whiting, [Unspecified]	2	58
Family Sparidae	Snapper & Bream, [Unspecified]	8	1
Favonigobius exquisitus	Exquisite Sand-Goby	16	
Favonigobius lateralis	Goby, Long-finned	6	
Galaxias maculatus	Galaxias, Common	1	
Gerres subfasciatus	Silverbiddy, Sourthern	211	120
Gobiopterus semivestitus	Goby, Glass	14	164
Herklotsichthys castelnaui	Sprat	1	4
Hyperlophus vittatus	Sprat, Sandy	535	695
Liza argenta	Mullet, Flat-tail		50
Monodactylus argenteus	Butter-bream		1
Mugil cephalus	Mullet, Sea	31	25
Nototodarus spp.	Squid, [Unspecified]	1	14
Pelates sexlineatus	Trumpeter, Eastern Striped	1	3
Platycephalus fuscus	Flathead, Dusky	1	
Plotosus lineatus	Catfish, Striped	2430	163
Pomatomus saltatrix	Tailor	10	1
Pseudogobius olorum	Goby, Blue spot	5	
Redigobius macrostoma	Goby, Large-Mouthed	1	
Sillago ciliata	Whiting, Sand	1	1

Snowy River, Victoria, Site 1 by-catch species list and abundance.

Scientific Name	Common Name	1999		1998		1997	
		Total	Total	Total	Total	Total	Total
Acanthopagus butcheri	Bream, Black		1		186		6
Afurcagobius tamarensis	Goby, Tamar River		202		2949		>990
Aldrichetta forseri	Mullet, Yellow-eyed		27		2		
Alpheus strennus	Snapping-prawn		2	5	653		31
Ambassia marianus	Glassfish, Ramsay's		39		14		90
Anguilla australis	Eel, (Adult Anguilla)				3		
Anguilla reinhardtii	Eel, (Adult Anguilla)				1		1
Anguilla spp.	Eel, (Anguilla Elver), [Unspecified]		16		311		100
Arenigobius bifrenatus	Goby, Bridled		3		616		
Arripis spp.	Salmon/Bay trout, [Unspecified]						6
Atherinosoma microstoma	Hardyhead, Small-mouth				73		
Callianassa australiensis	Ghost-shrimp		7				
Chrysophrys auratus	Snapper				9		
Class Gastropoda	Snails, [Unspecified]	0.1	1				
Diodon nicthemerus	Globefish		13		3		28
Engraulis australis	Anchovy, Australian		2667	25.7	265		33
Enoplosus armatus	Angelfish/Old Wife				1		
Family Gobiidae	Goby, [Unspecified]		3		433		298
Family Hippolytidae	Weed-prawns, [Unspecified]				60		
Family Hymenosomatidae	Crabs, Spider [Unspecified]		1495		1660		808
Family Loliginidae	Squid, [Unspecified]		6				1
Family Mictyridae	Crabs, Soldier						1
Family Monacanthidae	Leatherjacket, [Unspecified]		1		13		2
Family Mugilidae	Mullet, [Unspecified]		2		177		84
Family Notonectidae/Corixidae	Backswimmers/Water boatman, [Unspecified]				6		
Family Petromyzontidae	Lamprey, [Unspecified]				19		22
Family Syngnathidae	Pipefish, [Unspecified]		1		46		105
Family Tetraodontidae	Toadfish, [Unspecified]		15		36		91
Family Triglidae	Gurnard, [Unspecified]				1		13
Galaxias brevipinnis	Galaxias, Climbing		206	0.6	2465		159
Galaxias maculatus	Galaxias, Common		3904	0.7	3043		2373
Galaxias spp.	Whitebait, [Unspecified]						1070
Geotria australis	Lamprey, Pouched		10		50		26
Girella tricuspidata	Luderick/Blackfish		7		143		128
Gobiopterus semivestitus	Goby, Glass	9.1	19468	2.9	3512		
Gymnapistes marmoratus	Cobbler/Soldierfish		93		791		305
Haplostylus dakini	Shrimp, Opossum	62.2	1690	117.7	1650	251.8	>2002
Hyperlophus vittatus	Sprat, Sandy	337.3	2701		93	12.6	>5882
Hyporhamphus regularis	Garfish, River		13		3		2
Leptatherina presbyteroides	Silverfish				16		2
Macquaria colonorum	Perch, Estuary				25		23
Metapenaeus bennettae	Prawns, Greasyback		224		200		21
Mordacia mordax	Lamprey, Short-headed		24		688		77
Mugil cephalus	Mullet, Sea		29		2		
Muraenichthys australis	Worm Eel, Shortfin		14		1		5
Myxus elongatus	Mullet, Sand		1				
Order Amphipoda	Scuds, [Unspecified]		454				2
Order Coleoptera	Water Beetles, [Unspecified]				2		
Order Isopoda	Sea lice, [Unspecified]	1.4	10734		4688	14.2	>2791
Order Octopoda	Octopus, [Unspecified]		1				
Order Polychaeta	Sea-worms, [Unspecified]		250		555		64
Order Scyphozoa	Jellyfish, [Unspecified]		1		1		
Ovalipes australiensis	Crab, Sand		1				
Paratya australiensis	Shrimp, Common Freshwater		2765	8	2658		>2455
Parequula melbournesis	Silverbiddy/Silverbelly		6		1		1
Philypnodon grandiceps	Gudgeon, Flat-headed		136		9315		>1577
Philypnodon sp.	Gudgeon, Dwarf Flat-headed		1				
Pomatomus saltatrix	Tailor		132		42		57
Pseudaphritis urvilli	Tupong		22		424		350
Pseudocaranx spp.	Trevally, [Unspecified]				3		3
Pseudocaranx wrighti	Trevally, Skipjack		1				
Pseudogobius olorum	Goby, Bluespot				450		317
Pugnaso curtirostris	Pipefish, Short-snouted						70
Redigobius macrostoma	Goby, Largemouth				1		
Retropinna semoni	Smelt, Australian	0.3	7		1590		>561
Rhombosolea tapirina	Flounder, Greenback		1463		906		35
Scorpis marmoratus	Sweep, Sea		2		1		7
Family Sillanginidae	Whiting, [Unspecified]				1		
Subclass Copepoda	Copepods, [Unspecified]			3	0		
Suborder Anisoptera	Mudeye, [Unspecified]				1		
Suborder Brachyura	Crabs, [Unspecified]				5		277
Suborder Zygoptera	Damselfly nymphs, [Unspecified]				1		
Synaptura nigra	Sole, Black		60		25		81
Tasmanogobius lasti	Goby, Lagoon				1		
Tetractenos glaber	Toadfish, Smooth		25				
Vanacampus poecilolaemus	Pipefish, Longsnout						5

Prosser River, Tasmania, Site 1 by-catch species list and abundance.

Scientific Name	Common Name	1998	1997
		Total N°	Total N°
Acanthaluteres spilomelanurus	Leatherjacket, Bridled	2	
Aldrichetta forsterii	Mullet, Yellow-eye	802	548
Anguilla australis (Elvers)	Eel, Shortfin	2	
Anguilla australis (adult)	Eel, Shortfin	1	
Arripis trutta	Salmon, Eastern Australian	41	45
Atherinidae spp.	Hardyhead, [Unspecified]	3878	402
Brachaluteres jacksonianus	Leatherjacket, Sourthern Pigmy	2	
Carcinus maenus		1	
Contusus brevicaudus	Toadfish, Prickly	16	1
Engraulis australis	Anchovy, Australian	3	
Family Syngnathidae	Pipefish, [Unspecified]	47	1
Favinogobius tamarensis	Goby, Tamar River	267	175
Galaxias maculatus	Galaxias, Common	151	12
Gymnapistes marmoratus	Cobbler/Soldierfish	14	4
Hippocampus breviceps	Seahorse, Shortsnout	2	
Hyporhamphus melanochir	Garfish, Southern Sea	1	
Lovettia sealii	Whitebait, Tasmanian	192	132
Macrobrachium spp.	Shrimp	479	300
Family Monacanthidae	Leatherjacket, [Unspecified]	10	
Nototodarus spp.	Squid, [Unspecified]	6	
Order Amphipoda	Scuds, [Unspecified]	250	
Order Isopoda	Sea lice, [Unspecified]		1048
Ovalipes australiensis	Crab, Sand	3	
Paragrapsus spp.	Crab, Mud	1	
Platycephalus bassensis	Flathead, Sand	20	
Pseudaphritis urvillii	Tupong	2	
Pseudocaranx dentex	Trevally, Sea	23	
Pseudophycis bachus	Cod, Southern Rock	3	
Rhombosolea tapirina	Flounder, Greenback	18	11
Siphonognathus beddomei	Weed Whiting, Pencil	1	
Spratelloides robustus	Sprat, Blue		183
Suborder Brachyura	Crabs, [Unspecified]		11
Tetractenos glaber	Toadfish, Smooth	12	

3 ADVANCES IN THE WEANING AND REARING OF JUVENILE AUSTRALIAN SHORTFIN EELS (*ANGUILLA AUSTRALIS*)

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CONTENTS

3.1 INTRODUCTION

Previous research into the rearing of the Australian shortfin eel, *Anguilla australis* Richardson, conducted as part of a Fisheries Research and Development Corporation (FRDC) funded project (No. 94/067), investigated the tank and pond culture of juvenile stages (glass eels and elvers) (Ingram *et al.* 1996, Ingram and Gooley 1996, Gooley *et al.* 1999, Ingram *et al.* 2001). In particular, initial acclimation and feeding of glass eels after capture, weaning onto artificial diets, extensive rearing of glass eels and elvers in fertilised earthen ponds, and basic husbandry practices, including the effects of culture temperature, feeding rates and stocking densities, were investigated. This earlier study showed that the initial feeding and weaning of glass eels were critical to their survival throughout the nursery phase, and therefore to the subsequent performance of the juveniles under intensive/semi-intensive culture conditions. Indeed this is not specific to *A. australis* as the initial rearing period of both the European eel, *A. anguilla* and Japanese eel, *A. japonica*, during which glass eels have to adapt to artificial foods, is generally regarded as the most difficult stage of the rearing process for these species (Kamstra and Heinsbroek 1991). Non-acceptance of food, cannibalism and disease can cause excessive mortalities (ranging from 15% to 90%) of juvenile eels in the first few months of captivity (Appelbaum 1980; Degani and Levanon 1986; Heinsbroek 1989). Glass eels make up 23-38% of production costs of eel farms (Gousset 1992), further emphasising the importance of high survival during the weaning process on the overall commercial viability of eel farming operations.

In recognition of the importance of these early stages to farming *A. australis*, the present study focused on the initial feeding and weaning of *A. australis* glass eels, with the aim being to refine and optimise husbandry practices in order to further improve survival and growth. More specifically, a primary objective of the present study was to investigate and identify suitable diets for the initial feeding of glass eels prior to weaning. Newly caught glass eels of

*A. anguilla*s are most commonly fed the roe of Atlantic cod (*Gadus morhua* L.) prior to commencement of weaning (Heinsbroek 1991). Previously, the glass eels of *A. australis* have been offered a range of initial diets including minced fish flesh, *Artemia*, ox liver and trout fines (Ingram and Gooley 1996, Gooley *et al.* 1999, Ingram *et al.* 2001). As part of the present study, experiments were conducted to determine the suitability of roe from several locally available fish species for the initial feeding of newly-caught glass eels. Additional experiments were also undertaken to further refine practices associated with subsequent weaning and rearing of glass eels and pigmented elvers. These experiments included investigations into the effects of time in captivity prior to weaning, duration of the weaning phase, and diet type and presentation on growth and survival of glass eels during and immediately after weaning, and the effects of stocking density on the growth of weaned, pigmented elvers.

Preliminary experiments into the extensive pond rearing of *A. australis* were limited by the availably of glass eels for experiments (Gooley *et al.* 1999), and as a result, optimal stocking densities for the rearing of glass eels in fertilised earthen ponds were not identified. A further, single, non-replicated trial was undertaken as part of the current project in order to identify the effects of stocking density of glass eel growth and survival in fertilised earthen ponds, without the addition of supplementary feed.

3.2 MATERIALS AND METHODS

3.2.1 Collection, transport and acclimation of glass eels

All glass eels used in experiments were harvested from the estuary of the Snowy River as part of the assessment component of the present study (Chapter 2). Glass eel collection and handling methods employed in the field are described in McKinnon and Gooley (1998), Gooley *et al.* (1999) and McKinnon *et al.* (2001), as well as Chapter 2 and Appendix I of this publication. Glass eels were transferred to the Marine and Freshwater Resources Institute (MAFRI), Snobs Creek, in north-eastern Victoria in sealed plastic bags inflated with oxygen and containing a small amount of water collected from the point of capture. These bags were placed into an insulated box containing a freezer block to maintain low temperatures ($<10^{O}$C) during transport.

On arrival at MAFRI, Snobs Creek, glass eels were placed into temporary holding tanks in a quarantine system and allowed to acclimate to freshwater, laboratory (controlled environment) conditions for a period of up to five days. During acclimation the eels were starved and the water temperature in which the eels were being held was gradually increased from ambient (typically 10-17^{o}C) to 20-25^{o}C, and the salinity was reduced from 5-10 g/l (transportation level) to freshwater. In addition, the tanks were initially covered with black plastic to reduce light intensity.

3.2.2 Culture facilities and techniques

All tank culture experiments were conducted indoors under controlled environment conditions at MAFRI, Snobs Creek, between August 1997 and September 1999. For all experiments fish were held in 160 l circular fibreglass tanks, which were maintained at a volume of 100 l, supplied with a continuous, filtered and recirculated flow of water at temperatures between 20^{o}C and 25^{o}C, at a rate of approximately 1.0 –5.0 l/min, and with supplementary aeration. A further description of these facilities is provided by Gooley *et al.* (1999).

For each treatment being tested within each experiment, three or four tanks were used as replicates, and allocation of treatments to each tank was randomised to avoid any inherent bias associated with tank location. Each tank was provided with a floating platform (approximately 225 cm^2, consisting of 5 - 10 mm aperture black polypropylene mesh attached to a rectangular PVC flotation collar), which provided a feeding and resting station for the eels. All tanks were cleaned daily, with uneaten food and faecal material being removed and the sides and floor scrubbed clean. Apart from specific experimentation to test optimal stocking densities, the biomass of eels used in tanks during each experiment largely depended on the number of eels available at the time. To prevent crowding affects however, initial stocking densities were generally kept below 20 kg/m^3.

A series of experiments aimed to gain further information on the initial feeding, weaning and rearing of glass eels of *A. australis* were conducted, and their details are summarised in Table 3.1. After initial allocation of eels to tanks for each experiment, random samples of 10-30 individual fish from each tank were anaesthetised and measured. Sedation of glass eels was achieved using 15-25 mg/l metomidate hydrochloride (Marinil™, Syndel Corporation). Weight was measured to the nearest 0.001g for glass eels and to the nearest 0.01g for larger, pigmented glass eels and elvers. Every 10-14 days during and at the termination of each experiment, a random sample of 10-30 individual eels were measured from each tank. At the beginning and end of each experiment the total biomass of each tank was determined by wet weighing as a group, all eels allocated to that tank. For this purpose, eels were removed from the tank, excess water was drained, and the eels were then were placed into a beaker on a balance and the weight recorded to the nearest 0.1g. Throughout the experiments, mortalities in each tank were recorded daily.

3.2.3 Feeding regime

A typical feeding regime for cultured glass eels used in the present study is described in Appendix I, and includes the following key developmental and production stages:

Acclimation: Acclimation from conditions under which eels were captured in the wild to 'aquaculture' conditions, typically up to 5 days during which time the fish are starved. Note that glass eels in the wild are thought to fast (do not feed) during the immediate post-metamorphosis/estuarine invasion phase of their life-cycle, and active feeding is suggested to re-commence at later pigmented developmental stages once they have entered the estuary (Tesch 1977). The glass eels are typically captured for aquaculture purposes at the point or soon after entry to the estuary, although they can also be taken further upstream closer to the freshwater interface, at which time they should have commenced active feeding.

Breaking fast and initial feeding (pre-weaning): Following acclimation, glass eels are offered a 'natural' diet of freshly minced fish flesh or fish roe to 'break the fast' and to initiate active feeding. This stage would typically last for 5-10 days. Initial feeding diets are placed on the floating platform and fed 2-4 times daily to satiation. At this stage glass eels are developing physically into the typical pigmented elver/juvenile eel form.

Table 3.1 Summary of tank and pond culture experiments conducted on the glass eels and elvers of *A. australis* during the present study

Experiment.	Initial mean stocking density (kg/m^3)	Initial mean eel weight (g)	Mean No. eels per replicate	Duration (days)	Treatments	Culture temperature (oC)	Feeding regime
Developmental stage at weaning	3.7	0.148	2500	55	10 days in captivity prior to weaning 36 days in captivity prior to weaning	21.3	Satiation, up to 4 feeds per day
Weaning duration	3.7	0.148	2500	55	Weaned over a 3 week period Weaned over a 4.5 week period	21.3	Satiation, up to 4 feeds per day
Diet type and form	3.7	0.151	2500	55	Weaned onto dry Kinta diet Weaned onto moist Kinta diet Weaned onto moist Taiwanese diet Weaned onto moist experimental diet	20.1	Satiation, up to 4 feeds per day
Fish roe Experiment 1	5.0	0.169	2960	55	Initial diet carp roe Initial diet minced fish flesh Initial diet warehou roe	17.4	Satiation, up to 4 feeds per day
Fish roe Experiment 2	5.0	0.172	2900	28 (42)	Initial diet carp roe Initial diet warehou roe Initial diet mirror dory roe Initial diet orange roughy roe	20.6	Satiation, up to 4 feeds per day
Stocking density	10.0 – 40.0	1.212	400-1,660	57	10 kg/m^3 20 kg/m^3 40 kg/m^3	22.8	5%/day, 4 feeds per day
Commercial eel diet type	4.6	0.614	755	43	Provimi eel diet Kinta eel diet	24.6	8%/day, 4 feeds per day

Weaning: Weaning of pigmented elvers/juvenile eels onto an artificial, typically manufactured, compound/formulated diet commences once a vigorous feeding response on the natural diet is exhibited. Typically, weaning begins 5-10 days after commencement of feeding on the natural diet and lasts for 15-20 days.

Grow-out: When fully weaned onto the preferred artificial diet, elvers are typically fed on such diets at varying feed rates, frequency and pellet size according to specific species requirements, developmental stage, feed type, husbandry requirements, farming system requirements and other operational requirements etc.

These stages however varied somewhat for many of the experiments in the present study in order to investigate and refine various aspects of the weaning and feeding regimes. All such variations are detailed under the relevant experimental design descriptions following.

In general, food was provided during the experiments by hand, 2-6 times daily, to either satiation or to set feed rates as required. Set feed rates ranged from 5% to 10% (dry feed weight to wet body weight) of body weight per day and were adjusted periodically after calculation of change in fish (mean) weight and number. Natural and moist artificial feeds were placed directly onto the floating platforms for feeding purposes.

A summary of the proximate composition and energy content of diets and feeds used during experiments is presented in Table 3.2. Minced fish was the flesh of farmed rainbow trout (*Oncorhynchus mykiss*) obtained from MAFRI, Snobs Creek. The roe of wild-caught carp (*Cyprinus carpio*) was obtained frozen from K & C Fisheries, Sale, Victoria. The roe of wild-caught pink ling (*Genypterus blacodes*), warehou (mostly *Seriolella brama* and some *S. punctata*), mirror dory (*Zenopsis nebulosus*) and orange roughy (*Hoplostethus atlanticus*) were obtained frozen from MAFRI, Queenscliff. Three commercial, artificial eel diets and one experimental artificial diet developed by Deakin University (see Chapter 4) were used during the experiments. The Taiwanese eel diet (imported by Primo Aquaculture, Coffs Harbour, New south Wales) was a powder-based starter feed specifically formulated for juvenile *A. japonica*. In the present study this diet was presented to the eels as a paste by addition of water to the powder prior to feeding on a daily basis. The Kinta eel feed (Kinta Pty Ltd., Mulwala, New South Wales) was a dry crumble/pelleted diet manufactured for *A. australis*. The Provimi Eel Starter Select diet is a commercial dry diet sourced from Europe and formulated for juvenile *A. anguilla*.

3.2.4 Tank culture trials

3.2.4.1 Developmental stage at weaning

In order to determine the effects of duration in captivity and associated developmental stage prior to weaning onto an artificial diet, weaning of one group of eels did not commence until 36 days after capture from the Snowy River on 12 July, 1997. Following a five-day acclimation period these eels were fed to satiation on minced fish twice daily prior to weaning. Weaning of a second group of eels commenced 10 days after capture from the Snowy River on 12 August 1997. These eels were acclimated over 5 days then fed on minced fish to satiation twice daily for 5 days before weaning commenced. Eels from each group were weaned onto a commercial diet (Taiwanese eel diet) prepared as a moist paste over a three week period. Growth and survival were monitored for a total weaning and grow-out period of 55 days during which time the eels were feed to satiation four times daily.

Table 3.2 Mean proximate composition and energy content of diets and feeds used in experiments during the present study

Diet	Parameter (mean)				
	Moisture (%)	Protein (%)	Lipids (%)	Ash (%)	Energy (kJ/g)
Minced fish flesh*	78.7	84.2	14.8	6.4	24.9
Carp roe	63.2	78.0	17.1	3.8	
Mirror dory roe	69.1	73.1	20.1	2.9	
Orange roughy roe	81.6	63.6	25.0	5.6	
Warehou roe	74.2	67.1	25.6	3.9	
Kinta eel diet	8.9	53.8	10.5	13.0	21.9
Provima Eel Starter Select diet	9.0	55.0	13.0	9.5	
Taiwanese eel diet	6.9	45.7	13.2	15.2	19.0

* rainbow trout (*Oncorhynchus mykiss*)

3.2.4.2 Weaning duration

The effects of duration of the weaning period were investigated in an experiment in which elvers were weaned over a period of either 3 or 4.5 weeks. Prior to commencement of weaning the eels were initially fed on minced fish. Weaning schedules used for each group (weaning duration) of eels are presented in Table 3.3. During the weaning period, elvers from each group were weaned onto a commercial diet (Taiwanese eel diet) prepared as a moist paste. Growth and survival were monitored for a total weaning and grow-out period of 55 days during which time the eels were feed to satiation four times daily.

3.2.4.3 Diet type and form

The growth and survival of glass eels weaned onto four different diet preparations, based on three different artificial diet formulations, were investigated over a 55 day period. The three diet formulations tested were: (1) Kinta eel diet, (2) Taiwanese eel diet and (3) an experimental eel diet developed by Deakin University (Warrnambool) (see Chapter 4). These diets were presented to the glass eels as a moist paste and, in addition, the Kinta eel diet was also presented as a dry food. Prior to commencement of weaning the eels were fed on minced fish. Over the first three weeks of the experiment, glass eels from each group were weaned from minced fish onto the diet being tested. Growth and survival were monitored for a total weaning and grow-out period of 55 days during which time eels were feed to satiation four times daily.

Table 3.3 Weaning schedules for glass eels weaned over either 3 weeks or 4.5 weeks (400 g glass eels per tank)

Day	3 week weaning period		4.5 week weaning period	
	Eel diet* (g dry wt)	Minced fish (g wet wt)	Eel diet* (g dry wt)	Minced fish (g wet wt)
1	2	38	2	38
2	2	38	2	38
3	2	38	2	38
4	4	36	2	38
5	4	36	4	36
6	4	36	4	36
7	8	32	4	36
8	8	32	8	32
9	8	32	8	32
10	16	24	8	32
11	16	24	12	28
12	16	24	12	28
13	24	16	12	28
14	24	16	16	24
15	24	16	16	24
16	32	8	16	24
17	32	8	20	20
18	32	8	20	20
19	36	4	20	20
20	36	4	24	16
21	36	4	24	16
22	40	0	24	16
23			28	12
24			28	12
25			28	12
26			32	8
27			32	8
28			32	8
29			36	4
30			36	4
31			36	4
32			40	0

* Taiwanese eel diet (prepared as a moist paste)

3.2.4.4 Fish roe diet type

Two separate experiments were conducted to determine the influence of fish roe as an initial feeding (pre-weaning) diet on the growth, survival and eventual weaning success of glass eels. During the first experiment (#1), which commenced on the 5 August 1998 and ran for 55 days, newly acclimated glass eels were offered either carp roe, minced fish flesh or warehou roe (each in three replicates) for two weeks before being weaned onto the Kinta eel diet over a further 3 week period. During the second experiment (#2), which commenced on the 26 July 1999, glass eels were offered either carp roe, warehou roe, mirror dory or orange roughy (each in four replicates) for three weeks before commencement of weaning onto the Kinta eel diet. In both experiments, small pieces of roe (approximately 2-3cm^3) were placed on the floating platform in each tank. During the second experiment samples of eels and fish roe were collected for composition analysis, which is described in more detail in Chapter 4.

3.2.4.5 Stocking density

The effect of stocking density on the growth and survival of pigmented eels (elvers) was investigated in an experiment in which fully weaned eels were stocked into tanks at either 10 kg/m^3, 20 kg/m^3, and 40 kg/m^3. Prior to commencing the experiment eels were graded to reduce size variation. During the experiment, which commenced on February 1998 and ran for 57 days, eels were fed Kinta eel diet at a rate of 5 %/day.

3.2.4.6 Commercial eel diet type

The growth and survival of weaned pigmented eels (elvers) fed either the Kinta eel diet or the Provimi eel diet, both offered as dry feeds, were investigated over a 43 day experiment which commenced 11 December 1997. Unfortunately, due to the limited amount of the imported Provimi eel diet that was available at the time, this experiment could not be continued behind 43 days. Prior to commencing the experiment, eels were graded to reduce size variation. Eels were fed to apparent satiation four times daily (up to 8 %/day).

3.2.4.7 Water quality

During all experiments, water temperature was measured every 15 minutes using a Datataker 100 data logger (single probe positioned in one tank). Dissolved oxygen (as mg/l) in each tank was measured with a YSI meter, 1-3 times each week. During the diet type and presentation experiment, the fish roes experiments, the stocking density experiment and the commercial eel diet experiment, total Ammonia Nitrogen (TAN) (Nessler Method), total Phosphorus (total P) as phosphate (Acid Persulphate Digestion Method) and pH were measured in inlet and outlet waters 1-3 times weekly. Water samples were analysed using a Hach 4000 spectrophotometer. Net TAN and net total P were calculated by subtracting the concentration of TAN and total P in the inlet water from concentrations of TAN and total P in the discharge water, respectively.

3.2.4.8 Data analysis

Specific growth rates (SGRs), which were expressed as the percentage increase in body weight per day (%/day) were determined for all experiments by using the following formula:

$$SGR = \frac{\ln Wt - \ln Wo}{t} \times 100$$

where: t = time in days
$lnWo$ = natural logarithm of the average weight at time zero
$lnWt$ = natural logarithm of the average weight at time t.

SGRs were used to compare growth rates of eels within each experiment only. Due to variations in SGRs associated with age of eels, water temperatures and other factors, no comparisons of SGRs were drawn between experiments.

For each experiment fish growth, SGRs, survival rates and water quality data were analysed using the SAS General Linear Models Procedure and Tukey's Studentised Range Test (SAS Institute Inc. 1990), following testing for homogeneity using Cochran's Test and log transformation of data wherever necessary. Standard error bars for all graphs were generated from SAS and were equal to two standard deviations of the mean.

3.2.5 Commercial intensive grow-out trial

Between July and August 1998, approximately 37 kg of glass eels (initial weight 0.12-0.6 g), which had previously been collected from the Snowy River and weaned at MAFRI, Snobs Creek, were transferred to *Australian Aquaculture Products (AAP) P/L*, Euroa, Victoria, for grow-out under commercial conditions. At AAP, glass eels were initially placed into 1,600l tanks (Fig. 3.1) and, when a sufficient biomass of eels was available, were subsequently transferred to 15,000l tanks at a minimum density of 40 kg/m^3. These tanks were part of a *Hesy* eel recirculation system which is described by O'Sullivan (1999). Water temperature and dissolved oxygen saturation in the system were maintained at 23-26^oC and greater than 90%, respectively. Water flow rates were 4.5-6.5 m^3/hr. During this period, eels were fed to satiation on a commercially available, extruded salmon diet (45:22) (pellet size dependent on eel size). Eels were fed via an automatic belt feeder situated on each tank. Because eels were graded and re-allocated to tanks according to size every three to five weeks, it was not possible to monitor specific groups of eels during their grow-out, no replicated experimentation was undertaken as part of this trial, and no statistical analyses were therefore undertaken on data collected.

Fig. 3.1 1,600 l tanks at Australian Aquaculture Products, which were part of a Hesy recirculation system used in the commercial grow-out trial of eels

3.2.6 Extensive pond culture trial: effect of stocking density

On 28 November 1997, glass eels (initial mean weight 0.29 g), which had been collected from the Snowy River and weaned onto an artificial diet at MAFRI, Snobs Creek, were stocked into two earthen ponds at Deakin University, Warrnambool (surface area 0.1 ha). Both ponds had been fertilised to encourage the growth of plankton blooms. No supplementary feeding of either pond was undertaken, rather the sole source of food for the eels was naturally occurring aquatic animals (zooplankton, aquatic insects, etc.). A more detailed description of the preparation and operation of these ponds is presented in Gooley *et al.* (1999) and Ingram *et al.* (2001). Ponds were stocked at two different densities. One pond was stocked with approximately 5,000 (5 eels/m^2) while the other with 10,000 eels (10 eels/m^2). At the beginning and end of the trial, and every two weeks during the trial, a sample of at least 60 eels were collected from each pond and each eel was measured to the nearest 0.1 g and 1 mm, before being returned to the ponds. Pond water quality and plankton densities and composition were monitored weekly. After 14.5 weeks (late March), the ponds were drained, and eels were harvested, weighed and counted to determine harvest biomass and survival. The purpose of this stocking trial was to determine if growth and survival was effected by initial stocking density. As only one pond was stocked at each density, no statistical analyses were undertaken.

3.3 RESULTS

3.3.1 Tank culture trials

3.3.1.1 Developmental stage at weaning

SGRs between replicates within each treatment were highly variable. Although the mean SGR for glass eels weaned after 36 days in captivity (SGR 0.72%/day) was considerably higher than for glass eels weaned after 10 days in captivity only (0.47%/day) (Table 3.4), this trend was not significant. However, change in weight for glass eels over the duration of the experiment was significantly greater for eels weaned after 36 days in captivity than for those weaned after 10 days in captivity only ($F_{1,4}$=8.93, P=0.004) (Fig. 3.2) Growth of eels in both treatments declined during weeks 3-6 of the experiment, then increased in latter weeks. Survival rates, which ranged from 82% -85% (Table 3.4) over the 55 days of the experiment, were not significantly different for the period of time in which the glass eels were in captivity prior to commencing weaning.

3.3.1.2 Weaning duration

The duration of the weaning period (between commencing of feeding an artificial diet and ceasing feeding of a natural diet (Table 3.3), did not significantly effect the rate of change in weight of eels over time (Fig. 3.3). Similarly, weaning duration did not significantly effect SGRs (Table 3.4). As observed in the previous experiment (Developmental Stage at Weaning), during weeks 3-6 of the experiment glass eels lost weight in both treatments, but subsequently gained weight in latter weeks. Survival 55 days after commencing weaning was slightly higher for glass eels weaned over 4.5 weeks (88%) than for those weaned over three weeks (82%) (Table 3.4), however this result was not significant.

Table 3.4 Initial and final mean weights, specific growth rates (SGR) and survival rates of juvenile eels during tank culture experiments.

PARAMETER	TREATMENT[1] (mean + s.e.*)			
Developmental Stage and weaning	**10 days**	**36 days**		
Initial weight (g)	0.15 + 0.005	0.15 + 0.004		
Final weight (g)	0.19 + 0.011	0.22 + 0.017		
Survival rate (%+ s.e.)	82.3 + 1.7	85.1 + 0.5		
SGR (%/day + s.e.)	0.47 + 0.13	0.72 + 0.12		
Weaning duration	**3 weeks**	**4.5 weeks**		
Initial weight (g)	0.15 + 0.005	0.15 + 0.005		
Final weight (g)	0.19 + 0.011	0.21 + 0.016		
Survival rate (%+ s.e.)	82.3 + 1.7	87.7 + 1.9		
SGR (%/day + s.e.)	0.47 + 0.15	0.58 + 0.32		
Diet type and form	**Kinta dry**	**Kinta moist**	**Experimental moist**	**Taiwanese moist**
Initial weight (g)	0.14 + 0.004	0.16 + 0.004	0.15 + 0.005	0.15 + 0.005
Final weight (g)	0.14 + 0.009	0.20 + 0.014	0.22 + 0.013	0.19 + 0.011
Survival rate (%+ s.e.)	77.5 + 1.3	87.7 + 0.9	85.1 + 7.7	82.3 + 1.7
SGR (%/day + s.e.)	-0.02 + 0.4	0.41 + 0.33	0.62 + 0.10	0.47 + 0.13
Fish roe Experiment 1	**Carp roe**	**Warehou roe**	**Minced fish**	
Initial weight (g)	0.17 + 0.004	0.17 + 0.004	0.17 + 0.005	
Final weight (g)	0.13 + 0.008	0.11 + 0.006	0.11 + 0.008	
Survival rate (%+ s.e.)1	54.7 + 2.8b	82.3 + 3.8a	55.3 + 4.8b	
SGR (%/day + s.e.)	-0.51 + 0.23	-0.68 + 0.07	-0.73 + 0.12	
Fish roe Experiment 2	**Carp roe**	**Warehou roe**	**Orange roughy roe**	**Mirror dory roe**
Initial weight (g)	0.17 + 0.004	0.17 + 0.003	0.17 + 0.004	0.17 + 0.004
Final weight (g)	0.16 + 0.005	0.15 + 0.004	0.14 + 0.004	0.12 + 0.004
Survival rate (%+ s.e.)	99.5 + 0.04	99.4 + 0.1	99.1 + 0.2	99.4 + 0.1
SGR (%/day + s.e.)1	-0.19 + 0.3a	-0.12 + 0.24a	-0.88 + 0.10b	-1.27 + 0.08b
Stocking density	**10 kg/m3**	**20 kg/m3**	**40 kg/m3**	
Initial weight (g)	1.32 + 0.08	1.28 + 0.11	1.20 + 0.04	
Final weight (g)	1.69 + 0.08	1.66 + 0.07	1.65 + 0.07	
Survival rate (%+ s.e.)	100	100	99.8 + 0.2	
SGR (%/day + s.e.)	0.43 + 0.14	0.60 + 0.01	0.43 + 0.14	
Commercial eel diet type	**Kinta eel diet**	**Provimi eel diet**		
Initial weight (g)	0.60 + 0.028	0.63 + 0.024		
Final weight (g)	1.02 + 0.04	1.08 + 0.04		
Survival rate (%+ s.e.)	99.8 + 0.1	99.5 + 0.3		
SGR (%/day + s.e.)	2.02 + 0.16	2.03 + 0.07		

* s.e. standard error

1. Treatments with the same letter (superscript) are not significantly different from each other (Tukey's Studentised Range Test)

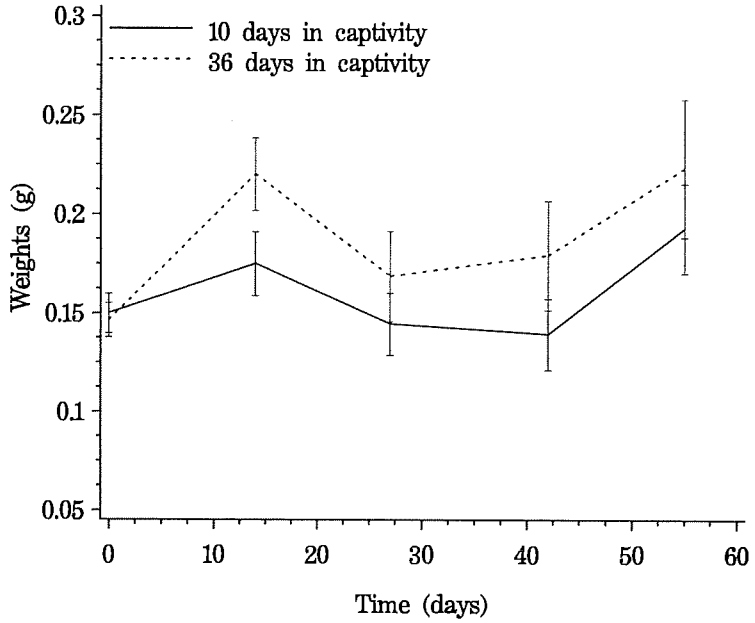

Fig. 3.2 Effects of age of glass eels (days in captivity prior to weaning) on the growth (mean weight ± s.e.) of glass eels during weaning

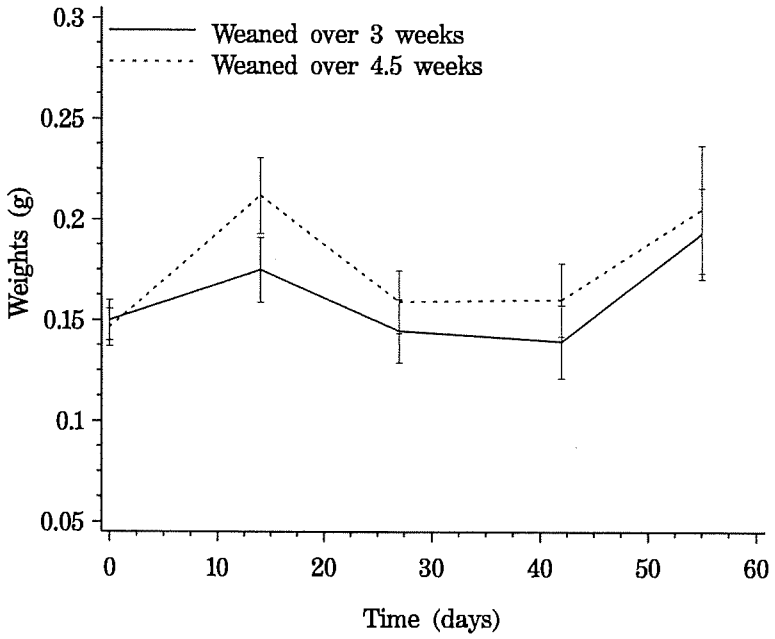

Fig. 3.3 Effects of duration of weaning period on the growth (mean weight ± s.e.) of glass eels during weaning

3.3.1.3 Diet type and form

Diet type and form did not significantly (P>0.05) effect change in weight of glass eels over time and associated SGR's (Table 3.4, Fig. 3.4). However, glass eels fed the Kinta dry diet, had a negative SGR (–0.2%/day) whereas those fed moist diets had positive SGRs (averages between 0.41%/day and 0.62%/day) (Table 3.4, Fig. 3.4). Growth of eels generally declined during the middle weeks of the experiment, but increased in latter weeks. Survival rates after 55 days ranged from 77.5% (Kinta dry) to 87.7% (Kinta moist) (Table 3.4), but were not significantly affected by either diet type or diet form.

Highly significant differences in TAN, and total P were observed in the effluent water from tanks receiving different diets during the experiment (P<0.05) (Table 3.5). TAN concentrations were lowest in the inlet water followed by effluent water from the tanks receiving the Taiwanese moist diet, while highest concentrations were observed in effluent waters from tanks receiving Kinta moist, Experimental moist and Kinta dry diets (Fig. 3.5). Similar trends were observed for net TAN (Table 3.5). In general, concentrations of total P were considerably lower in the inlet water than in the effluent water from each of the tanks (Fig. 3.5). On average, the total P in the effluent water from tanks receiving the experimental moist diet, was lower than those for other diets, however, the Tukey's Studentised Range test failed to detect a significant different between the treatments (Table 3.5). No significant differences were observed for pH readings.

3.3.1.4 Fish roe diet type

Experiment 1

The initial feeding/pre-weaning diet fed to glass eels did not significantly (P>0.05) affect change in weight of eels over time and associated SGRs (Table 3.4, Fig. 3.6). However, glass eels that received warehou roe as an initial diet prior to weaning had a significantly higher survival rate (82.3%) than glass eels which received either minced fish (55.3%) or carp roe (54.7%) prior to weaning ($F_{1,6}$=13.68, P=0.0058).

Concentrations of both TAN, and total P were significantly (P<0.05) lower in the inlet water than effluent water from tanks receiving different diets during the experiment (Table 3.5, Fig. 3.7). However, no significant differences were detected in nutrient concentrations in the effluent waters between treatments. The pH readings in the effluent water from tanks that received carp roe and warehou roe were slightly lower than pH readings from the inlet water and tanks receiving minced fish (Table 3.5).

Experiment 2

Glass eels in treatments that received either carp or warehou roe readily accepted these diets and fed vigorously. In contrast, those eels in treatments that received roe from either orange roughy or mirror dory did not feed as strongly as observed in other treatments and did not responding favourably to the weaning schedule. Consequently after 28 days, to avoid inevitable mortalities associated with starvation, eels fed on orange roughy and mirror dory roe were removed from the experiment and placed on a diet of carp roe to recover condition before weaning at a later date. Other treatments were continued until day 42. After 28 days SGRs in all treatments were negative. However, there was a significant difference in SGR (%/day) between diets ($F_{3,12}$=13.09, P=0.0004) (Table 3.4). Fish initially fed on either warehou roe or carp roe exhibited the highest SGRs and were not significantly different from each other, but were both significantly higher than SGRs for glass eels initially fed either orange roughy or mirror dory row (Table 3.4). Likewise, a significant change in weight was observed over time ($F_{3,12}$=8.20, P=0.0031) (Fig. 3.8).

Table 3.5 Water quality variables (mean with standard error in brackets) measured during the experiments.

Parameter	Inlet	Treatment outlet*			
Diet type and form		**Kinta dry**	**Kinta moist**	**Experimental moist**	**Taiwanese moist**
PH	6.68 (0.01)^{a}	6.60 (0.01)^{ab}	6.60 (0.01)^{ab}	6.53 (0.02)^{b}	6.66 (0.06)^{a}
TAN[1] (mg/1)	0.19 (0.02)^{cd}	0.43 (0.05)^{abc}	0.44 (0.05)^{ab}	0.43 (0.04)^{abc}	0.29 (0.03)^{bcd}
Net[2] TAN (mg/1)		0.22 (0.04)^{ab}	0.23 (0.04)^{ab}	0.21 (0.03)^{ab}	0.09 (0.01)^{b}
Total P (mg/l)	0.18 (0.04)	0.68 (0.19)	0.65 (0.18)	0.56 (0.14)	0.59 (0.16)
Net[2] Total P (mg/l)		0.49 (0.16)	0.40 (0.13)	0.34 (0.09)	0.40 (0.13)
Dissolved Oxygen (mg/l)	6.77 (0.32)	6.32 (0.18)	6.16 (0.18)	6.16 (0.26)	6.41 (0.15)
Temperature (^{o}C)	19.6 (0.3)				
Fish roe Experiment 1		**Carp roe**	**Warehou roe**	**Minced fish**	
PH	6.66 (0.02)^{a}	6.60 (0.04)^{ab}	6.53 (0.02)^{ab}	6.66 (0.02)^{a}	
TAN[1] (mg/1)	0.22 (0.02)^{a}	0.35 (0.02)^{b}	0.35 (0.02)^{b}	0.36 (0.03)^{b}	
Net[2] TAN (mg/1)		0.13 (0.01)	0.13 (0.01)	0.15 (0.02)	
Total P (mg/l)	0.38 (0.04)^{a}	0.97 (0.14)^{b}	1.10 (0.10)^{b}	0.97 (0.11)^{b}	
Net[2] Total P (mg/l)		0.62 (0.13)	0.73 (0.10)	0.61 (0.10)	
Dissolved Oxygen (mg/l)	7.00 (0.11)				
Temperature (^{o}C)	17.4 (0.4)				
Fish roe Experiment 2		**Carp**	**Warehou**	**Orange roughy**	**Mirror dory**
PH	6.80 (0.02)	6.67 (0.02)	6.70 (0.02)	6.70 (0.01)	6.71 (0.02)
TAN[1] (mg/1)	0.07 (0.01)^{b}	0.08 (0.02)^{ab}	0.09 (0.01)^{ab}	0.13 (0.03)^{a}	0.11 (0.03)^{ab}
Net[2] TAN (mg/1)		0.03 (0.01)	0.04 (0.00)	0.03 (0.01)	0.05 (0.01)
Total P (mg/l)	0.26 (0.01)^{b}	0.53 (0.06)^{a}	0.56 (0.05)^{a}	0.53 (0.07)^{a}	0.58 (0.05)^{a}
Net[2] Total P (mg/l)		0.29 (0.06)	0.29 (0.05)	0.27 (0.07)	0.29 (0.05)
Dissolved Oxygen (mg/l)	8.22 (0.02)				
Temperature (^{o}C)	20.7 (0.2)				
Stocking density		**10 kg/m^{3}**	**20 kg/m^{3}**	**40 kg/m^{3}**	
PH	6.81 (0.05)^{a}	6.69 (0.03)^{ab}	6.55 (0.04)^{bc}	6.47 (0.05)^{c}	
TAN[1] (mg/1)	0.05 (0.00)^{c}	0.13 (0.01)^{bc}	0.22 (0.02)^{ab}	0.31 (0.04)a	
Net[2] TAN (mg/1)		0.08 (0.01)^{b}	0.16 (0.02)^{b}	0.28 (0.04)^{a}	
Total P (mg/l)	0.14 (0.02)^{b}	0.25 (0.04)^{b}	0.39 (0.07)^{ab}	0.54 (0.10)^{a}	
Net[2] Total P (mg/l)		0.11 (0.03)^{b}	0.24 (0.05)^{ab}	0.43 (0.09)^{a}	
Dissolved Oxygen (mg/l)	6.39 (0.14)^{b}	7.11 (0.13)^{a}	6.41 (0.20)^{b}	5.37 (0.19)^{c}	
Temperature (^{o}C)	23.3 (0.4)				
Commercial eel diet type		**Kinta diet**	**Provimi diet**		
PH	6.85 (0.03)^{a}	6.70 (0.03)^{b}	6.67 (0.02)^{b}		
TAN[1] (mg/1)	0.15 (0.03)^{b}	0.33 (0.02)^{a}	0.38 (0.04)^{a}		
Net[2] TAN (mg/1)		0.18 (0.02)	0.23 (0.02)		
Total P (mg/l)	0.17 (0.01)^{c}	0.50 (0.03)^{b}	0.74 (0.08)^{a}		
Net[2] Total P (mg/l)		0.33 (0.03)^{a}	0.57 (0.08)^{a}		
Dissolved Oxygen (mg/l)	6.82 (0.14)	6.41 (0.13)	6.35 (0.14)		
Temperature (^{o}C)	23.8 (0.3)				

Net = discharge concentration less inlet concentration.

* Treatments with the same letter (superscript) are not significantly different from each other

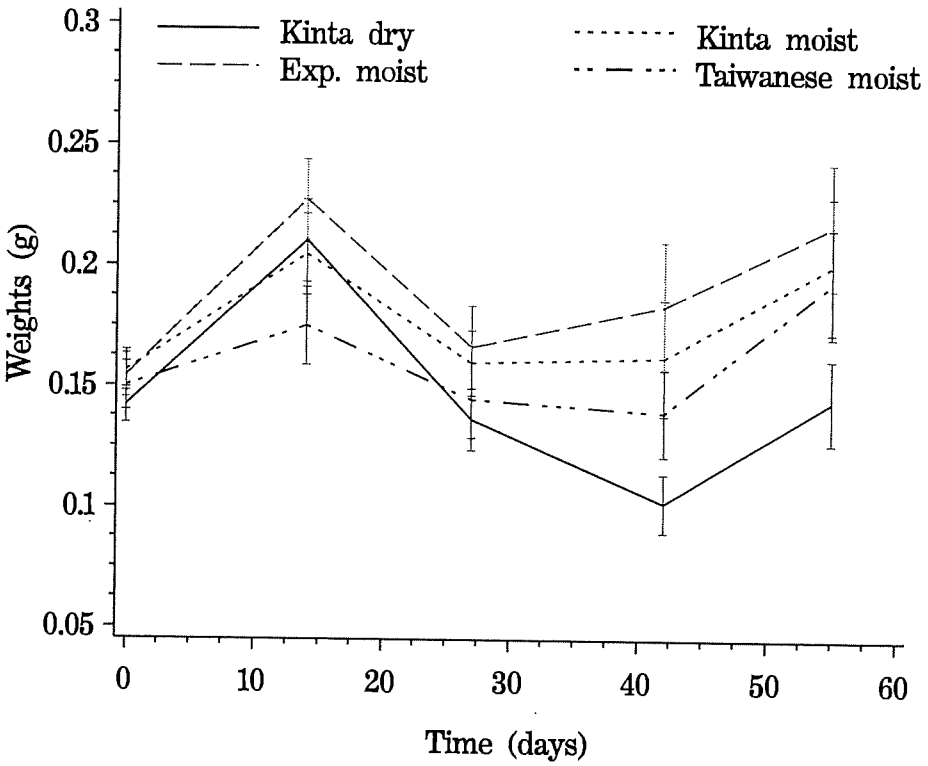

Fig. 3.4 Effects of diet type and form on the growth (mean weight ± s.e.) of glass eels during weaning

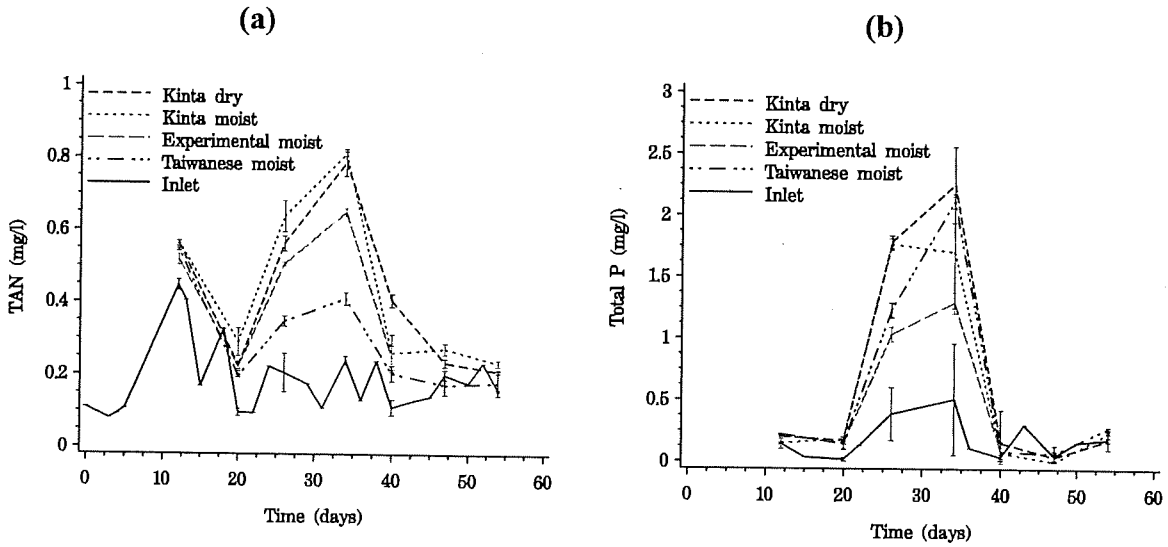

Fig. 3.5 Water quality recorded from inlet water and effluent water from eel culture tanks receiving four different types and forms of artificial diet. (a) TAN (mean ± s.e.). (b) Total phosphorus (as phosphate) (mean ± s.e.).

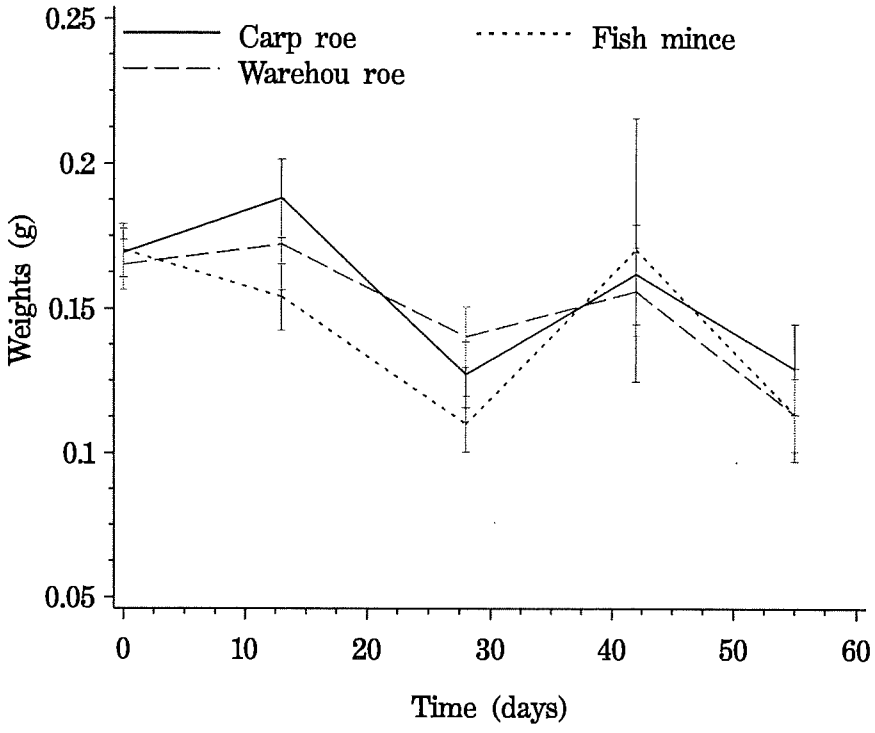

Fig. 3.6 Fish roe experiment 1: Growth (mean weight ± s.e.) of glass eels initially fed on three different diets prior to weaning

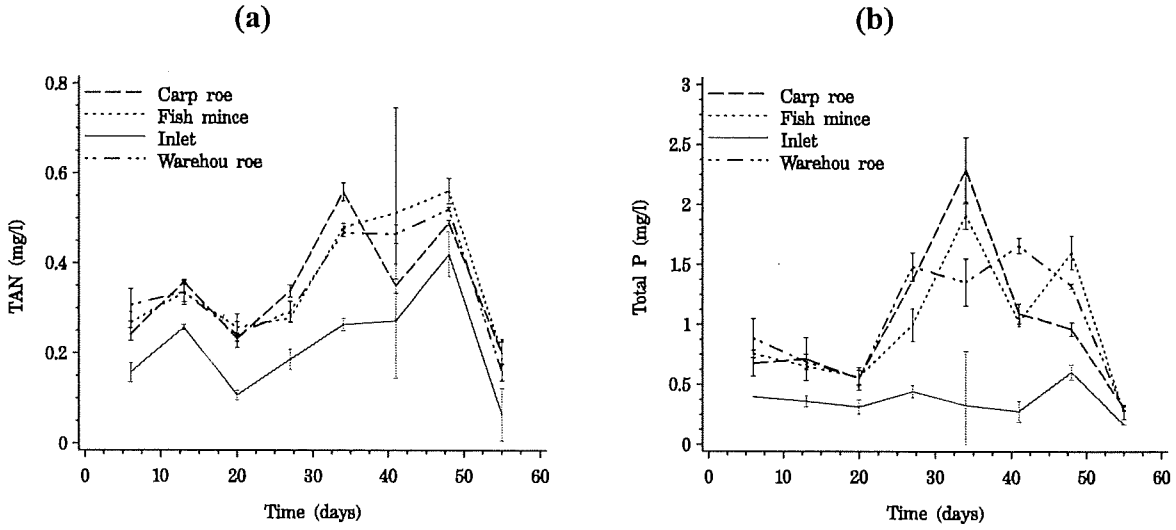

Fig. 3.7 Water quality recorded from inlet water and effluent water from eel culture tanks receiving three different roe diets. (a) TAN (mean ± s.e.). (b) Total phosphorus (as phosphate) (mean ± s.e.).

Between day 28 and day 42 of the experiment, the weight of eels that remained in the experiment increased, but no significant difference was detected between the two treatments after 42 days. No significant difference was observed in survival of eels during the first 42 days of the experiment (Table 3.4).

During the experiment, TAN concentration in both the inlet water and effluent water from all treatments declined (Fig. 3.9a). A significant difference ($P<0.05$) was detected between TAN concentrations in the inlet water and effluent water from the orange roughy treatment only, but no significant differences were detected between effluent waters from each of the treatments (Table 3.5). Throughout the experiment, total P concentrations were significantly higher ($P<0.05$) in the effluent water from each treatment than recorded in the inlet water, but no significant differences were observed in total P concentrations in effluent water from each of the treatments (Table 3.5, Fig. 3.9b).

3.3.1.5 Stocking density

No significant differences in SGRs were observed in juvenile eels reared at three different stocking densities (10, 20 and 40 kg/m^3) over 57 days (Table 3.4,). SGRs ranged from 0.4%/day (densities 10 and $40kg/m^3$) to 0.6%/day (density $20kg/m^3$). Though not significant, in the latter half of the experiment, growth of eels reared at the lower two densities declined whereas growth of eels reared at the highest density did not (Fig. 3.10). At termination of the experiment survival rates were better than 99% at all densities, and were not significantly different between treatments (Table 3.4).

Significant differences ($P<0.05$) between inlet and discharge waters, and between discharge waters for each stocking density were observed in all water quality variables measured during both experiments (Table 3.5). The pH levels in discharge waters for higher stocking densities were significantly lower than those for lower densities and the inlet water. TAN concentrations in inlet water were significantly lower than concentrations in the discharge waters from all treatments, while concentrations in the discharge water from the higher density treatments were significantly greater than for other treatments. Total P concentrations in the discharge water from the higher density treatments were significantly greater than for other treatments and the inlet waters.

Significant differences ($P<0.05$) were detected in all water quality parameters measured during the experiment (Table 3.5). The pH readings were highest in the inlet water and decreased significantly in effluent waters with increasing stocking density (Table 3.5). Similarly, dissolved oxygen concentrations in effluent waters decreased with increasing stocking densities. In contrast, both TAN and total P concentrations, including net concentrations, increased significantly in the effluent waters with increasing eel stocking density (Table 3.5, Fig. 3.11). However, no significant difference was detected between TAN and total P concentrations in the inlet water and concentrations in effluent waters from tanks stocked at the low density (Table 3.5).

3.3.1.6 Diet type

After 43 days, no significant differences ($P>0.05$) were observed in growth of eels fed either the Kinta eel diet or the imported Provimi eel diet (Table 3.4, Fig. 3.12). Likewise survival rates, which were greater than 99% in both treatments after 43 days, were not significantly different for diet type (Table 3.4). The eels readily accepted both diets and no apparent differences were observed in the feeding responses to the two diets.

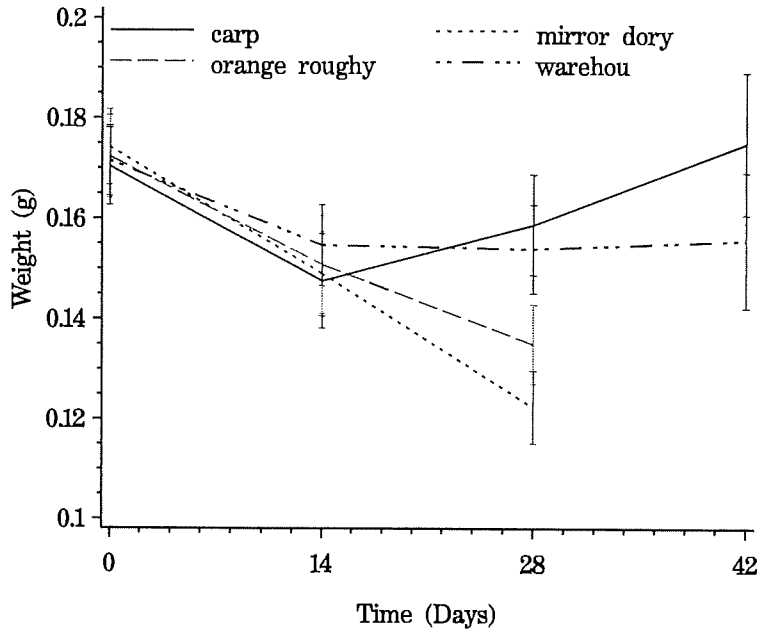

Fig. 3.8 Fish roe experiment 2: Growth (mean weight ± s.e.) of glass eels initially fed on four different types of fish roe prior to weaning

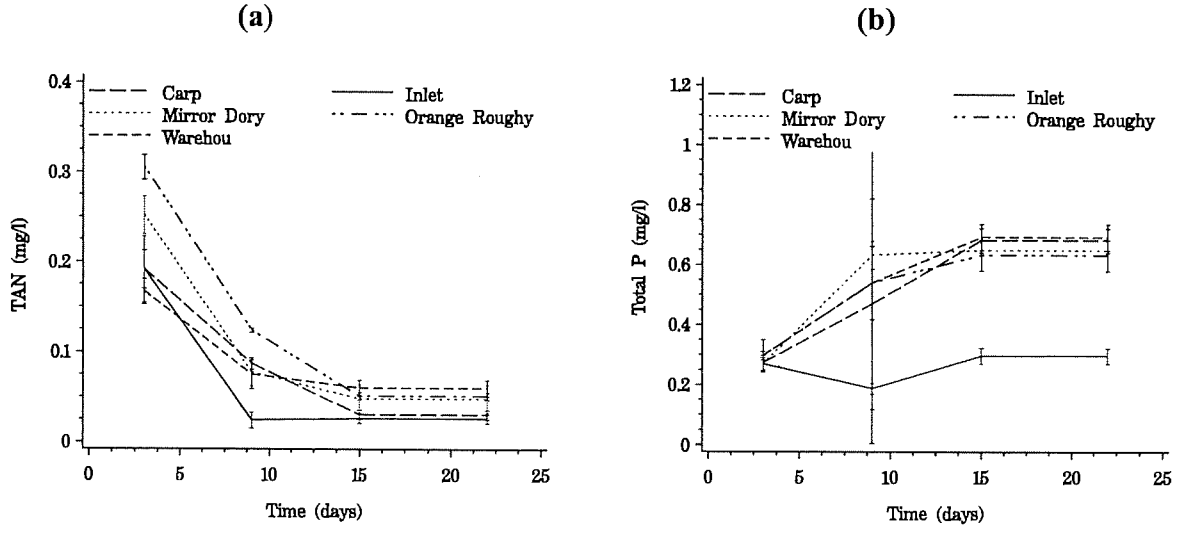

Fig. 3.9 Water quality recorded from inlet water and effluent water from eel culture tanks which receiving four different diet treatments. (a) TAN (mean ± s.e.). (b) Total phosphorus (as phosphate) (mean ± s.e.).

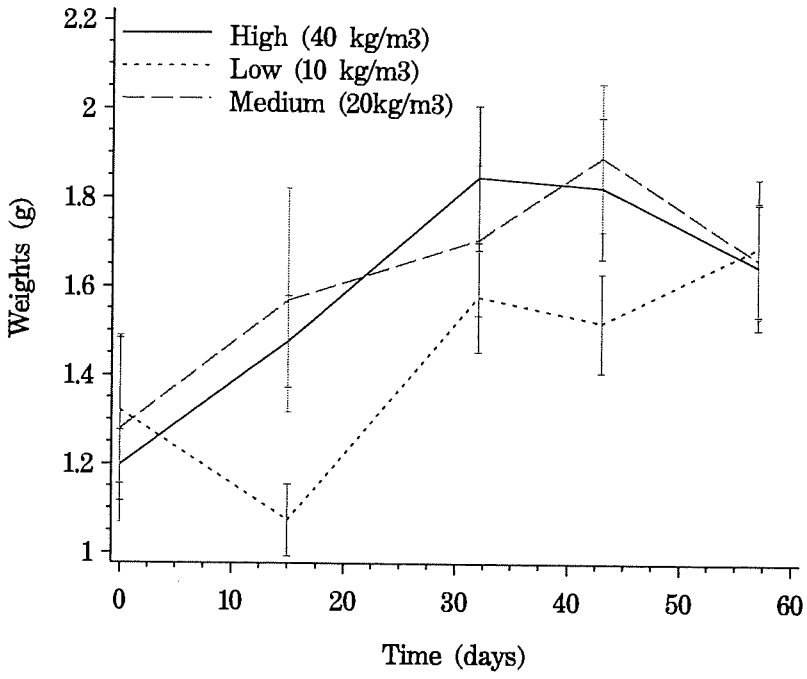

Fig. 3.10 Effects of initial stocking density on the growth (mean weight ± s.e.) of pigmented eels

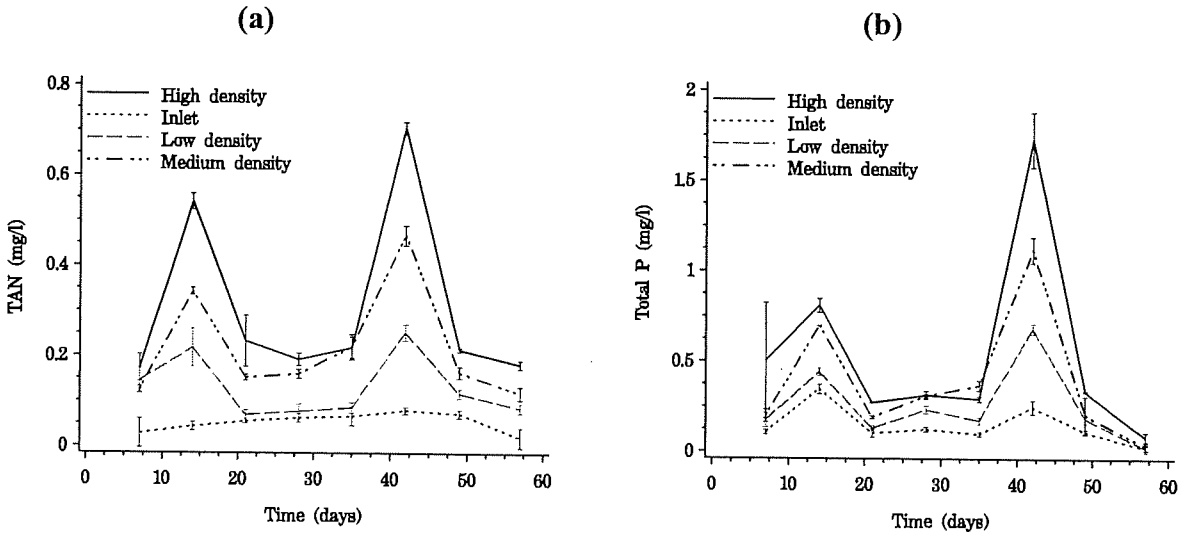

Fig. 3.11 Water quality recorded from inlet water and effluent water from eel culture tanks which were stocked at three different densities of eels. (a) TAN (mean ± s.e.). (b) Total phosphorus (as phosphate) (mean ± s.e.).

Concentrations of TAN and total P were significantly ($P<0.05$) higher in the effluent waters from tanks receiving both diets, than in the inlet water (Table 3.5, Fig. 3.13). Significantly higher concentrations of total P ($P<0.05$) were recorded in the effluent water from tanks receiving the Provimi diet whereas concentrations of TAN in the effluent waters were not significant different between diets (Table 3.5, Fig. 3.13).

3.3.2 Commercial intensive grow-out trial

Over a period of 2 months during 1998, approximately 37 kg of Snowy River glass eels (approx. 150,000 pieces) was stocked into the recirculation system. The growth and survival of this cohort of eels (a single season's intake) was monitored over a period of eight months. Growth rates, which ranged from 0.5 to 14.0 %/day, were highly variable, particularly in the first three months in captivity, and declined as weight of eels increased (Fig. 3.14). For the most part, growth rates during the nursery stage (initial feeding of glass eels – initial elver growout) were 0.5-3.5%/week, while for the later growout stage (ie eels > 25 g weight) were 0.5-1.5%/day. The weight of eels generally increased exponentially over time (Fig. 3.15). The fastest growing eels reached the minimum market size of 180 g in about 5 months after capture (Fig. 3.16). Extrapolation of the mean weight of eels indicated that market size is reached in 7-8 months after capture (Fig. 3.16). In the main however, about 10% of eels would reach minimum market size in about six months while the bulk of the stock from a single season's intake would take between 9 and 18 months of capture.

Mortalities were highest in the first two months following stocking, but declined dramatically in subsequent months (Fig. 3.17). Overall survival for the cohort had declined to about 80% after two months, and by March was about 75%. Very little mortality occurred after December. Based on these survival rates, it was estimated that about 500-600kg of marketable eels (min. weight 180g) would be obtained from every kg of glass eels. No major mortality events attributed to diseases occurred during the trial.

Stocking densities in tanks ranged from 2-115 kg/m^3 during this period. Because larger eels tended to dominate the feeding stations preventing smaller eels from gaining access to food, tanks were graded every 3-5 weeks to reduce size variation. Cannibalism was not observed during the trial, however, some smaller eels exhibited bite marks on the sides of their bodies. Presumably, regular grading reduced the risk of cannibalism and increased the efficiency of feed delivery to the eels.

Glass eels were initially fed on a 0.4 mm salmon crumble at a rate of 5%/day. As the eels increased in size the feed rate was gradually decreased (Fig. 3.18) and pellet size was increased. During the grow-out stage, an extruded salmon diet (45:22) was fed to eels at a rate of 0.5-1.5 %/day. FCRs were highly variable and ranged from 0.9 to 8.3, however average monthly FCRs were between 0.8 and 2.0 (Fig. 3.19).

3.3.3 Extensive pond culture trial: effect of stocking density

During the trial, eels stocked at the higher density appeared to be growing at a greater rate than those stocked at the lower density (Fig. 3.20). However, at harvest (14.5 weeks after stocking), eels stocked at the lower density had a greater mean final weight (2.51 g) than those stocked at the higher density (1.77 g) (Table 3.6). Survival at harvest was higher for eels stocked at the lower density (5 pieces/m^2: 49.1%) than at the higher density (10 pieces/m^2: 37.9%) (Table 3.6). Water temperature during most of the trial varied from 17^{o}C to 24^{o}C, except for a period around the middle of January where the temperature reached 27^{o}C.

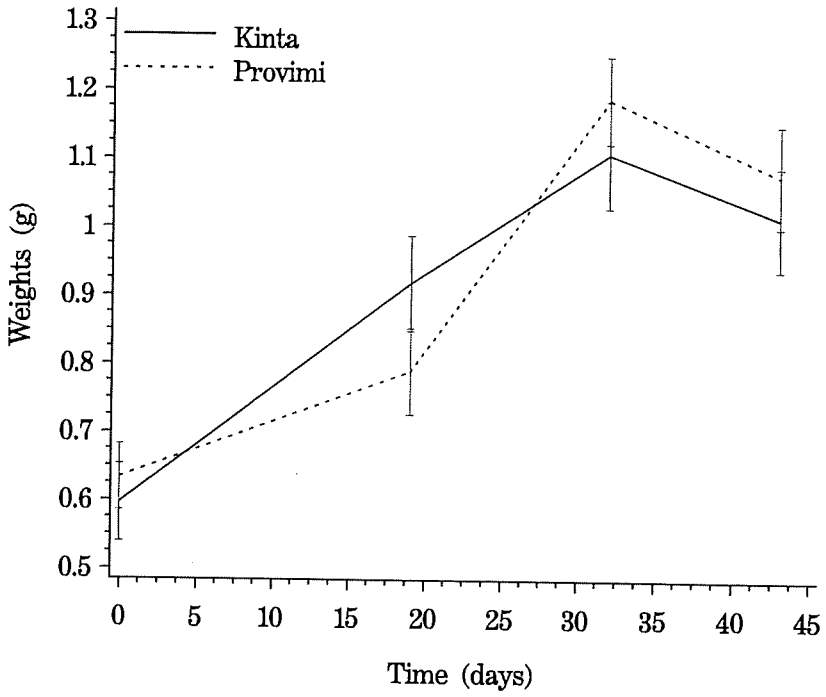

Fig. 3.12 Effects of diet type (two different commercial eel diets) on the growth (mean weight ± s.e.) of pigmented eels

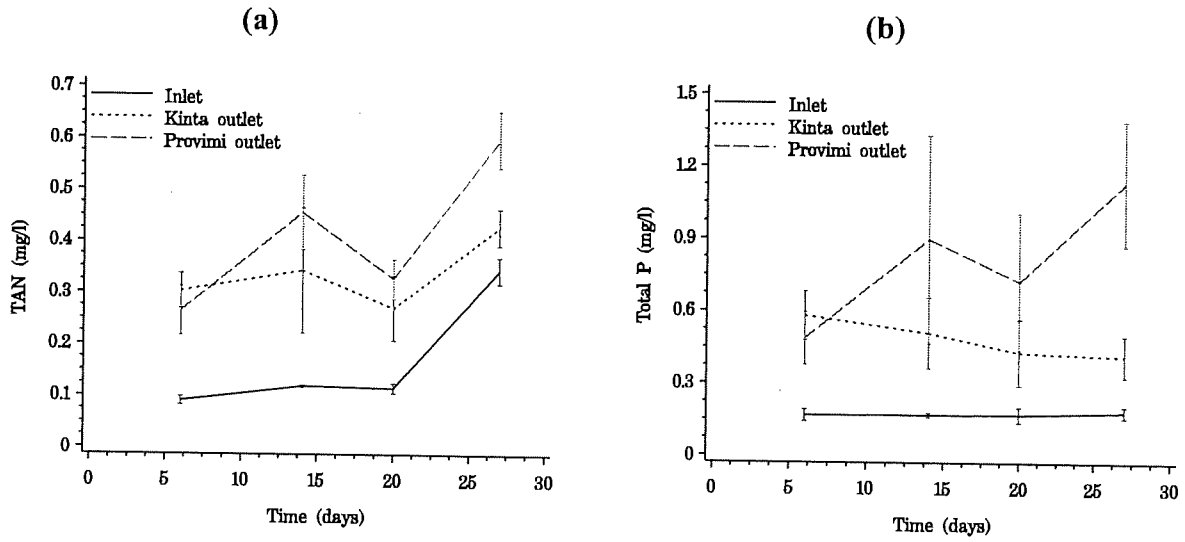

Fig. 3.13 Water quality recorded from inlet water and effluent water from eel culture tanks received two different diet types. (a) TAN (mean ± s.e.). (b) Total phosphorus (as phosphate) (mean ± s.e.).

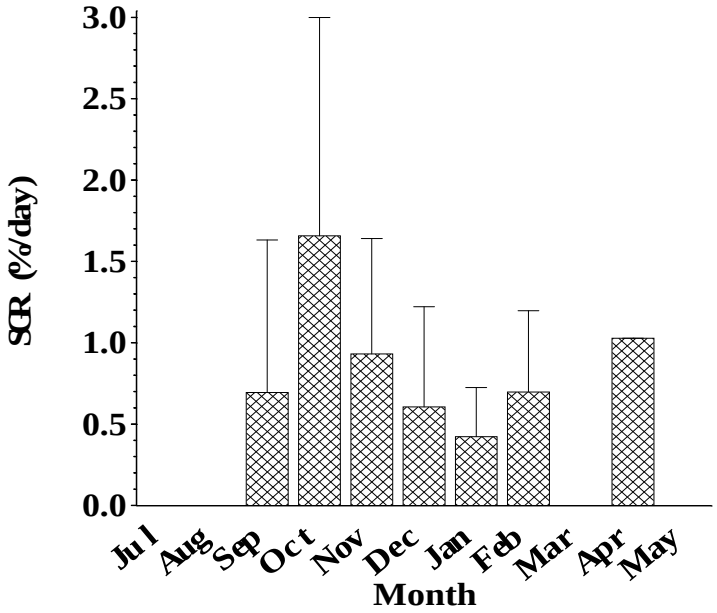

Fig. 3.14 SGR's (mean ± 95% confidence limits) of eels reared in an intensive recirculation system under commercial production conditions.

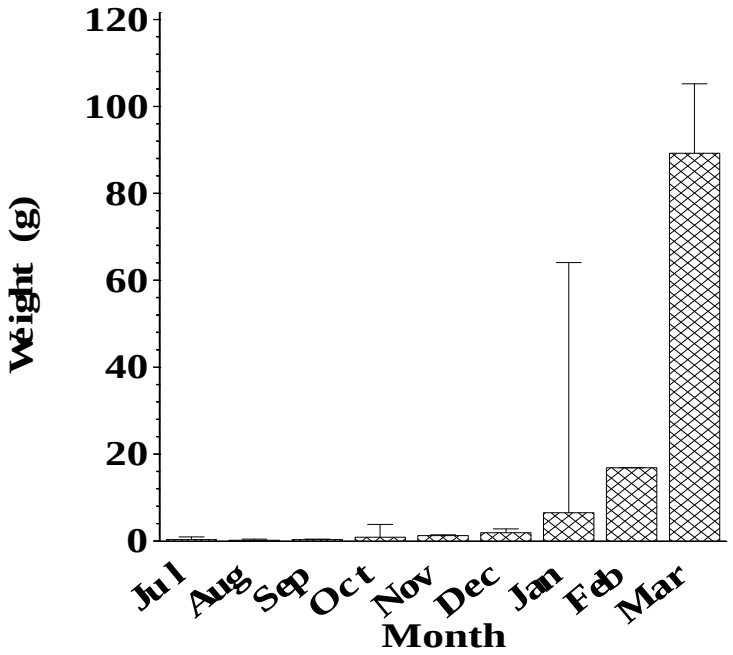

Fig. 3.15 Mean monthly weight (± 95% confidence limits) of eels reared in an intensive recirculation system under commercial production conditions

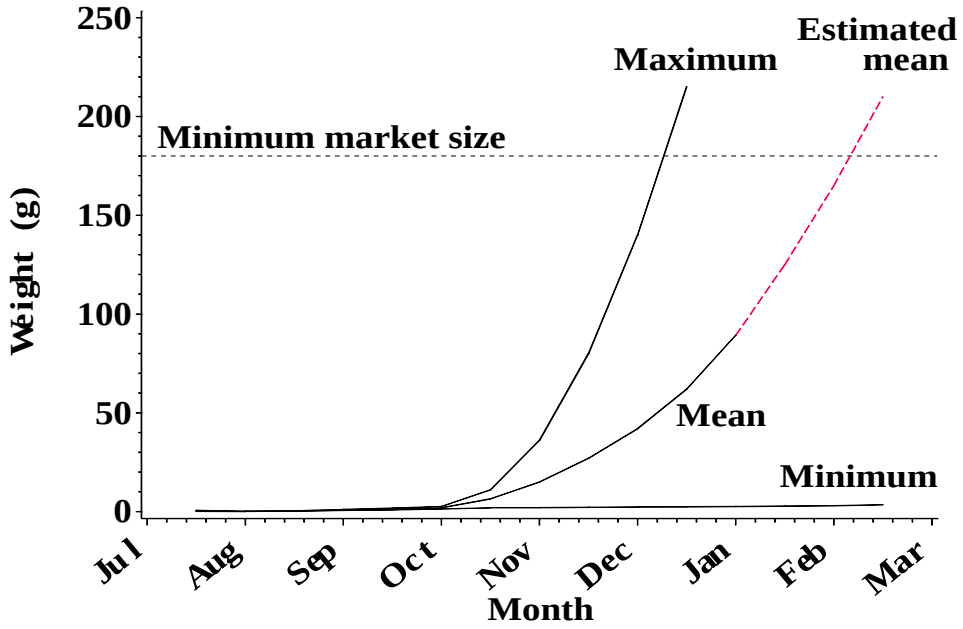

Fig. 3.16 Mean, minimum and maximum weight of eels reared in an intensive recirculation system under commercial production conditions, and estimated projection of mean weight required to exceed minimum market size

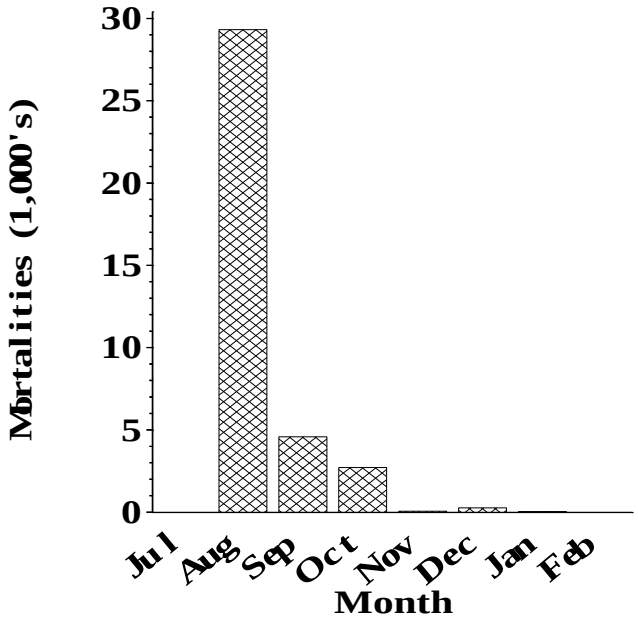

Fig. 3.17 Mortalities of eels during a grow-out trial in an intensive recirculation system under commercial conditions

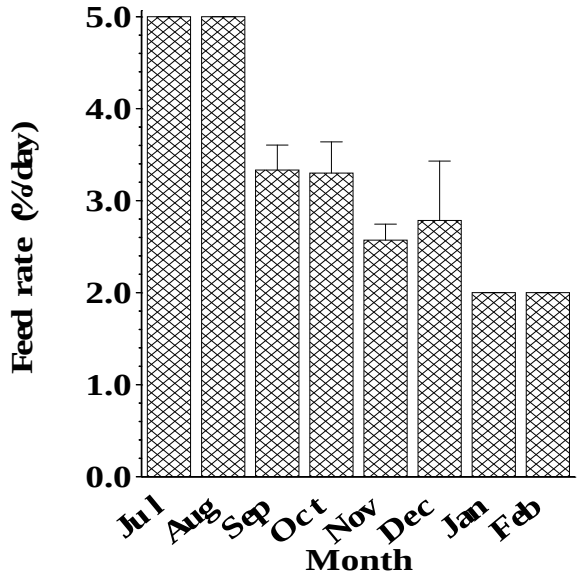

Fig. 3.18 Feed rates (% of dry weight of feed to wet weight of eels per day) (mean ± 95% confidence limits) of juvenile eels during a grow-out trial in an intensive recirculation system under commercial conditions

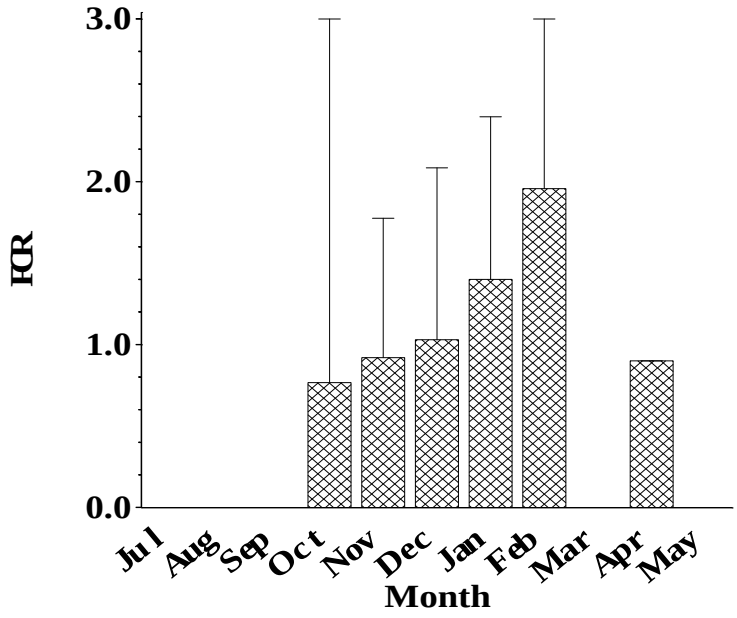

Fig. 3.19 Mean monthly food conversion ratios (FCR's) (± 95% confidence limits) observed for juvenile eels reared in an intensive recirculation system.

Table 3.6 Growth and survival of juvenile eels reared in two ponds at two different stocking densities over 14.5 weeks at Deakin University, Warrnambool

Parameter		**Low density** (5 fish/m^2)	**High density** (10 fish/m^2)
Stocked:	Mean weight (g)*	0.29 ± 0.16	0.29 ± 0.16
	Density (g/m^2)	1.45	2.9
	Biomass (kg/pond)	1.46	2.92
	Number	5,058	10,110
Harvested:	Mean weight (g)*	2.51 ± 0.84	1.77 ± 1.32
	Biomass (kg/pond)	6.22	6.77
	Number	2,482	3,832
	SGR (%/day)	2.19	1.75
	Survival rate (%)	49.1	37.9

* Mean ± standard error.

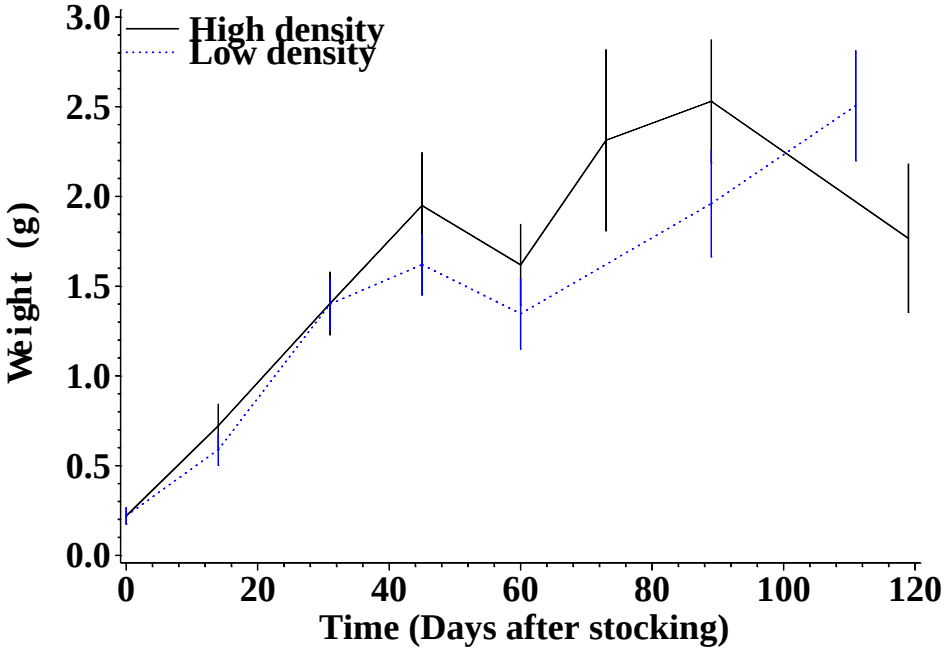

Fig. 3.20 Growth (mean weight ± s.e.) of juvenile eels reared in two earthen ponds at two stocking densities (Low: 5 fish/m^2. High: fish/m^2) at Deakin University, Warrnambool

3.4 DISCUSSION

The weaning of glass eel onto artificial diets is recognised as an important and critical stage in the farming of anguillids (Kamstra and Heinsbroek 1991, Gousset 1992), including *A. australis* (Gooley *et al.* 1999, Ingram *et al.* 2001). The present study showed that the period of time glass eels are held in captivity (ie 10 or 36 days) and fed on a fresh diet of fish flesh, did not effect the survival rate during weaning to an artificial diet. However, the results indicated that rate of growth for glass eels fed on fish flesh for a longer period of time (ie 36 days before weaning) was greater than for those eels weaned earlier after a shorter period in captivity. A longer period in captivity and being fed on minced fish may have resulted in these eels being in better condition, and therefore more prepared for the stress associated with the weaning process. More specifically, it may be that the larger size of fish held under initial (pre-weaning) conditions, at the point of commencement of weaning, may be conducive to weaning success. No previous studies have examined the effects of duration in captivity prior to weaning. However, factors which may influence the success of weaning glass eels may include age and size at time of capture, feeding status in the wild prior to capture, stress associated with capture and transport and associated health status, and suitability of acclimation conditions. Newly caught glass eels *of A. anguilla* are usually fed a diet of cod roe for 2-4 weeks before commencement of weaning (Heinsbroek 1991). Current practices applied to the weaning of glass eels of *A. australis* at MAFRI, Snobs Creek do not involve a set period of time in captivity prior to weaning. Rather, once newly caught glass eels exhibit vigorous feeding on an initial diet of minced fish flesh or fish roe, based on a subjective, visual assessment, the weaning process is commenced. Typically, this varies from one batch of newly caught glass eels to another, and one operator to another, and may take from one to three weeks in practice.

Previous research has shown that glass eels of *A. australis* weaned over a 5-day period did not grow as fast, and fewer survived, than glass eels weaned over a 15-day period (Gooley *et al.* 1999, Ingram *et al.* 2001). In the present study, however, weaning over longer periods of time (21 days and 31 days) did not influence growth and survival. Melotti and Perrucci (1989) found that gradual weaning (10% change every 5 days) of the elvers of *A. anguilla* resulted in better survival rates and final weights than accelerated weaning (30% change every 10 days). In Japan, a range of weaning methods are employed, but generally the glass eels of *A. japonica* are weaned onto artificial diets over about 20-25 days (Heinsbroek 1991). The results from the present study, combined with previous research (Gooley *et al.* 1999, Ingram *et al.* 2001), suggest that, once initial feeding has commenced, a weaning period of not less than two weeks be applied to the glass eels of *A. australis*. Shorter weaning periods may significantly reduce subsequent growth and survival of juvenile eels under intensive culture conditions.

Newly captured glass eels by and large need to be presented a 'natural' diet in order to break an apparent natural fasting period, prior to weaning onto manufactured, compound diets (Heinsbroek 1989; Heinsbroek and Kreuger 1992). Following capture, and prior to weaning, the newly caught glass eels of *A. anguilla* are most commonly fed the roe of Atlantic cod *Gadus morhua* L. (Heinsbroek 1991). Jones (Chapter 5, this publication) indicated that fish roe (mackeral) was a suitable diet for the initial feeding of newly caught glass eels of *A. reinhardtii*. The present study indicated that the roe of carp or warehou were suitable as an initial diet for breaking the fast of glass eels after initial capture. This study also showed that not all fish roes are suitable for feeding glass eels in captivity, such as indicated by the poor results for roe of mirror dory and orange roughy. Physical characteristics (texture etc) and nutritional composition may account for variations in acceptance and palatability by glass eels

and subsequent growth and survival. De Silva *et al.* (2001) found that carp and warehou roes had significantly different amounts of *n*-6 polyunsaturated fatty acids and ratios of n-3 to n-6 to roe of mirror dory and orange roughy. Further, the fatty acid profiles of metamorphosing glass eels of *A. australis* were similar to that of carp and warehou (De Silva *et al.* 2001) (see Chapter 4). Selection of a suitable fish roe for the initial feeding of glass eels may also be dictated by the practical availability of the roe (eg. geographic distribution and seasonality of abundance of the target species).

During the present study, glass eels undergoing weaning tended to loose weight during the initial weeks of feeding before weight gain recommenced. This trend is not uncommon in glass eels as it has been observed in other species of *Anguilla* (Heinsbroek 1989, Appelbaum *et al.* 1998) and in previous studies on *A. australis* (Gooley *et al.* 1999, De Silva *et al.* 2001). This trend has been attributed to eels needing time to complete metamorphosis and to adapt to changing environmental conditions associated with acclimation to aquaculture conditions (Appelbaum *et al.* 1998).

Despite the absence of significant trends in the growth and survival of glass eels weaned onto different diets (type and form) in the present study, the results indicated that glass eels weaned onto a moist diet appeared to grow slightly faster than those weaned onto a dry diet. Moist diets have been used for the rearing of the glass eels of *A. japonica* (Heinsbroek 1991, Gousset 1992). However, dry diets are widely used in the farming of *A. anguilla*, from the completion of weaning (Heinsbroek 1991). In fact dry diets are preferred in intensive recirculation systems as they are easer to use than moist diets, leakage of nutrients into solution is less (Uematsu 1986 in Gousset 1992), and uneaten food is more easily removed (Gousset 1992). Dry salmonid diets are currently used in the commercial farming of *A. australis*, and have shown to be suitable for the rearing of *A. reinhardtii* (see Chapter 5, this publication). Knowledge of the nutritional requirements of *A. australis* is limited (see Chapter 4) and, despite the preliminary development of a 'reference' diet for *A. australis*, further work is required to refine this diet in the form of a dry formulation for rearing eels in recirculation systems.

In a previous study, the growth and survival rates of pigmented eels of *A. australis* were not significantly different when reared at densities between 2.5 and 10.0kg/m^3 (Gooley *et al.* 1999, Ingram *et al.* 2001). However, these densities are thought to be well below commercially realistic levels, and were limited at the time by seedstock availability. The present study showed that higher, more commercially realistic stocking densities of between 10 and 40 kg/m^3 also did not significantly effect the growth and survival of pigmented eels. In Europe, the glass eels of *A. anguilla* are initially stocked into tanks at densities of 5-15kg/m^2, but juveniles are on-grown at higher densities (30-60 kg/m^2) (Heinsbroek 1991). In Japan, the glass eels of *A. japonica* are stocked into nursery ponds at densities of 0.15-0.5kg/m^2, and later on-grown in greenhouses at densities of 6-30kg/m^2 (Heinsbroek 1991). The use of recirculation systems for commercial production has seen substantial increases in stocking densities of more than 100 kg/m^2 in the later grow-out phase (Brusle 1990). These results, coupled with results from previous work (Gooley *et al.* 1999, Ingram *et al.* 2001) and observations on juvenile *A. anguilla* and *A. japonica* suggest that juvenile *A. australis* may be reared in tanks at a range of densities during the nursery phase, but stocking densities that optimise growth and survival at this and later developmental/production stages have yet to be ascertained experimentally.

No significant differences were observed in the performance of two commercial eel growing diets (one Australian and one European) for rearing pigmented eels of *A. australis*. However, the duration of this experiment (43 days) may not have been sufficient to fully test the

effectiveness of these two diets in the grow-out of *A. australis*. In Australia, commercial diets specifically formulated for Australian eels are non-existent. Kinta Pty Ltd, the sole supplier of commercial eel diets in Australia and which provided some eels feeds used during the present study, has since ceased production of aquaculture feeds. To a large extent this is due to the relatively small size and developmental nature of the existing intensive eel farming industry in Australia. Consequently lack of a local volume market for a species specific, formulated eel diet has prevented major feed manufacturers from investing in the development of such a product for Australian eels thus far.

With increasing growth of aquaculture industries, there is an increasing awareness of the potential for the industry to impact detrimentally on the environment, in particular through discharge of water laden with nutrients (N and P) (Pillay 1992). Likewise, it is essential that the nutrient profile of aquaculture effluent streams be understood and where possible quantified in relation to routine farm inputs (eg. food type and quality), in order for farming system design and routine maintenance and operational procedures to be optimised. The present study showed that stocking density and diet type and form affected the concentrations of N (as TAN) and P (as phosphate) in waters discharged from experiment tanks. Mean net concentrations of TAN and total P ranged from 0.08 to 0.28 mg/l and 0.11 to 0.73 mg/L respectively (Table 3.5). Differences in the composition and water stability of respective diets may have contributed to variation in effluent water quality, while increased feed rates associated with higher stocking densities accounted for higher nutrient concentration.

Recirculating aquaculture systems (RAS), such as those being used for farming of eels in Europe, and now also Australia, are considered more environmentally sound than open, flow-through aquaculture systems in terms of waste production (Mayer and McLean 1995). These systems allow for concentration and therefore substantial reductions in the volume of wastewater discharged, removal of substantial quantities of suspended solids and associated nutrients by microscreen filtration processes, and conversion of some nutrients via biofiltration (Rosenthal and Black 1993, Piedrahita 1994, Mayer and McLean 1995). Culture of eels at high densities in RAS requires close monitoring of water quality, especially dissolved oxygen, pH, TAN (and unionised ammonia) and nitrite to ensure that critical levels are not reached or exceeded. Stocking eels in RAS at high densities can expose them to constant, elevated concentrations of ammonia and/or nitrite, which can suppress growth (Degani *et al.* 1988, Knights 1989). These studies suggest that, under appropriate conditions, such as high dissolved oxygen and low ammonia concentrations, *A. australis* may be cultured at densities far in excess of those densities used during the present study. In commercial operations problems associated with dissolved oxygen and pH are controlled by use of pure oxygen (liquid oxygen or oxygen generators) to maintain oxygen saturation in the water at or over 100%, and continual dosing of water with buffering agents to maintain a desired pH level. Further, control of pH to achieve suppressed levels (< 7) also limits the proportion of TAN which is in the toxic unionised form.

During the present study the grow-out of *A. australis* was monitored in a commercial recirculating aquaculture farm. Although monitoring was conducted over an eight-month period only, information collected provided an insight into the potential for commercial production of the species. Indeed, these results compared favourably with other species of farmed anguiliids (Table 3.7).

Table 3.7 Comparison of culture conditions and production performance indicators for four species of farmed eel (*Anguilla* spp.)

Parameter		***A. australis*[1]**	***A. reinhardtii*[2]**	***A. japonica*[3]**	***A. anguilla*[4]**
Temperature (^{o}C)		23-25	24-28	20-30	25
Initial size (g)		0.15-0.18	0.13-0.17	0.2	0.25
Pieces per kg		6,000-8,000	5,900-7,700	5,000-6,000	2,500-4,000
Starter diet		fish, fish roe	fish roe, blackworms	*Tubifex*, squid, krill, fish	cod roe
Grow-out diet		artificial dry	artificial dry	Artificial wet & dry	artificial dry
Culture method:	- nursery	tanks	tanks	ponds	tanks
	- growout	tanks	ponds	ponds	tanks
Feed rates (%/day):	- nursery	3-5	3-8	3-8	2-7
	- growout	1-2	2	1-3	1-2.5
Growth rates (%/day):	- nursery	0.5-3.5	1.5-2.3	2-4	0.5-3.5
	- growout	0.5-1.5	0.4-1	0.8-2	0.4-2
FCR		0.9-8	0.9-5	1.4-1.9	1.2-4
Densities (kg/m^3)*:	- nursery	5-10	6-8	0.15-0.5	up to 22
	- growout	40-150	unknown	0.5-30[5]	up to 330
Size at 2-3 months (g)		1.4-2.6	1-3	2-3	
Survival after 2-3 months (%)		75	75 to >90	80-90	80-90
% to market size (180-200 g) after 6 months		10	10-20	10-20	
Months to market size (180-200 g)		9-18	6-18	12-18	8-15
Kg marketable eels per kg glass eels		500-600	500-1,000	600-900	200-400

1. Present study and R. Camm (AAP Pty Ltd) (*pers comm*).
2. Jones (Chapter 5, this publication) and C. Jones (*pers comm*).
3. Heinsbroek (1991), Usui (1991), Gousset (1992) and Jiaxin (1999).
4. Heinsbroek (1991), Anon (1998) and G. Gooley (unpublished data).
5. 0.5-2 kg/m^3 for outdoor ponds and 6-30 kg/m^3 for greenhouse ponds

* Some literature presented densities as kg/m^2, these figures are presented here as kg/m^3.

The high mortalities in the first few months for all cultured anguillid species reflects the difficulty associated with the initial acclimation and weaning of glass eels in aquaculture tanks (Table 3.7). Accordingly, a draft Best Practice weaning guidelines have been developed for *A. australis* as part of the present study, based largely on a combination of experimental results and observations from the commercial trial at AAP. These guidelines are intended to be used as an extension tool by industry to improve survival during this critical period and to increase overall culture system productivity (see Appendix I). Stocking densities at AAP during the present study did not exceed 115 kg/m^3. However, the use of such purpose built

recirculation aquaculture systems, has the potential for *A. australis* to be cultured at substantially higher densities consistent with routine practice for farming of *A. anguilla* in Europe (Table 3.7). For example, *A. anguilla* have been intensively reared at densities in excess of 300 kg/m^2 (Anon 1998). Indeed, since this study, *A. australis* has been routinely cultured at densities up to 150 kg/m^3 (R. Camm, *pers. comm*). The highly variable FCR's observed at AAP during the present study reflected a lack of baseline information on the feeding dynamics and preferred dietary requirements of juvenile of *A. australis* during the early stages of this enterprise. More recently however, more consistently lower FCR's, ranging up to 2.5, have been reported by AAP with the adoption of more efficient feeding regimes (R. Camm, *pers. comm*).

Previous studies indicated that survival and growth of juvenile *A. australis* in fertilised earthen ponds is not significantly affected by supplementary feeding with an artificial eel feed (Gooley *et al.* 1999). These results were not unexpected considering the relatively low initial stocking densities of the eels (ie. initial mean stocking density: 1.0-2.0 g/m2). In a New Zealand study, glass eels of *A. australis* were stocked into fertilised earthen ponds at about 1,000 g/m^2 (Jones *et al.* 1983). However, low yields from these ponds were attributed to low rates of weaning of *A. australis* (approximately 30% successfully weaned onto a compound diet), poor culture techniques, sub-optimal diet and winter mortalities (Jones *et al.* 1983). At higher densities, use of artificial diets as a supplementary feed for eels in ponds, such as practiced in the pond culture of *A. japonica* (Heinsbroek 1991, Gousset 1992), may improve growth rates. At even higher densities artificial feeds may be the only source of food for eels once naturally occurring live foods are depleted. In Japan, glass eels of *A. japonica* are stocked into ponds at densities of 100-500 g/m^2 and their diet is made up solely by feed supplied by the farmer (Heinsbroek 1991, Usui 1991, Gousset 1992). In the present study, eels stocked at the higher density were smaller at harvest than those stocked at the lower density. Overgrazing of naturally occurring food (principally aquatic invertebrates) by eels in the more heavily stocked pond may have caused the decline in growth, observed in the latter weeks of the trial. Belpaire *et al.* (1990) showed that higher initial pond stocking densities (ie. 20 g/m^2) reduced the growth and survival of juvenile *A. anguilla*.

Production of *A. australis* in earthen ponds in southern clines, such as Victoria, will be limited largely by the short growing season associated with a cooler climate. In northern areas, pond production including the use of greenhouses is expected to be viable. A similar pattern of eel production is observed in Europe and China, where open pond production is restricted to warmer southern regions such as Italy and the Guangdong Province, respectively (Anon 1996, Gooley 1999, Jiaxin 1999). In cooler regions (Denmark, Holland, Japan and northern Chinese provinces), use of greenhouses over ponds and intensive recirculation systems are more prevalent.

The present study has considerably broadened the knowledge on the culture of *A. australis*, particularly during the early stages of culture under intensive conditions. Production performance under intensive commercial conditions in particular is very similar to other species of farmed anguiliids (Table 3.7), which indicates the viability of the species for aquaculture. Indeed, commercial farming of *A. australis*, albeit at a small scale, is occurring in tanks under intensive, controlled environment conditions in Victoria and to a lesser extent in ponds under semi-intensive/extensive ambient conditions in NSW and southern Qld. However, issues related to availability of, and access to, glass eel seedstock, production costs and fluctuating prices of marketable eels, will need to be addressed for the industry to be profitable and expand beyond this point (see Chapters 6 and 7).

3.5 ACKNOWLEDGMENTS

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3.6 REFERENCES

Anon. (1996). Inter Eascam eel farm is the first in Ireland. *Fish Farming International* 23(2): 3.

Anon. (1998). Eel farming in the Netherlands. *Aquaculture Magazine* 24(4): 52-61.

Appelbaum, S. (1980). Zur Aufnahme von granuliertem Futter bei Aalen (*Anguilla anguilla* L.) und dessen Einwirkung auf das Auseinanderwachsen der Fische. *Archiv fur. Ischereiwissinschalt* 31: 15-20.

Appelbaum, S., Chernitsky, A. and Birkan, V. (1998). Growth observations on European (*Anguilla anguilla* L.) and American (*Anguilla rostrata* Le Sueur) glass eels. *Bulletin Francais de La Peche et de La Pisciculture* 349: 187-193.

Belpaire, C., Vlasselaer, L.-v., Podoor, N. and Ollevier, F. (1990). Short note on pond culture experiments with glass eel of the European eel (*Anguilla anguilla* L.). *International Revue der Gesamten Hydrobiologie* 75(6): 893-894.

Brusle, J. (1990). Eels and eel farming. In: *Aquaculture Volume 2* (ed. by G. Barnabé), pp 756-785. Ellis Horwood Ltd, West Sussex.

De Silva, S.S., Gunasekera, R.M., Ingram, B.A. and Dobson, J.L. (2001). Weaning of Australian shortfin glass eels (*Anguilla australis*): a comparison on the effectiveness of four types of fish roe. *Aquaculture* In Press.

Degani, G. and Levanon, D. (1986). The influence of different feeds on growth and body composition of glass eels (*Anguilla anguilla* L.). *Bamidgeh* 38(1): 13-22.

Degani, G., Levanon, D. and Meltzer, A. (1988). Influence of high loading density on growth and survival of European glass eels. *The Progressive Fish-Culturist* 50(3): 178-181.

Gooley, G. (1999). *Eel Breeding Research Mission to the Freshwater Fisheries Research Centre, Wuxi, China 19-29 March, 1999. Final Report.* Marine and Freshwater Resources Institute, Department of Natural Resources and Environment. Alexandra, Victoria. 31 pp.

Gooley, G.J., McKinnon, L.J., Ingram, B.A., Larkin, B., Collins, R.O. and de Silva, S.S. (1999). *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production. Final Report FRDC Project No 94/067.* Marine and Freshwater Resources Institute, Alexandra, Australia. 124 pp.

Gousset, B. (1992). *Eel Culture in Japan*. Bulletin de l'Institut océanographique, Monaco, no spécial 10, Monaco. 128 pp.

Heinsbroek, L.T.N. (1989). Preliminary investigations on husbandry, nutrition and growth of glass eels and elvers, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 20: 119-127.

Heinsbroek, L.T.N. (1991). A review of eel culture in Japan and Europe. *Aquaculture and Fisheries Management* 22: 57-72.

Heinsbroek, L.T.N. and Kreuger, J.G. (1992). Feeding and growth of glass eels, *Anguilla anguilla* L.: The effect of feeding stimulants on feed intake, energy metabolism and growth. *Aquaculture and Fisheries Management* 23(3): 327-336.

Ingram, B. and Gooley, G. (1996). Intensive tank and pond culture of Australian short finned glass eels in Victoria. *Austasia Aquaculture* 10(4): 74-75.

Ingram, B., Gooley, G., Larkin, B., De Silva, S. and Collins, R. (1996). Progress towards development of culture methods for glass eels of the Australian short-finned eel *Anguilla australis*. In: *Developing and sustaining world fisheries resources: the state of science and management* (ed. by D.A. Hancock and J.P. Beumer), pp 96-97, Brisbane.

Ingram, B.A., Gooley, G.J., De Silva, S.S., Larkin, B.J. and Collins, R.A. (2001). Preliminary observations on the tank and pond culture of the glass eels of the Australian shortfin eel, *Anguilla australis* Richardson. *Aquaculture Research* 32: 833-848.

Jiaxin, C. (1999). China's eel culture industry. *Eurofish* 3/99: 64-67.

Jones, J.B., Astill, M. and Kerei, E. (1983). The pond culture of *Anguilla australis* in New Zealand - with special reference to techniques and management of the experimental farm at The Kaha, Bay of Plenty. *Estratto dalla Rivista Italiana di Piscicoltura e Ittiopatologia* 18(3 & 4): 85-117 & 138-166.

Kamstra, A. and Heinsbroek, L.T.N. (1991). Effects of attractants on start of feeding of glass eel, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 22(1): 47-56.

Knights, B. (1989). Effects of ammonia accumulation on metabolic rates and growth of European eel, *Anguilla anguilla* L., in relation to warmwater aquaculture. *Aquaculture and Fisheries Management* 20: 111-117.

Mayer, I. and McLean, E. (1995). Bioengineering and biotechnological strategies for reduced waste aquaculture. *Water. Sci. Technol.* 31(10): 85-102.

McKinnon, L.J. and Gooley, G.J. (1998). Key environmental criteria associated with the invasion of *Anguilla australis* glass eels into estuaries of south-eastern Australia. *Bulletin Français de la Pêche et de la Pisciculture* 349: 117-128.

McKinnon, L.J., Ingram, B.A., Larkin, B. and Gasior, R.J. (2001). *Best Practice Guidelines for Australian Glass Eel Fishing and Aquaculture.* Report No. 48. Marine and Freshwater Resources Institute. Alexandra. 21 pp.

Melotti, P. and Perrucci, G. (1989). Weaning trials on elvers of European eel, *Anguilla anguilla* L. *Rivista Italiana di Acquacoltura* 24(1): 119-124.

O'Sullivan, D. (1999). Euroa farm looks to profit from eels and cod. *Austasia Aquaculture* Aug/Sept: 22-25.

Piedrahita, R.H. (1994). Managing environmental impacts in aquaculture. *Bulletin of the National Research Institute of Aquaculture* (Suppl. 1): 13-20.

Pillay, T.V.R. (1992). *Aquaculture and the Environment*. Fishing News Books, Oxford. 189 pp.

Rosenthal, H. and Black, E.A. (1993). Recirculation systems in aquaculture. In: *Techiques for Modern Aquaculture* (ed. by J.K. Wang), pp 285-294. American Society of Agricultural Engineers, St. Joseph, MI.

Tesch, F.-W. (1977). *The Eel. Biology and Management of Anguillid Eels*. Chapman and Hall, London. 434 pp.

Usui, A. (1991). *Eel Culture*. Fishing News Books, Oxford. 148 pp.

4 PRELIMINARY EVALUATION OF NUTRITIONAL REQUIREMENTS OF INTENSIVELY CULTURED AUSTRALIAN SHORTFIN GLASS EELS AND ELVERS (*ANGUILLA AUSTRALIS*)

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CONTENTS

4.1 INTRODUCTION

Although there is an existing culture-based fishery on the Australian shortfin eel, *Anguilla australis* Richardson, it was not cultured intensively until recently (Gooley 1998; Gooley *et al.* 1999). As such, it is not surprising that there is a paucity of published information on aspects of the nutrition of *A. australis*. Gooley *et al.* 1999 undertook preliminary investigations into the aquaculture of *A. australis*, including evaluating various aspects of feed types and associated feeding regimes, however no information was provided specifically on the nutritional requirements of the species *per se*.

In contrast, there is a considerable quantum of information on the biology and general life history of this species under natural conditions, both in Australian and New Zealand waters. In New Zealand waters particularly, aspects on age and growth, and the feeding ecology of *A. australis* have been widely studied by Jellyman (1979), Ryan (1984), Ryan (1986) Chisnall (1989), Chisnall and Hayes (1991) and Chisnall and Kalish (1993) amongst others. Food and feeding habits of *A. australis* in New Zealand waters are also well documented (Ryan 1984, Ryan 1986, Jellyman 1989). On the other hand, there have been fewer studies of eels in Australian waters. Beumer (1979) studied the feeding and movement of *A. australis* and the Australian longfin eel, *A. reinhardtii* Steindachner, Sloane (1984a) and Sloane (1984b) documented the distribution, growth and feeding habits of *A. australis* specifically in Tasmanian waters, and De Silva *et al.* (1997) documented the changes in fatty acid profiles of *A. australis* in relation to early development.

The nutrition requirements of fish species differ widely, with carnivorous species generally tending to have relatively higher dietary protein requirements compared to omnivorous fish. Fish species also differ in their lipid dietary requirements, as well as the ability to utilise carbohydrates as an energy source (Wilson 1994). As expected, the nutrient requirements of the European eel, *A. anguilla* L. and the Japanese eel, *A. japonica* Temminck & Schlegel, the two anguillid species that are most commonly cultured in the world, are relatively well known (Arai 1991). Accordingly, it has been established that these anguillids require the same ten essential amino acids as other cultured fish species, that their dietary protein requirement is about 40 - 45% (dry weight), and that they do not perform well when the dietary lipid content exceeds 15%. Furthermore, anguillids in general are thought to require both linolenic (18:3n-3) and linoleic (18:2n-6) acids, and that they possess the ability to desaturate and elongate these base acids to meet the metabolic needs for HUFA (Arai 1991). For more information, Degani and Gallagher (1995) provide a detailed analysis of the nutritional work *on A. anguilla* and *A. japonica.*

Feed costs typically account for 40-60% of the recurring cost of culturing carnivorous fish species, which are generally produced under intensive conditions in which all of the nutritional requirements of the species are provided in the form of a complete, compound diet. As such, a pre-requisite for successful culture of intensively cultured species is an artificial diet that adequately and cost-effectively meets such requirements. However, to determine all the nutrient requirements (essential amino acids, essential fatty acids, protein, lipid, energy, etc) of a new and developing aquaculture species is a long-drawn out process which generally requires a number of years of controlled experimentation, often at considerable cost. On the other hand, when time and funds are limited, and when the basic requirements of closely related species are known, nutritional investigations for candidate aquaculture species can be targeted on certain key areas that could be considered important for the development of a suitable diet.

In the present study, this latter approach has been adopted for the purposes of investigating the nutritional requirements of *A. australis* and for the development of a suitable artificial diet for intensive culture. Accordingly, a number of nutrition studies on *A. australis* were instigated in which the main objectives were to:

- determine the most suitable dietary lipid level at pre-determined protein levels
- evaluate the possibilities of incorporating soybean meal in eel diets, particularly in view of the fact that European and Japanese eels are known to be incapable of tolerating more than 10% of soybean meal in the diet,
- determine the digestibility of readily available products such as soybean meal, meat meal by short fin eel, and
- determine the digestibility of four oil types, particularly in view of the increasing demand and price of fish oils in the world.

In addition, experiments were also conducted on initial feeding of *A. australis* glass eels prior to weaning onto an artificial diet (see Chapter 3). In this study the effectiveness of four different types of readily available fish roe were evaluated as a first feed for glass eels. In the European eel farming industry, fish roe is the most popular ‘natural food’ presented to freshly caught *A. anguilla* glass eels in the process of weaning to a dry, artificial diet.

4.2 MATERIALS & METHODS

4.2.1 Source of eels

All studies were based on juvenile shortfin eels, caught from the Snowy River between 1995-1997 as part of surveys conducted during the present study (see Chapter 2). All experimental eels were initially transferred to MAFRI Snobs Creek from the point of capture for initial acclimation and weaning (see Chapter 3) prior to transfer to Deakin University, Warrnambool, at differing stages of development. Apart from the experiment on pre-weaning diets carried out at MAFRI Snobs Creek (see Chapter 3), all other experiments were conducted on weaned, pigmented, tank reared elvers held at Deakin University on a commercial diet (Kinta weaner No. 1 & 2) for a minimum of three months prior.

4.2.2 Facilities and experimental design

The basic design of the experimental systems used in the present study was similar throughout, with all experiments being carried out in various tank-based recirculating systems incorporating both continuous biological and solids filtration and supplementary aeration. Tank sizes for the different trials included 60l, 160l and 780l capacity units, with the selection of tank size based on the initial size of the experimental animals. In all instances, each (dietary) treatment was carried out in triplicate under a 12:12 hr light:dark cycle and at a fixed temperature of 24 (±1.0)°C. During all experiments pH, NO_{-2} and NH_3 were monitored at least three times weekly. A total of four separate experiments were completed, viz:

Experiment 1 – Comparison of dietary protein, lipid and soybean meal levels

Growth comparison of elvers fed pelleted, compound diets, formulated and produced at Deakin University using a bench-top extruder, at differing protein levels (40 and 50% by dry weight) and each tested at differing lipid levels (15, 20 and 25%) (designated $P_{40}L_{15}$, $P_{40}L_{20}$, $P_{40}L_{25}$, $P_{50}L_{15}$ etc). All these diets contained 5% soybean meal, and in addition $P_{50}L_{20}$ diets were formulated to contain 10 and 20% soybean meal (designated S1 & S2 respectively: De Silva *et al.* 2001a). The experiment was undertaken in 60l units at Deakin University, with weaned juvenile eels within an initial size range of 2.3-2.8g, at a stocking density of 18 fish/tank, and continued for a total of ten weeks.

Experiment 2 – Comparison of digestibility and amino acid availability of three protein rich dietary ingredients

Comparison of digestibility and amino acid availability of three protein-rich ingredients, soybean meal, shark meat meal waste and meat meal, incorporated in pelleted compound diets formulated and produced at Deakin University. Specifically, standard digestibility experiments were carried out to determine the digestibility of these ingredients using a reference diet and test diets made up of 30% of test ingredient and 70% reference diet (De Silva *et al.* 2000). The apparent dry matter (ADM), protein (PD) and energy (ED) digestibility, and the amino acid availability (essential- EAAA, non-essential- NEAAA, total-TAAA) of ingredients were evaluated. The experiment was undertaken in 160l units at Deakin University, with weaned juvenile eels within an initial size range of 110-120g, at a stocking density of 32 fish/tank and continued for a total of 4 weeks.

Experiment 3 – Comparison of the digestibility of four different dietary oil types

Comparison of the digestibility of four different oil types; codliver oil, linseed oil, sunflower oil and trout oil, incorporated in pelleted compound diets formulated and produced at Deakin University. All experimental diets were isonitrogenous and isocalorific and digestibility analyses were as described for Experiment 3. The experiment was undertaken in 160l units at

Deakin University, with weaned juvenile eels within an initial size range of 140-160g, at a stocking density of 18 fish/tank and continued for a total of 6 weeks.

Experiment 4 – Comparison of the nutritional profile of four different types of fish roe
Comparison of the nutritional profile of four different types of fish roe used for first feeding of the glass eels immediately following the acclimation stage. Roe types included: carp (*Cyprinus carpio*), mirror dory (*Zenopsis nebulosus*), orange roughy (*Hoplostethus atlanticus*) and warehou (*Seriolella brama*). This experiment was conducted at MAFRI, Snobs Creek over a 42 day period and the samples of eels and diets tested were subsequently analysed at Deakin University. A full description of the design for this experiment, including results describing the growth and survival of the eels, is provided in Chapter 3.

At the beginning of the experiment, and 28 days later, glass eels were randomly sampled (5 per replicate) and killed in excess anaesthetic and stored at –30°C for whole body analysis. The treatments on carp and warehou roe were continued for a further 14 days (total 42 days), and samples of eels taken for analysis as above. Proximate composition (percent moisture, protein, total lipid and ash), amino acid and fatty acid analyses were conducted on each type of fish roe, as fed (portions of the ovary) and oocytes only**,** and glass eels weaned on each roe type. In each instance three samples were taken, for each of the chemical analyses, and on each sample, each determination was done in triplicate. In the case of individual oocytes, each sample consisted of about 160-200 oocytes. For the eel samples, five fish from each replicate were cut into small pieces, thoroughly mixed, and three sub-samples taken and homogenised before analysis. Each of the roe types was classified into a maturity stage based on standard fishery biology classifications.

Further details on facilities, methodology and experimental design employed for all trials in the present study are provided by De Silva *et al.* (2000), De Silva *et al.* (2001a) and De Silva *et al.* (2001b).

4.2.3 Chemical analysis and digestibility studies

Standard AOAC procedures were adopted in proximate analysis (protein by Kjeldahl nitrogen; total lipid by chloroform: methanol extraction; ash by burning in a muffle furnace at 550°C for 12 hrs; energy by burning in an oxygen atmosphere in a ballistic bomb calorimeter) of dietary ingredients, diets and carcass composition. Details of the methods used are given in De Silva *et al.* (2000).

The protocol adopted for digestibility studies is given in detail in De Silva *et al.* (2000). In all the studies Cr_2O_3 was used as an external marker, and digestibility estimations were based on faecal samples accumulated through the night. In all instances the fish were acclimatised to the experimental diets at least for a week, prior to the collection of faecal samples for analysis, and during this period fish were gradually acclimated to the feeding, tank cleaning and faecal collection regimes that would be used in the following two week period. Faecal samples collected for each replicate of each treatment over seven two-day periods were used for chemical analysis, and subsequent estimations of apparent dry matter and nutrient digestibility (De Silva *et al.* 2000).

4.2.4 Statistical analysis

In the present study, Specific Growth Rate (SGR) (as % increase in body weight day^{-1}) is calculated as:

$$SGR = 100[(\ln w_2 - \ln w_1) \div t]$$

where w_1 and w_2 are mean weight in g at the start and end of the experiment, respectively, and t = the duration of the experiment in days.

Food Conversion Ratio (FCR) is calculated as:

$$FCR = \frac{\text{Amount of food (dry) presented (g)}}{\text{Increase in wet biomass (g)}}$$

Protein Efficiency Ratio (PER) is calculated as:

$$PER = \frac{\text{Increase in wet biomass (g)}}{\text{Amount of protein presented (g)}} \times 100$$

Hepato-Somatic Index (HSI) is calculated as:

$$HSI = \frac{\text{Wet liver weight x 100}}{\text{Somatic weight}}$$

All data were first checked for homogeneity of variances (Zar 1984) using Levene's test. The data were then subjected to a one-way ANOVA, followed by Duncan's Multiple Range Test to determine significant differences amongst treatments, for growth parameters and proximate composition. All statistical analyses were performed using SPSS PC software package.

4.3 RESULTS

4.3.1 Experiment 1

A summary of content and proximate composition of ingredients for the test diets used in Experiment 1 is provided in Table 4.1. The proximate composition of the ingredients (M-% moisture, P-% protein, Tl-% total lipid, A-% ash and E-energy in kJ g^{-1}) were: fishmeal- 6.6M, 69.0P, 13.1Tl, 11.9A, 21.0 E; soybean meal- 7.3M, 46.0P, 3.3Tl, 6.8A, 19.1E; wheat flour- 8.6M, 10.8P, 0.7Tl, 0.6A, 19.0E. Mean (±SEM) final body weight, Specific Growth Rate (%SGR), Food Conversion Ratio (FCR), Protein Efficiency Ratio (PER) and Hepato Somatic Index (HSI) are summarised in Table 4.2 in relation to the different dietary treatments. A summary of proximate composition of eels fed the test diets used in Experiment 1 is provided in Table 4.3.

Eels grew fastest on the P50L15 diet (Table 4.2), with an average SGR of 2.26%. The FCR and PER ranged from 1.21 ($P_{50}L_{15}$) to 2.12 ($P_{40}L_{25}$), and 0.92 ($P_{50}L_{25}$) to 1.65 ($P_{50}L_{15}$), respectively. Based on all criteria the best growth performance of *A. australis* was on the $P_{50}L_{15}$ diet, followed by $P_{40}L_{20}$ and $P_{40}L_{15}$. At both protein levels, eels reared on diets with

25% lipid performed poorly. The performance of *A. australis* was not affected by the amount of soybean meal in the diet, up to a maximum of 20% dietary inclusion.

In Experiment 1, no significant differences in muscle protein were evident in *A. australis* reared on different dietary treatments, nor was the lipid content of muscle related to dietary lipid level. In summary, the key outcomes of Experiment 1 are:

- the maximum SGR of 2.26% day^{-1} observed in the present study compares favourably with growth rates reported for *A. anguilla*, at comparable temperature and for fish of similar size range. indeed, the SGR observed for all the dietary treatments exceeded those reported in several previous studies on other cultured eel species at a comparable stage of the life cycle and fed diets exceeding 40% protein.
- it appears that juvenile shortfin eel perform relatively poorly when the dietary lipid level exceeds 15%.
- that inclusion of soybean meal up to 20% by dry weight in the diet did not adversely affect the performance of *A. australis* under intensive culture.

Table 4.1 Ingredient (g kg^{-1} feed) and proximate compositions of the experimental eel diets. All values are given in dry weights. S1 and S2 refer to two diets of 50% protein and 20% lipid, but with 10 and 20% soybean meal, respectively.

Ingredients (g/kg diet)	**Protein / Lipid level (%)/ Dietary code**							
	$P_{40}L_{15}$	**$P_{40}L_{20}$**	**$P_{40}L_{25}$**	**$P_{50}L_{15}$**	**$P_{50}L_{20}$**	**$P_{50}L_{25}$**	**S1**	**S2**
Fish meal	520	530	540	680	690	700	660	600
Defatted soybean	50	50	50	50	50	50	100	200
Wheat flour	280	220	160	135	75	20	60	15
Cellulose	20	20	20	20	20	20	20	20
Vit. + Mineral Mix*.	30	30	30	30	30	30	30	30
Oil **	80	130	180	65	115	160	110	115
CMC (Binder)	20	20	20	20	20	20	20	20
Proximate composition (dry matter basis)								
% Protein	41.1	40.8	40.3	49.9	51.2	51.8	51.2	52.1
% Lipid	14.7	19.4	24.2	14.7	20.4	24.7	19.5	19.3
% Ash	7.3	9.1	8.2	9.4	11.5	9.5	9.8	10.0
Energy kJ g^{-1}	21.3	22.9	24.6	21.3	22.6	24.6	22.1	22.6
P:E (mg kJ^{-1})	20.4	19.4	18.4	24.9	23.7	22.7	23.8	23.8

* commercial preparation purchased from Ridley Agriproducts; ** 1 Cod liver oil : 2 sunflower oil; CMC- carboxymethyl cellulose

Table 4.2 Mean (±SEM) final body weight, Percent Specific Growth Rate (%SGR), Food Conversion Ratio (FCR), Protein Efficiency Ratio (PER) and Hepato Somatic Index (HSI) in shortfin eel in relation to different dietary treatments. For any one parameter values with the same superscript are not significantly different.

Parameter	Dietary treatment							
	P40/L15	P40/L20	P40/L25	P50/L15	P50/L20	P50/L25	S1	S2
Weight (g)	24.5 ^{bc}	23.2 ^{b}	18.9 ^{a}	26.8^{c}	22.6^{b}	18.7^{a}	21.1 ^{b}	23.9^{b}
	±0.72	±1.65	±0.74	±1.67	±1.14	±0.53	±1.26	±0.73
SGR (%)	2.11^{b}	2.11 ^{b}	1.82^{a}	2.26^{c}	2.01 $^{a\,b}$	1.79 ^{a}	1.92^{b}	2.12^{b}
	±0.04	±0.03	±0.01	±0.03	±0.09	±0.07	±0.04	±0.04
FCR	1.61 ^{b}	1.48 ^{b}	2.12 ^{c}	1.21^{a}	1.61 ^{b}	2.10 ^{c}	1.85^{bc}	1.60^{b}
	±0.04	±0.07	±0.03	±0.07	±0.01	±0.05	±0.07	±0.03
PER	1.50 ^{c}	1.65^{d}	1.16$^{a\,b}$	1.65^{d}	1.21 ^{b}	0.92 ^{a}	1.05 ^{a}	1.20^{b}
	±0.03	±0.09	±0.08	±0.06	±0.04	±0.03	±0.07	±0.03
HSI *	1.96 ^{ab}	2.41 ^{b}	1.83^{a}	1.95^{ab}	2.15^{b}	1.84 ^{a}	1.88 ^{a}	1.81^{a}
	±0.30	±0.21	±0.07	±0.07	±0.28	±0.13	±0.11	±0.16

* (liver weight ÷ body weight) 100

Table 4.3 Results of proximate analysis of body muscle (wet weight basis) of eels, at the commencement of the experiment (initial) and at termination reared under different dietary regimes. The means (±SEM) are based on three samples (each of three fish) for each treatment analysed in triplicate. Values with the same superscript in each column are not significantly different (p>0.05)

Dietary code	Moisture (%)	Protein(%)	Lipid (%)	Ash (%)
Initial	69.5±0.51	15.8±0.63^{a}	15.0±0.07 ^{c}	0.9±0.02
P40/L15	68.7±1.07	17.8±0.47 ^{b}	16.1±0.09 ^{c}	1.0±0.02
P40/L20	68.3±0.41	17.7±0.02 ^{b}	12.5±0.1 ^{b}	1.1±0.21
P40/L25	68.4±0.51	17.9±0.2 ^{b}	11.7±0.06 ^{b}	0.9±0.08
P50/L15	68.6±0.51	17.6±0.26 ^{b}	11.1±0.03 $^{a\,b}$	1.0±0.11
P50/L20	68.6±0.30	18.0±0.33 ^{b}	12.8±0.06 ^{b}	0.9±0.04
P50/L25	68.8±0.39	18.0±0.45 ^{b}	14.5±0.11 $^{b\,c}$	1.0±0.01
S1	70..9±0.80	17.6±0.21 ^{b}	9.8±0.01 ^{a}	0.9±0.06
S2	69.8±0.25	18.0±0.40 ^{b}	9.2±0.12 ^{a}	1.1±0.06

4.3.2 Experiment 2

The digestibility of ingredients used in diets for Experiment 2 were determined by standard digestibility experiments using a reference diet (RD-Sfe) (Table 4.4), and test diets made up of 30% of test ingredient and 70% reference diet (De Silva *et al.* 2000). The amino acid composition of the ingredients for the test diets, the reference diet, and for the fish themselves are summarised in Table 4.5, and the availability of essential amino acids for A. australis in the test and reference diets is summarised in Table 4.6.

The highest level (%) of ADM (Apparent Dry Matter) and PD (Protein Digestibility) of the test diets was observed for shark meat meal (73.1±1.58 and 87.5±1.27) and soybean meal (70.6±0.82 and 86.5±0.49) diets, respectively. The PD of the meat meal incorporated diets was significantly low compared with other experimental diets, however the ED of the diets did not differ significantly. The above observations were also reflected in dry matter and nutrient digestibility of ingredients.

The TEAAA for the meat meal incorporated diet (50.5±4.25) was significantly lower than for all the other diets, and all essential amino acids for all diets were available in excess of 80%, with the exception of lysine (66.5±6.05% for SBM) (Table 4.6). The present data on PD and EAAA, combined with previously published data indicate a close correlation between these two parameters, suggesting that PD may provide a fairly reliable indication of the amino acid availability for *A. australis*.

In summary, the key outcomes of Experiment 2 can be summarised as follows:

- soybean meal was relatively well digested by *A. australis*, as is the case of most finfish.
- The relatively high digestibility of soybean meal incorporated test diet and soybean meal (ADM, PD and ED) by *A. australis* may be indicative of differences in the digestive physiology amongst cultured *Anguilla* species, and warrants comparative studies on this important group
- The lower ADM, PD and ED of meat meal by *A.australis* may have been due to the relatively high ash content.

The ADM, PD and ED of meat meal incorporated diet, as well as that of the ingredient *per se*, in *A.australis* were relative low compared to other species such as, for example, Murray cod, *Maccullochella peelii peelii* (De Silva *et al.* 2000). The above trend was also reflected in TEAAA, TNEAAA and TAAA of meat meal incorporated diet in *A. australis*, in contrast to that in Murray cod (as well as compared to the other two ingredients in *A. australis*).

Table 4.4 Ingredient (g kg $^{-1}$ diet) and proximate composition (as fed basis) of reference diet (RD-Sfe) used in the digestibility experiments on *A.australis*.

Ingredient	Eel (RD-Sfe)
Fishmeal	630
Wheat flour	215
α- Cellulose	20
Vit+ Min. mix*	30
Oil	75**
CMC	20
Cr_2O_3	10
Proximate composition	
Moisture	1.6
Protein	46.1
Lipid	15.7
Ash	9.6
Energy (kJ g^{-1})	20.9

*Commercial Preparation (Ridley Agriproducts Ltd., Sydney, Australia);
** 1:2 cod liver oil: sunflower oil; CMC- carboxy methyl cellulose

Table 4.5 The amino acid composition in μ moles g^{-1} of test ingredients(dry weight)(SBM- Soybean meal; MM- meat meal; SMM- shark meat meal) and that of *A.australis* (mean of three size groups)(wet weight) basis. For comparison that of the fish meal (FM) used in the present study is also given

Amino acid	SBM	SMM	MM	FM	Sfin eel
Essential (EAA)					
Arginine	111.3 ±3.9	162.5±11.0	123.9 ±2.5	134.3±2.4	45.3 ±0.6
Histidine	53.7 ±1.7	53.9 ±6.6	48.7 ±1.2	91.7 ±3.8	25.5 ±0.7
Isoleucine	41.7 ±1.7	57.8 ±3.2	27.6 ±0.5	53.3 ±0.9	32.1 ±0.7
Leucine	177.1 ±6.4	192.2±12.4	185.7 ±2.9	213.0 ±2.6	74.2 ±1.3
Lysine	141.1 ±2.3	194.0±13.2	158.1 ±7.2	199.1 ±4.9	89.7 ±3.8
Methionine	50.6 ±2.9	112.3 ±8.3	60.3 ±1.3	107.1 ±1.8	21.7 ±0.4
Phenylalanine	84.4 ±2.9	93.9 ±4.5	77.0 ±1.3	87.9 ±1.6	29.2 ±0.3
Threonine	120.8 ±4.9	206.1±13.0	226.7±18.3	178.9 ±3.4	52.1 ±1.2
Valine	55.3 ±2.2	69.4 ±4.9	69.9 ±1.5	75.6 ±1.2	38.7 ±0.6
∑EAA	**819**	**1142**	**974**	**1141**	**409**
Non- essential (NEAA)					
Alanine	145.9 ±8.3	236.9±19.0	277.0±12.5	226.1 ±6.1	84.5 ±1.9
Aspartic acid	205.0±12.1	185.8 ±9.6	158.3 ±8.0	240.4 ±7.7	70.5 ±2.9
Cystine	104.3 ±3.8	97.9 ±7.5	75.5 ±0.8	119.0 ±5.4	14.9 ±0.6
Glutamic acid	322.6 ±6.6	235.0±15.3	226.1 ±9.9	285.1 ±6.5	102.5 ±3.0
Glycine	187.6 ±2.6	582.6±23.4	505.6±20.1	317.4 ±4.4	102.3 ±2.5
Proline	164.2 ±2.8	267.9 ±9.6	299.9 ±3.2	219.7 ±3.1	54.8 ±0.8
Serine	167.7 ±6.2	184.7±11.6	153.5 ±3.9	188.5 ±3.2	60.0 ±1.1
Tyrosine	59.6 ±2.0	70.4 ±3.5	51.8 ±0.7	74.2 ±2.1	28.1 ±1.2
∑NEAA	**1342**	**1861**	**1748**	**1670**	**518**
TAA	**2161**	**3003**	**2722**	**2811**	**926**

Table 4.6 Availability of individual essential amino acids (EAAA), together with that of total essential amino acid (TEAAA), total non essential amino acids (TNEAAA) and total amino acids (TAAA) in shortfin eel for the reference diets (RD) and test diets incorporated with 30% of the test ingredients. For each amino acid or group of amino acid, in each species, values with the same superscript are not significantly different (P>0.05)

Amino Acid	Diet/Ingredient (% availability)			
	RD	SBM	SMM	MM
Arginine	89.6 ^{c}±0.86	91.6 ^{c}±0.39	85.2 ^{b}±0.86	45.9 ^{a}±5.40
Histidine	94.3 ^{b}±0.56	89.3 ^{a} ±1.06	93.1 ^{b}±0.50	na
Isoleucine	89.8 ^{b}±1.02	89.3 ^{b}±0.82	86.3 ^{b}±0.75	73.9 ^{a}±2.67
Leucine	90.0 ^{b}±0.94	86.9 $^{a\ b}$±0.69	86.4 ^{a}±0.70	na
Lysine	87.2 ^{b}±1.53	66.5 ^{a}±6.05	86.1 ^{b}±2.02	70.3 ^{a}±2.60
Methionine	85.3 ^{b}±1.36	91.4 ^{c}±1.00	83.4 ^{b}±1.10	37.3 ^{a}±2.29
Phenylal.	88.0±0.84	87.0±0.54	87.4±0.70	na
Threonine	91.9 ^{b}±0.85	89.1 ^{b}±1.48	83.9 ^{b}±1.90	23.6 ^{a}±3.78
Valine	88.9 ^{b}±1.12	85.4 $^{a\ b}$±0.64	83.9 ^{a}±0.83	na
TEAAA	89.7 ^{b}±0.91	86.8 ^{b}±0.6	85.9 ^{b}±0.57	50.5 ^{a}±4.25
TNEAAA	85.1 ^{c}±0.84	85.9 ^{c}±0.63	78.4 ^{b}±1.26	46.7 ^{a}±4.85
TAAA	87.0 ^{c}±0.86	86.3 ^{c}±0.58	81.73 ^{b}±0.69	48.9 ^{a}±4.95

na- not available

4.3.3 Experiment 3

The proximate composition of the isonitrogenous and isocalorific diets used in this study, and the fatty acid composition of these diets, are given in Table 4.7 and Table 4.8, respectively.

The diets differed in their fatty acid composition in a number of ways, most significantly in the amounts of n-3 and n-6 HUFA levels. For example the linseed oil and sunflower oil diets did not contain any HUFA but were richer in 18:3n-3 and 18:2n-6. The percent apparent dry matter, protein, lipid and energy digestibility of the diets are given in Table 4.9. The protein and energy digestibility of the diets were not affected by the dietary oil source but the lipid digestibility was, with the highest lipid digestibility being in diets containing cod liver oil. However, the lipid digestibility of the diet with sunflower oil did not differ significantly from that with cod liver oil (P> 0.05).

The individual fatty acid digestibilities of the diets are given in Table 4.10, and the amount of each major group of fatty acids in each of the diets and the digestibility thereof is shown in Figure 4.1. It is evident that in general all the fatty acids, either singly or when considered as major groups (saturates, monoenes, PUFA and HUFA), were well digested, with the digestibility being in most instances being over 90%.

In summary, the key outcome from Experiment 3 is:

- Considering all factors, of the four oil types tested, trout oil performed the poorest and cod liver oil the best in terms of digestibility.

Table 4.7 Proximate composition (percent) of the test diets. Energy is expressed in kJ g^{-1}; CLO- cod liver oil; LO- linseed oil; SFO- sunflower oil; TO- trout oil**.**

Oil type	Moisture	Protein	Lipid	Ash	Energy
CLO	9.0	50.8	14.7	7.4	20.2
LO	9.7	48.9	14.4	7.4	19.1
SFO	9.5	49.8	15.2	7.5	20.3
TO	9.3	49.2	14.4	7.5	19.8
CLO: SFO (1:1)	9.2	50.6	14.3	7.4	20.8

Table 4.8 Fatty acid composition of the diets (μg mg^{-1} sample); CLO- cod liver oil; LO- linseed oil; SFO- sunflower oil; TO- trout oil.

Fatty acid	Diet				
	CLO	LO	SFO	TO	CLO:SFO
14:0	3.8±0.03	0.1±0.0	0.1±0.0	2.3±0.03	2.0±0.04
16:0	17.2±0.05	8.0±0.06	9.34±0.11	20.9±0.24	13.6±0.24
18:0	2.7±0.04	3.4±0.01	6.0±0.06	5.8±0.07	4.5±0.05
20:0	0.3±0.02	0.2±0.01	0.5±0.05	0.2±0.01	0.4±0.01
22:0	0.2±0.03	0.2±0.0	0.9±0.03	0.1±0.02	0.5±0.01
∑ saturates	24.2±0.06	11.9±0.08	16.9±0.21	29.4±0.37	21.0±0.36
16:1n-7	7.4±0.03	0.1±0.01	0.2±0.01	6.3±0.10	3.9±0.07
18:1n-9	18.8±0.36	18.6±0.13	34.3±0.37	35.7±0.44	27.1±0.51
18:1n-7	2.4±0.04	0.6±0.01	1.0±0.01	3.2±0.04	1.7±0.02
20:1n-9	9.1±0.04	0.2±0.03	0.4±0.01	5.6±0.03	4.9±0.11
22:1n11	11.1±0.04	-	0.2±0.02	2.1±0.03	5.7±0.13
∑ monoenes	48.9±0.49	19.6±0.12	36.1±0.39	53.0±0.65	43.4±0.84
18:2n-6	6.6±0.02	21.7±0.14	81.6±0.86	12.3±0.15	43.8±0.87
18:3n-3	2.4±0.09	86.6±0.92	2.3±0.04	1.6±0.04	2.3±0.04
18:3n-6	0.2±0.09	-	-	0.2±0.0	0.1±0.01
18:4n-3	3.5±0.05	-	-	0.7±0.01	1.8±0.07
20:2n-6	0.5±0.0	-	-	0.7±0.01	0.3±0.01
20:3n-3	0.3±0.03	-	-	0.2±0.0	0.2±0.05
20:3n-6	0.1±0.01	-	-	0.3±0.01	0.1±0.02
20:4n-6	0.5±0.03	-	-	0.6±0.01	0.2±0.01
20:5n-3	8.5±0.02	-	-	3.1±0.06	4.5±0.11
22:5n-3	1.7±0.08	-	-	1.1±0.03	1.0±0.06
22:6n-3	12.1±0.03	-	-	9.7±0.14	6.3±0.18
∑ n-3	28.5±0.20	86.7±0.91	2.6±0.05	16.4±0.28	16.1±0.43
∑ n-6	7.9±0.01	21.9±0.14	81.6±0.86	14.2±0.18	44.5±0.86
∑ PUFA	36.4±0.21	108.5±1.0	84.1±0.90	30.6±0.46	60.6±1.21
∑HUFA	23.7±0.07	-	-	15.7±0.26	12.5±0.30
∑UNSAT	85.3±0.67	128.2±1.17	120.2±1.3	83.6±1.12	104.1±2.0
∑ Total	109.5±0.74	140.1±1.25	137.2±1.52	113.0±1.5	125.1±2.41

Table 4.9 Mean percent (±SE) apparent dry matter (%ADM), protein digestibility (%PD), lipid digestibility (%LD) and energy digestibility (%ED) of the test diets containing different oils as the lipid source; CLO- cod liver oil; LO- linseed oil; SFO- sunflower oil; TO- trout oil**.**

Digestibility (%)	**Diet/ Oil type**				
	CLO	**LO**	**SFO**	**TO**	**COL:SFO**
Dry matter (%ADM)	87.6 ^{b} ±0.2	89.2 ^{b} ±0.2	87.9 ^{b}±0.6	85.2^{a}±0.3	88.4 ^{b} ±0.6
Protein (%PD)	95.7±0.2	97.2±0.1	96.3±0.4	95.8±0.4	95.6±0.7
Lipid (% LD)	95.6 ^{d} ±0.2	90.2 ^{b} ±0.6	94.9 ^{cd}±0.2	88.1^{a} ±0.5	93.8 ^{c}±0.2
Energy (%ED)	91.2	90.8	89.4	87.3	91.1

Table 4.10 Apparent percent digestibility of the fatty acids of the different experimental diets; CLO- cod liver oil; LO- linseed oil; SFO- sunflower oil; TO- trout oil.

Fatty acid	**Diet**				
	CLO	**LO**	**SFO**	**TO**	**COL:SFO**
14:0	97.9±0.03^{d}	66.5±2.9 ^{a}	82.77±1.01 ^{b}	91.4±0.36 ^{c}	96.3±0.30 ^{d}
16:0	96.5±0.02 ^{b}	87.8±1.39 ^{a}	95.0±0.33 ^{b}	87.22±0.37 ^{a}	94.32±0.52 ^{b}
18:0	94.2±0.10 ^{c}	86.5±1.46 ^{b}	93.7±0.36 ^{c}	83.4±0.56 ^{a}	92.3±0.76 ^{c}
16:1n7	98.2±0.10 ^{d}	70.8±2.04 ^{a}	79.0±1.14 ^{b}	92.7±0.57 ^{c}	96.1±0.15 ^{d}
18:1n9	97.7±0.12 ^{b}	89.2±1.08 ^{a}	96.9±0.36 ^{b}	89.4±0.91 ^{a}	95.6±0.43 ^{b}
18:1n7	97.3±0.09 ^{c}	87.5±1.26 ^{a}	95.3±0.35 ^{bc}	88.7±0.89 ^{a}	94.7±0.37 ^{b}
20:1n11	97.6±0.05 ^{b}	86.3±2.88 ^{a}	93.2±0.36 ^{b}	87.2±1.15 ^{a}	94.8±0.51 ^{b}
22:1n11	96.94±0.10 ^{b}	-	94.0±1.33 ^{b}	85.1±1.55 ^{a}	94.1±0.62 ^{b}
18:2n6	97.1±0.09 ^{b}	92.5±0.59 ^{a}	98.1±0.18 ^{b}	91.9±0.78 ^{a}	97.0±0.22 ^{b}
18:3n3	96.3±0.43 ^{b}	95.3±0.37 ^{b}	96.6±0.42 ^{b}	89.1±1.99 ^{a}	96.2±0.17 ^{b}
18:4n3	99.5±0.02 ^{a}	-	-	80.5±16.1 ^{a}	98.5±0.07 ^{a}
20:5n3	99.2±0.04 ^{c}	-	-	96.2±0.17 ^{a}	98.1±0.17 ^{b}
22:5n3	98.8±0.09 ^{c}	-	-	94.5±0.38 ^{a}	97.1±0.36 ^{b}
22:6n3	98.55±0.03 ^{c}	-	-	95.31±0.28 ^{a}	97.0±0.27 ^{b}
Saturates	96.4±0.03^{b}	87.2±1.40 ^{a}	94.2±0.32 ^{b}	86.7±0.36 ^{a}	93.9±0.57 ^{b}
Monoens	97.6±0.06 ^{b}	89.01±1.13 ^{a}	96.71±0.36 ^{b}	89.37±0.92 ^{a}	95.35±0.43 ^{b}
Unsaturates	97.9±0.04 ^{c}	93.6±0.53 ^{b}	97.4±0.25 ^{c}	90.8±0.78 ^{a}	96.3±0.31 ^{c}
n6	96.9±0.06 ^{b}	92.1±0.61 ^{a}	97.9±0.21 ^{b}	91.5±0.72 ^{a}	96.8±0.24 ^{b}
n3	98.7±0.02 ^{c}	94.9±0.37 ^{a}	93.8±0.45 ^{a}	94.8±0.42 ^{a}	97.4±0.20 ^{b}
PUFA	98.3±0.02 ^{d}	94.4±0.42 ^{b}	97.8±0.21 ^{cd}	93.3±0.55 ^{a}	97.0±0.22 ^{c}
HUFA	98.7±0.03 ^{a}	-	-	94.7±0.29 ^{a}	96.9±0.28 ^{a}
Total	97.5±0.03 ^{d}	93.0±0.6 ^{b}	97.0±0.26 ^{cd}	89.7±0.61 ^{a}	95.9±0.35 ^{c}

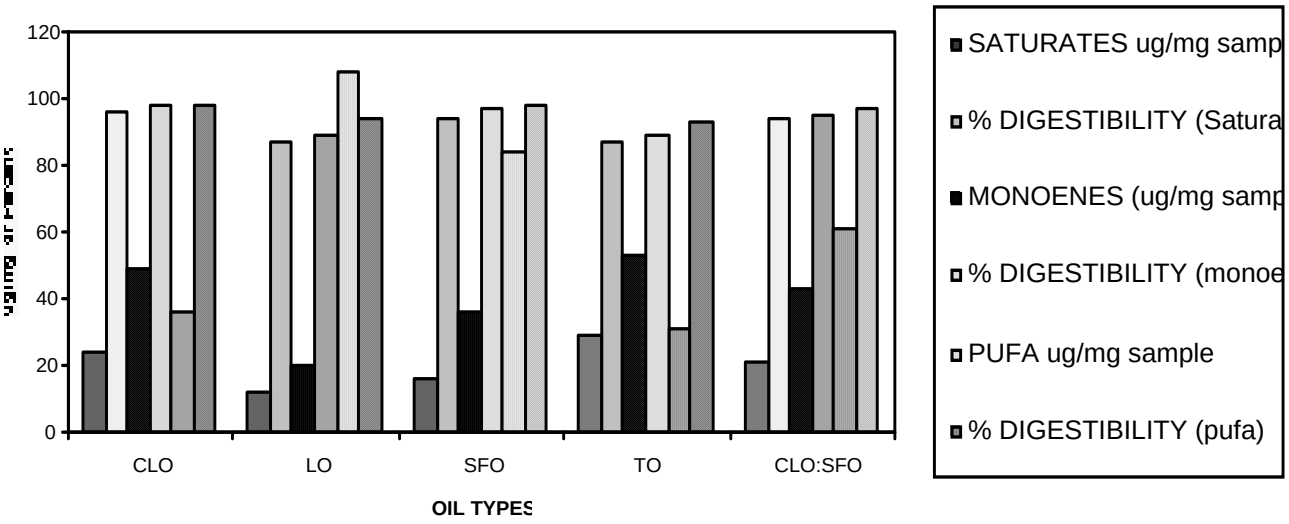

Figure 4.1. The amount of the major fatty acid categories in the experimental diets and the percent apparent digestibility of these; CLO- cod liver oil; LO- linseed oil; SFO- sunflower oil; TO- trout oil.

4.3.4 Experiment 4

The physical characteristics and the proximate composition of the four roe types tested are given in Table 4.11. The amino acid (free and total) and fatty acid composition of the roe types are given in De Silva *et al.* 2001b. All roes, except warehou, were in Stage IV maturity (stage prior to water absorption).

A description of the growth and survival of glass eels weaned using the four different types of fish roe is presented in Chapter 3. Initially, glass eels were found to feed on oocytes of all the roe types, although they did not appear to consume the ovarian membrane and/or connective tissue in the ovary, even though some accidental ingestion of connective material could not be ruled out. In all instances the eels lost weight initially, and around the beginning of the third week they were showing less and less interest in mirror dory and orange roughy roe specifically. These particular eels ceased feeding altogether on the 20th day or so, but after 14 days those fed carp and warehou roes began to gain weight. The final mean weight of eels weaned on carp and warehou roe were not significantly different, even though the former was consistently higher (see Chapter 3). On the 28th day, the mean weight of glass eels reared on carp and warehou was significantly higher than for eels fed on the other two roe types. The changes in mean weights of eels fed different roe types were also reflected in growth rates (measured fortnightly as SGR), with the SGR of eels on carp and warehou increasing significantly after the first fortnight (see Chapter 3).

In this experiment it was found that the amount of protein in roe and oocytes decreased in order, viz.: carp > mirror dory > warehou > orange roughy, and the differences between these types were significant ($P< 0.05$). The lowest total lipid also occurred in roe and oocytes of orange roughy (Table 4.11). Although there were significant differences in the moisture

content of the roe types and oocytes, the rank order of roe types and oocytes, with regard to the percent protein and or lipid content when expressed on a dry weight basis, remained unchanged. On a dry weight basis for example, the percent protein content of oocytes decreased in order, viz: carp (78.6), mirror dory (73.1), warehou (65.4) and orange roughy (60.6).

Major differences in the amino acid composition of roe and oocyte types were evident (De Silva e t al., 2001b). The most notable differences were in the total amino acid (TAA) and the essential amino acid content (EAA) of the roe and oocytes. It was evident that the amount of TAA, EAA (μ mol g^{-1} of roe and oocytes) decreased significantly (P <0.05), in order, viz.: carp > mirror dory > warehou > orange roughy**.** The E/A ratio (EAA:TAA) (Wilson and Poe 1985; Ngamsnae *et al.* 1999) of the four types of roe, on the other hand, did not differ markedly (data not shown).

Major differences in the fatty acids amongst the four roe and oocyte types analysed in Experiment 4 were evident. For example, the amount of saturates were significantly lower in roe and oocytes of orange roughy and warehou, but monoenes showed the opposite trend (Table 4.12). The amount of n-3 fatty acids in roe and oocytes decreased in order of mirror dory, warehou, orange roughy and carp (P< 0.05), and the n-6 fatty acids were found in highest amounts in order, viz.: carp and warehou > mirror dory > orange roughy. Arachidonic acid (AA; 20:4n-6) represented about 60% of the n-6 HUFA of roe, and about 50% of the oocytes of carp and warehou. The n-3 to n-6 ratio of the four roe and oocytes was 1.32, 5.92. 3.77 and 2.67, and 1.25, 4.83, 2.91 and 2.42, in carp, mirror dory, orange roughy and warehou, respectively. Up to the 28th day the survival of glass eels exceeded 99% (see Chapter 3). However, the treatments on orange roughy and mirror dory roes were abandoned because the fish did not show any interest in the food and were losing condition rapidly. Glass eels reared on carp and warehou roes continued to have a survival up to 99% until the termination of the experiment on the 42nd day (see Chapter 3).

In summary the main outcomes of Experiment 4, including relevant outcomes from the related aquaculture trials (see Chapter 3) were:

- After 28 days the eels did not show an interest in orange roughy and mirror dory roe.
- In all treatments there was a decrease in mean weight during this period, but survival was >99%.
- In the 28th to 42nd day period the mean weight and SGR of glass eels reared on carp and warehou roe increased, but the differences between these two treatments were not significant.
- The physical features of the roe and the oocytes thereof, the proximate composition, amino acid and fatty acid composition indicated major differences amongst the roe types, particularly with regard to the amount of n-6 polyunsaturated fatty acids (PUFA) and the ratio of n-3 to n-6.
- Carp and warehou roe (and oocytes) had a significantly higher arachidonic acid (AA-20:4n-6; over 60% of PUFA) content and a considerably lower n-3 to n-6 ratio than in the other two roe types (n-3 to n-6 ratio being 1.32, 5.92. 3.77 and 2.67 for roe types, and 1.25, 4.83, 2.91 and 2.42 for oocytes, of carp, mirror dory, orange roughy and warehou, respectively).
- The fatty acid profiles of carp and warehou roe were similar to that of metamorphosing *A. australis* glass eels

Table 4.11. Physical features of the roe types and oocytes, and the proximate composition of the roes and oocytes. Values with same superscript for any one tissue type, in each row are not significantly different (P >0.05); Ec- European carp (carp), Md- mirror dory, Or-orange roughy, Wh- warehou.

Parameter	Roe				Oocytes			
	Ec	**Md**	**Or**	**Wh**	**Ec**	**Md**	**Or**	**Wh**
Maturity stage	IV	IV	IV	III	As for roe			
Colour	G/b	Y/Og	DO/og	YO	Not determined			
Diameter (mm)	Not applicable				1.93^{c}	1.79^{c}	1.42^{b}	0.83^{a}
					±0.05	±0.04	±0.05	±0.02
Moisture (%)	63.2^{a}	69.1^{b}	81.6^{d}	74.2^{c}	62.7^{a}	66.6^{b}	79.2^{d}	71.7^{c}
	±0.26	±0.46	±0.94	±0.2	±0.95	±0.33	±1.66	±0.39
Protein	28.7^{d}	22.6^{c}	11.7^{a}	17.3^{b}	29.3^{d}	24.4^{c}	12.6^{a}	18.5^{b}
	±0.10	±0.16	±0.03	±0.09	±0.18	±0.05	±0.05	±0.17
Lipid	6.3^{b}	6.2^{b}	4.6^{a}	6.6^{b}	6.3^{b}	7.3^{c}	5.4^{a}	7.4^{c}
	±0.01	±0.23	±0.05	±0.13	±0.08	±0.12	±0.13	±0.04
Ash	1.4^{b}	0.9^{a}	1.03^{a}	1.01^{a}	1.4^{c}	1.01^{a}	1.23^{b}	1.1^{ab}
	±0	±0.02	±0.01	±0.02	±0.03	±0.01	±0.03	±0.04

G/b- greyish brown; Y/Og- yellowish with oil globules, DO/og- deep orange with oil globules, Yo- yellowish orange

4.4 DISCUSSION

Previous investigations into the nutritional requirements of *A. australis* are limited (De Silva *et al.* 1997), and the experimental diets in the present study therefore were largely formulated on the basis of information available for *A. anguilla* and *A. japonica* (Arai 1991).

The maximum SGR of 2.26 % day^{-1} observed in the present study compares favourably with growth rates reported for the European eel, at comparable temperature and for fish of similar size range (Degani *et al.* 1986; Gallego *et al.* 1994). Indeed, the SGR observed for all the dietary treatments exceeded those reported in several previous studies on other cultured eel species at a comparable stage of the life cycle and fed diets exceeding 40% protein (eg. Kuhlmann 1979; Kastelein 1983; Heinsbroek 1989; Tibbetts *et al.* 2000).

Juvenile eels are not particularly voracious feeders (Degani *et al.* 1988; Gallego *et al.* 1994). In such circumstances, FCR values obtained for all the dietary treatments were relatively good. Also, the FCR values observed in the present study for most of the dietary treatments were better than that reported elsewhere for similar sized *A. anguilla* and *A. japonica*. This was true also for PER, thus indicating the positive response of *A. australis* to suitably formulated artificial diets. Surprisingly, the lowest HSI was observed in *A. australis* elvers fed diets with 25% lipid, at both dietary protein levels, and the diets containing 10 and 20% soybean meal. In general, there was no clear trend in changes in the HSI in relation to dietary lipid content.

Table 4.12. The mean amount of individual fatty acids in μg mg-1 of wet material (±SE) in the four types of roe and oocytes. In any one row values with the same superscript, are not significantly different (P >0.05)

Fatty	Roe type				Oocytes			
Acid	Ec	Md	Or	Wh	Ec	Md	Or	Wh
14:0	0.5 ^{a} ±0.02	1.2 ^{d} ±0.01	0.8 ^{b} ±0.02	1.0 ^{c} ±0.10	0.5 ^{d} ±0.01	1.5 ^{a} ±0.08	0.9 ^{b} ±0.02	1.3 ^{c} ±0.07
16:0	10.5 ^{b} ±0.07	12.6 ^{c} ±0.28	7.2 ^{a} ±0.11	6.9 ^{a} ±0.05	10.6 ^{b} ±0.06	13.7 ^{c} ±0.01	8.1 ^{a} ±0.15	8.4 ^{a} ±0.23
18:0	2.1 ^{c} ±0.02	2.6 ^{d} ±0.05	0.9 ^{a} ±0.01	1.3 ^{b} ±0.01	2.1 ^{b} ±0.02	3.1 ^{c} ±0.01	1.1 ^{a} ±0.02	1.9 ^{b} ±0.06
20:0	<0.1 ±0.01	0.1 ^{a} ±0.04	0.2 ^{b} ±0.03	nd	0.1 ±0.04	0.3 ±0.01	0.2 ±0.03	0.1 ±0.06
22:0	0.1 ±0.03	0.1 ±0.01	<0.1	<0.1	0.2 ±0.05	0.3 ±0.09	<0.1	0.2 ±0.12
∑ saturates	13.4 ^{b} ±0.07	16.7 ^{c} ±0.03	9.2 ^{a} ±0.1	9.3 ^{a} ±0.06	13.5 ^{c} ±0.13	19.1 ^{d} ±0.25	10.4 ^{a} ±0.18	12.0 ^{b} ±0.42
16:1n-7	2.6 ^{c} ±0.03	1.1 ^{a} ±0.03	2.4 ^{b} ±0.03	1.2 ^{a} ±0.02	2.7 ^{b} ±0.01	1.3 ^{a} ±0.02	2.7 ^{b} ±0.04	1.4 ^{a} ±0.05
18:1n-9	5.1 ^{a} ±0.05	9.4 ^{b} ±0.19	10.1 ^{c} ±0.17	9.9 ^{c} ±0.10	5.1 ^{a} ±0.04	10.7 ^{b} ±0.07	11.4 ^{c} ±0.02	12.0 ^{d} ±0.3
18:1n-7	1.9 ^{d} ±0.02	1.1 ^{b} ±0.02	1.3 ^{c} ±0.02	1.0 ^{a} ±0.01	1.9 ^{b} ±0.01	1.3 ^{a} ±0.02	1.4 ^{a} ±0.02	1.3 ^{a} ±0.04
20:1n-9	0.2 ^{a} ±0.01	1.1 ^{c} ±0.02	2.4 ^{d} ±0.05	0.3 ^{b} ±0.01	0.2 ^{a} ±0.01	1.4 ^{c} ±0.06	2.6 ^{d} ±0.05	0.6 ^{b} ±0.01
∑ monoenes	10.1 ^{a} ±0.11	13.0 ^{b} ±0.27	16.4 ^{c} ±0.26	12.6 ^{b} ±0.15	10.1 ^{a} ±0.07	15.0 ^{b} ±0.15	18.4 ^{c} ±0.27	15.6 ^{b} ±0.41
18:2n-6	0.5 ^{c} ±0.08	0.4 ^{b} ±0.01	0.3 ^{a} ±0.01	0.5 ^{c} ±0.01	0.5 ^{b} ±0.01	0.5 ^{b} ±0.02	0.4 ^{a} ±0.01	0.6 ^{b} ±0.04
18:3n-3	0.2 ^{a} ±0.01	0.2 ^{a} ±0.01	<0.1	0.4 ^{b} ±0.01	0.3 ^{b} ±0.02	0.3 ^{b} ±0.04	0.1 ^{a} ±0.01	0.3 ^{b} ±0.03
18:3n-6	0.3 ^{a} ±0.01	0.5 ^{b} ±0.03	0.3 ^{a} ±0.06	0.4 $^{a\,b}$ ±0.02	0.9 ±0.02	1.1 ±0.12	1.5 ±0.39	1.5 ±0.06
18:4n-3	<0.1	0.1 ^{a} ±0.01	<0.1	1.1 ^{b} ±0.04	0.1 ^{a} ±0.03	0.4 ^{b} ±0.08	0.2 ^{a} ±0.02	1.4 ^{c} ±0.03
20:2n-6	0.2 ±0.01	0.2 ±0.05	0.1 ±0.01	0.2 ±0.04	0.3 ±0.02	0.3 ±0.05	0.4 ±0.05	0.4 ±0.11
20:3n-3	0.9 ^{c} ±0.02	0.2 ^{a} ±0.06	0.3 $^{a\,b}$ ±0.05	0.7 $^{b\,c}$ ±0.09	0.5 $^{a\,b}$ ±0.14	0.3 ^{a} ±0.07	0.2 ^{a} ±0.07	0.8 ^{b} ±0.11
20:3n-6	0.5 ^{c} ±0.02	0.3 ^{b} ±0.02	0.1 ^{a} ±0.02	0.3 ^{b} ±0.01	0.9 ^{b} ±0.14	0.4 ^{a} ±0.16	0.3 ^{a} ±0.03	0.4 ^{a} ±0.02
20:4n-6	4.9 ^{c} ±0.3	1.6 ^{a} ±0.1	1.7 ^{a} ±0.1	3.9 ^{b} ±0.2	4.3 ^{c} ±0.15	2.1 ^{b} ±0.17	1.3 ^{a} ±0.14	4.6 ^{c} ±0.26
20:5n-3	1.3 ^{a} ±0.01	2.7 ^{c} ±0.02	2.2 ^{b} ±0.01	3.3 ^{d} ±0.01	1.4 ^{a} ±0.02	3.3 ^{c} ±0.03	2.5 ^{b} ±0.01	3.8 ^{d} ±0.12
22:2n-6	1.0 ^{c} ±0.03	0.3 $^{a\,b}$ ±0.01	0.2 ^{a} ±0.02	0.4 ^{b} ±0.03	1.1 ^{c} ±0.07	0.5 ^{b} ±0.1	0.3 ^{a} ±0.06	0.7 ^{b} ±0.03
22:4n-6	0.4 ^{b} ±0.01	0.4 ^{b} ±0.04	0.2 ^{a} ±0.01	0.4 ^{b} ±0.03	0.4 ^{a} ±0.05	0.6 ^{b} ±0.04	0.3 ^{a} ±0.03	0.8 ^{c} ±0.06
22:5n-3	0.8 ^{c} ±0.01	1.2 ^{d} ±0.02	0.5 ^{a} ±0.01	0.7 ^{b} ±0.01	0.9 ^{b} ±0.05	1.5 ^{c} ±0.03	0.6 ^{a} ±0.04	1.0 ^{b} ±0.02
22:6n-3	7.1 ^{a} ±0.08	17.4 ^{d} ±0.26	8.5 ^{b} ±0.08	10.2 ^{c} ±0.03	7.3 ^{a} ±0.07	21.0 ^{d} ±0.11	9.7 ^{b} ±0.09	14.5 ^{c} ±0.40
∑ n-3	10.5 ^{a} ±0.03	22.5 ^{d} ±0.3	11.7 ^{b} ±0.09	16.6 ^{c} ±0.01	10.7 ^{a} ±0.22	27.1 ^{d} ±0.27	13.4 ^{b} ±0.20	22.1 ^{c} ±0.63
∑ n-6	7.9 ^{c} ±0.29	3.8 ^{a} ±0.44	3.1 ^{a} ±0.13	6.2 ^{b} ±0.21	8.5 ^{b} ±0.3	5.6 ^{a} ±0.4	4.6 ^{a} ±0.4	9.1 ^{b} ±0.3
∑ PUFA	18.4 ^{b} ±0.05	26.3 ^{d} ±0.06	14.8 ^{a} ±0.02	22.9 ^{c} ±0.29	19.3 ^{a} ±0.42	32.7 ^{b} ±0.58	18.1 ^{a} ±0.59	31.3 ^{b} ±0.07

It was evident in the present study that both dietary protein and lipid content influenced the performance of juvenile *A. australis*, and specifically that a dietary lipid level in excess of 20% had a negative influence on growth and food utilisation. Indeed it appears that juvenile *A. australis* perform relatively poorly when the dietary lipid level exceeds 15%, however the proximate composition of muscle tissue of *A. australis* maintained on the different dietary treatments in the present study are comparable to those reported for *A. anguilla* (Degani *et al.* 1986; Dosoretz and Degani 1987) and *A. rostrata* (Degani and Gallagher 1995) of a similar size range. In general, lipid levels in excess of 20% have been rarely tested for eels, although Dosoretz and Degani (1987) reported that adult *A. anguilla* grew better when the dietary lipid level was 30%. Clearly, this is an area which needs further investigation in respect of cultured eels for all species, including *A. australis.*

On the other hand, the present study appears to indicate that *A. australis* juveniles are capable of utilising diets with much higher soybean meal content than is the case for *A. anguilla* and *A. japonica*. Specifically, results of the present study indicate that soybean meal was relatively well digested by *A. australis*, as is the case for most finfish (Webster *et al.* 1992; Sadiku and Jauncey 1995; Boonyaratapalin *et al.* 1998), and that inclusion of soybean meal up to 20% by dry weight in the diet did not adversely affect the performance of *A. australis*.

By comparison, growth was retarded in *A. anguilla* when fed diets of 40% protein containing 10 and 20% soybean meal (Degani 1987; Degani and Gallagher 1995). This indicates that perhaps a relatively higher soybean meal content may be incorporated in *A. australis* diets as compared with diets for *A. anguilla* and *A. japonica*. However, these differences cannot be entirely accounted for in terms of content alone due to differences in soybean meal used in the respective diets. Also more recently, Garcia-Gallego *et al.* (1998) observed that *A. anguilla* utilised and digested diets incorporated with sunflower meal (supplemented with amino acids) better than those with meat meal. Certainly the relatively high digestibility of soybean meal incorporated test diet and soybean meal (ADM, PD and ED) *by A. australis* may be indicative of differences in the digestive physiology amongst cultured *Anguilla* species, and warrants further comparative studies on this important group. In general these results suggest that there are possibilities of practically reducing the cost of feeds for *A. australis* through the incorporation of agricultural by-products, and further research in this area is therefore also warranted.

Generally, high levels of ash and/or fibre (Cho and Slinger 1979; De Silva 1985; McGoogan and Reigh 1996), and the nitrogen-free extract (NFE) fraction (Gaylord and Gatlin 1996) in feed stuffs result in low ADM and PD. Similarly, the PD of an ingredient is not necessarily a reflection of the protein content of the ingredient (Nengas *et al.* 1995), although most ingredients with a high protein content results in high PD (McGoogan and Reigh 1996). The reduced PD of ingredients with high ash and/or fibre content has been attributed to a reduction in the activity of proteases (Falge *et al.* 1978) and shortened evacuation time (Steffens 1989). In the present study the lower ADM, PD and ED of meat meal exhibited by *A. australis* may have been due to the relatively high ash content in the diet. Certainly, the ADM, PD and ED of the meat meal incorporated diet, as well as that of the diet ingredients *per se*, were relative low in *A. australis* in the present study, such as for example compared to Murray cod (De Silva *et al.* 2000). This trend was also reflected in TEAAA, TNEAAA and TAAA of the meat meal incorporated diet for *A. australis*, in contrast to that in Murray cod (as well as compared to the other two ingredients in *A. australis*). As such it can be reasonably concluded that meat meal will not be suitable for incorporation into commercial compound diets for *A. australis*.

Glass eels have been weaned from natural to artificial diets under different weaning regimes, the primary aim being to familiarise and accustom the fish to new experiences in texture, taste, etc. Survival of glass eels to the elver stage following weaning, under intensive, commercial aquaculture conditions, is reported to range widely, between 20-95% (Heinsbroek 1989; Heinsbroek 1991; Gousset 1992). Therefore, an increase in survival and growth of glass eels is pivotal to the viability of the eel culture industry (Kamstra and Heinsbroek 1991), which often has to cope with irregularities in the supply of seed stock from the wild Wood 1999). Although pre-glass eel larval stages (leptocephali) are known to ingest food material (Tanaka *et al.* 1995), there appears to be a fasting period during the subsequent metamorphosis stage (Tesch 1977), and in most respects the weaning of glass eels is considered analogous to the first feeding of fish larvae following yolk-sac resorption.

Eels are comparatively slow growing in the early stages of life. For example, it has been estimated that *A. anguilla* takes approximately 448 days, from the time of hatching, to arrival at estuaries, and *A. rostrata* takes 255 days, with growth rates of 0.15 and 0.21 mm day^{-1}, respectively (Wang and Tzeng 2000). Age estimates of smaller *A. australis* glass eels collected in the present study suggest a somewhat shorter migration period, but still range in the order of 150-200 days (see Chapter 2). The fortnightly SGR of eels maintained on different types of fish roe differed, with the best results being obtained from feeding carp and warehou roe after the initial period of the experiment. In previous studies on weaning of glass eels, of both *A. australis* and other species of anguillid eels also, a decline in body weight has been reported, irrespective of the food type tested (Degani 1986; Heinsbroek 1989; Appelbaum *et al.* 1998; Gooley *et al.* 1999; Birrell *et al.* 2000) (see also Chapter 3).

Previous studies have shown that SGR of glass eels is highly variable. Gooley *et al.* (1999) and Ingram *et al.* (2001) attributed the wide range in SGR for juvenile *A. australis* (-2.1 to 3.6 % day^{-1}) to the wide range of conditions to which the eels were exposed during experimentation. Growth rates reported for glass eels and elvers under various culture conditions range from 0.5 to 2.8 % day^{-1} and 0.6 to 4 % day^{-1} for *A. anguilla* (Heinsbroek 1991; Kamstra and Heinsbroek 1991), and *A. japonica* (Heinsbroek 1991; Gousset 1992) eels, respectively. In the experiments on *A. anguilla* and *A. japonica*, the mean weight of glass eels at the commencement of the studies were 20 to 35% higher than in the present study on *A. australis*. It may be that *A. australis* glass eels, by virtue of their smaller size, take longer to start gaining weight at weaning.

Results from the present study confirm that the performance of glass eels was affected by the roe type. Indeed, the roes tested from the different species differed in their physical characteristics and stage of maturity, as well as the proximate, amino acid and fatty acid composition. The oocyte size of the four roe types also differed significantly, which was at least partially a reflection of the stage of maturity of each type. All oocytes were ingested however, and it is unlikely that oocyte size or the maturity stage of the roe were factors that directly affected the performance of glass eels, as there was no recognisable trend in the performance of glass eels in regard to these two criteria.

Important differences were also evident in the protein content of the roe and the oocytes used in the present study, and in the associated amino acid and fatty acid profiles. In general, carp roe and oocytes had a much higher amino acid content, and the amount of both essential amino acid (EAA) and non-essential amino acid content was higher than in the other three roes and oocytes. On the other hand, the minimal differences amongst the E/A ratios of the four types of roe tested is an indirect indication that nutritionally the differences are minor in regard to EAA. The similarity of the E/A ratios to that of the whole body of glass eels and

elvers (data not shown) would suggest that the roe types used are nutritionally adequate with regard to the EAA requirements of eels (Arai 1991).

The importance of the highly unsaturated fatty acids, in particular eicasopentaenoic acid (EPA; 20:5n-3) and docosahexaeonic acid (DHA; 22:6n-3), and arachidonic acid (AA; 20:4n-6), in the survival and well being of first feeding marine fish larvae is well documented (Watanabe 1993; Sargent *et al.* 1997). In glass eels the situation is further complicated as they are in a transition phase from a marine to a freshwater habitat, and it is known that during this transition the body fatty acid profile changes gradually, from that of a typical marine profile with a relatively high n-3 to n-6 ratio, to that of a freshwater profile in elvers, with a low n-3 to n-6 ratio (De Silva *et al.* 1997). A comparable trend was evident with regard to the DHA to AA ratio, of both metamorphosing glass eels (De Silva *et al.* 1997) and the roe and oocyte types tested in the present study. It may be that glass eels require more n-6 HUFA during metamorphosis. The n-3 to n-6 ratio of roe and oocytes increased in order, carp < warehou < orange roughy < mirror dory. This may be indicative of a deficiency of n-6 fatty acids in orange roughy and mirror dory roe and oocytes, and may have been responsible for the relatively poor performance of glass eels fed these roe types. The importance of high AA content in the diet and the proper ratio of n-3 to n-6 in growth and survival have also been demonstrated for other fish species, such as turbot (Castell *et al.* 1994; Bell *et al.* 1994).

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4.6 REFERENCES

Appelbaum, S., Chernitsky, A. and Birkan, V. (1998). Growth observations on European (*Anguilla anguilla* L.) and American (*Anguilla rostrata* Le Sueur) glass eels. *Bulletin Francais de La Peche et de La Pisciculture* 349: 187-193.

Arai, S. (1991). Eel, *Anguilla* spp. In: *Handbook of Nutrient Requirements of Finfish* (ed. by R.P. Wilson), pp 69-77. CRC Press, London.

Bell, J.G., Castell, J.D., Tocher, D.R., MacDonald, F.M. and Sargent, J.R. (1994). Effects of different dietary arachidonic: docosahexaenoic acid ratios on phospholipid fatty acid composition and prostaglandin production in juvenile turbot (*Scophthalmus maximus*). *Fish Physiology and Biochemistry* 14: 139-151.

Beumer, J.P. (1979). Feeding and movement of *Anguilla australis* and *A. reinhardtii* in Macleods Morass, Victoria, Australia. *Journal of Fish Biology* 14(6): 573-592.

Birrell, L., Cramb, G. and Hazon, G. (2000). Osmoregulation during the development of glass eel and elvers. *Journal of Fish Biology* 56: 1450-1459.

Boonyaratapalin, M., Suraneiranat, P. and Tunpibal, T. (1998). Replacement of fish meal with various types of soybean products in diets for the Asian seabass, *Lates calcarifer*. *Aquaculture* 161: 67-78.

Castell, J.D., Bell, J.G., Tocher, D.R. and Sargent, J.R. (1994). Effects of purified diets containing different combinations of arachidonic and docosahexaenoic acid, on survival, growth and fatty acid composition of juvenile turbot (*Scophthalmus maximus*). *Aquaculture* 128: 315-333.

Chisnall, B.L. (1989). Age, growth, and condition of freshwater eels (*Anguilla* sp.) in backwaters of the lower Waikato River, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 23(4): 459-465.

Chisnall, B.L. and Hayes, J.W. (1991). Age and growth of shortfinned eels (*Anguilla australis*) in the lower Waikato basin, North Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 25(1): 71-80.

Chisnall, B.L. and Kalish, J. (1993). Age validation and movement of freshwater eels (*Anguilla dieffenbachii* and *A. anguilla*) in a New Zealand pastoral stream. *New Zealand Journal of Marine and Freshwater Research* 27: 333-338.

Cho, C.Y. and Slinger, S.J. (1979). Apparent digestibility measurements in feedstuffs for rainbow trout. In: *Finfish Nutrition and Fish Feed Technology. Proceedings of a World Symposium , Vol. 2* (ed. by J.E. Halver and K. Tiews), pp 239-247. Heenemann, Berlin.

De Silva, S.S. (1985). Evaluation of the use of internal and external markers in digestibility studies. In: *Finfish Nutrition in Asia. Methodological Approaches to Research and Development* (ed. by C.Y. Cho, C.B. Cowey and T. Watanabe). International Development Research Centre, Canada.

De Silva, S.S., Gunasekera, R.M., Collins, R., Ingram, B.A. and Austin, C.M. (1997). Changes in the fatty acid profile of the Australian shortfin eel in relation to development. *Journal of Fish Biology* 50(5): 992-998.

De Silva, S.S., Gunasekera, R.M. and Gooley, G. (2000). Digestibility and amino acid availability of three protein-rich ingredient-incorporated diets by Murray cod *Maccullochella peelii peelii* (Mitchell) and the Australian shortfin eel *Anguilla australis* Richardson. *Aquaculture Research* 31: 195-205.

De Silva, S.S., Gunasekera, R.M., Gooley, G.J. and Ingram, B.A. (2001a). Growth of Australian shortfin eel (*Anguilla australis*) elvers given different dietary protein and lipid levels. *Aquaculture Nutrition* 7(1): 53-57.

De Silva, S.S., Gunasekera, R.M., Ingram, B.A. and Dobson, J.L. (2001b). Weaning of Australian shortfin glass eels (*Anguilla australis*): a comparison on the effectiveness of four types of fish roe. *Aquaculture* 195: 133-148.

Degani, G. (1986). Dietary effects of lipid source, lipid level and temperature on growth of glass eel (*Anguilla anguilla*). *Aquaculture* 56(3-4): 207-214.

Degani, G. (1987). Effect of replacement of fish and chicken meals by soybean meal in a purified diet on growth and body composition of juvenile European eel, *Anguilla anguilla*. *Indian Journal of Fisheries* 34(2): 213-217.

Degani, G. and Gallagher, M.L. (1995). *Growth and Nutrition of Eels*. Laser Pages Publishing Ltd, Jerusalem. 119 pp.

Degani, G., Migal, D.L. and Gallagher, M.L. (1988). Relationship between growth, food conversion, body size, body composition and temperature in the European eel, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 19(2): 139-143.

Degani, G., Viola, S. and Levanon, D. (1986). Effects of dietary carbohydrate source on growth and body composition of the European eel (*Anguilla anguilla* L.). *Aquaculture* 52(2): 97-104.

Dosoretz, C. and Degani, G. (1987). Effect of fat-rich diet and temperature on growth and body composition of European eels (*Anguilla anguilla*). *Comp. Biochem. Physiol.* 87A(3): 733-736.

Falge, R., Schpanof, L. and Jurss, K. (1978). Amylase, esterase and protease activity in the intestine content of rainbow *Salmo gairdneri* Rich., after feeding with feed containing different amounts of starch and protein. *Journal of Ichthyology* 18: 283-287.

Gallego, M.G., Bazoco, J., Akharbach, H., Suarez, M.D. and Sanz, A. (1994). Utilization of different carbohydrates by the European eel (*Anguilla anguilla*). *Aquaculture* 124(1-4): 99-108.

Garcia-Gallego, M., Akharbach, H. and de la Higuera, M. (1998). Use of protein sources alternative to fish meal in diets with amino acids supplementation for the European eel (*Anguilla anguilla*). *Animal Science* 66: 285-292.

Gaylord, T.G. and Gatlin, D.M. (1996). Determination of digestibility coefficients of various feedstuffs for red drum (*Sciaenops ocellatus*). *Aquaculture* 139: 303-314.

Gooley, G.J. (1998). Eels. In: *The New Rural Industries - A Handbook for Farmers and Investors* (ed. by K. Hyde), pp 101-107. Rural Industries Research and Development Corporation, Canberra.

Gooley, G.J., McKinnon, L.J., Ingram, B.A., Larkin, B., Collins, R.O. and de Silva, S.S. (1999). *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production. Final Report FRDC Project No 94/067*. Marine and Freshwater Resources Institute, Alexandra, Australia. 124 pp.

Gousset, B. (1992). *Eel Culture in Japan*. Bulletin de l'Institut océanographique, Monaco, no spécial 10, Monaco. 128 pp.

Heinsbroek, L.T.N. (1989). Preliminary investigations on husbandry, nutrition and growth of glass eels and elvers, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 20: 119-127.

Heinsbroek, L.T.N. (1991). A review of eel culture in Japan and Europe. *Aquaculture and Fisheries Management* 22: 57-72.

Ingram, B.A., Gooley, G.J., De Silva, S.S., Larkin, B.J. and Collins, R.A. (2001). Preliminary observations on the tank and pond culture of the glass eels of the Australian shortfin eel, *Anguilla australis* Richardson. *Aquaculture Research* 32: 833-848.

Jellyman, D.J. (1979). Scale development and age determination in New Zealand freshwater eels (*Anguilla* spp.). *New Zealand Journal of Marine and Freshwater Research* 13: 23-30.

Jellyman, D.J. (1989). Diet of two species of freshwater eel (*Anguilla* spp.) in Lake Pounui, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 23(1): 1-10.

Kamstra, A. and Heinsbroek, L.T.N. (1991). Effects of attractants on start of feeding of glass eel, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 22(1): 47-56.

Kastelein, P. (1983). Survival and growth of elvers (*Anguilla anguilla* L.) reared on an expanded granulated diet. *Aquaculture* 30(1-4): 155-172.

Kuhlmann, H. (1979). The influence of temperature, food, initial size, and origin on the growth of elvers (*Anguilla anguilla* L.). *J. du Conseil* 174: 59-63.

McGoogan, B.B. and Reigh, R.C. (1996). Apparent digestibility of selected ingredients in red drum (*Sciaenops ocellatus*) diets. *Aquaculture* 141: 233-244.

Nengas, I., Alexis, M.N., Davies, S.J. and G., P. (1995). Investigation to determine digestibility coefficients of various raw materials in diets for gilthead sea bream, *Sparus auratus* L. *Aquaculture Research* 26: 185-194.

Ngamsnae, P., De Silva, S.S. and Gunasekera, R.M. (1999). Arginine and phenylalanine requirement of juvenile silver perch *Bidyanus bidyanus* and validation of the use of body amino acid composition for estimating individual amino acid requirements. *Aquaculture Nutrition* 5(3): 173-180.

Ryan, P.A. (1984). Diel and seasonal feeding activity of the short-finned eel, *Anguilla australis* schmidtii, in Lake Ellesmere, Canterbury, New Zealand. *Environ. Biol. Fish.* 11(3): 229-234.

Ryan, P.A. (1986). Seasonal and size-related changes in the food of the short-finned eel, *Anguilla australis* in Lake Ellesmere, Canterbury, New Zealand. *Environmental Biology of Fishes* 15: 47-58.

Sadiku, S.O. and Jauncey, K. (1995). Digestibility, apparent amino acid availability and waste generation potential of soybean flour: poultry meat meal blend based diets for tilapia, *Oreochromis niloticus* (L.), fingerlings. *Aquaculture Research* 26: 651-657.

Sargent, J.R., McEvoy, L.A. and Bell, J.G. (1997). Requirements, presentation and sources of polyunsaturated fatty acids in marine fish larval diets. *Journal of Applied Ichthyology* 11: 183-198.

Sloane, R.D. (1984a). Distribution, abundance, growth and food of freshwater eels (*Anguilla* spp.) in the Douglas River, Tasmania. *Australian Journal of Marine and Freshwater Research* 35(3): 325-339.

Sloane, R.D. (1984b). Distribution and abundance of freshwater eels (*Anguilla* spp.) in Tasmania. *Australian Journal of Marine and Freshwater Research* 35(4): 463-470.

Steffens, W. (1989). *Principles of Fish Nutrition*. Ellis Harwood Ltd., Chichester, UK. 384 pp.

Tanaka, H., Kagawa, H., Ohta, H., Okuzawa, K. and Hirose, K. (1995). The first report of eel larvae ingesting rotifers. *Fisheries Science* 61(1): 171-172.

Tesch, F.-W. (1977). *The Eel. Biology and Management of Anguillid Eels*. Chapman and Hall, London. 434 pp.

Tibbetts, S.M., Lall, S.P. and Anderson, D.M. (2000). Dietary protein requirement of juvenile American eel (*Anguilla rostrata*) fed practical diets. *Aquaculture* 186(1-2): 145-155.

Wang, C.H. and Tzeng, W.N. (2000). The timing of metamorphosis and growth rates of American and European eel leptocephali: A mechanism of larval segregative migration. *Fisheries Research* 46: 191-205.

Watanabe, T. (1993). Importance of docosahexaenoic acid in marine fish larvae. *Journal of the World Aquaculture Society* 24: 152-161.

Webster, C.D., Yancey, D.H. and Tidwell, J.H. (1992). Effect of partially or totally replacing fish meal with soybean meal on growth of blue catfish (*Ictalurus furcatus*). *Aquaculture* 103: 141-152.

Wilson, R.P. (1994). Utilization of dietary carbohydrate by fish. *Aquaculture* 124(1-4): 67-80.

Wilson, R.P. and Poe, W.E. (1985). Relationship of whole body and egg essential amino acid patterns to amino acid requirement patterns in channel catfish, *Ictalurus punctata*. *Comp. Biochem. Physiol.* 80B: 385-388.

Wood, P. (1999). What crisis? *Fish Farming International* 26 March 1999: 11.

Zar, J.H. (1984). *Biostatistical Analysis*. Prentice-Hall, Englewood Cliffs, N.J. 718 pp.

5 PRELIMINARY ASSESSMENT OF THE AQUACULTURE POTENTIAL OF THE AUSTRALIAN LONGFIN EEL (*ANGUILLA REINHARDTII*)

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Jones, C.M. (2002). Preliminary assessment of the aquaculture of the Aquaculture potential of longfin eel, *Anguilla reinhardtii*. In: *Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture* (ed. G.J. Gooley and B.A. Ingram), pp 137-182. Final Report to Fisheries Research and Development Corporation (Project No. 97/312 and No. 99/330). Marine and Freshwater Resources Institute, Alexandra, Victoria, Australia.

CONTENTS

5.1 INTRODUCTION

5.1.1 Background

Interest in the aquaculture of Australian eel species developed in the mid 1990's as glass eel catches in Asia and Europe were continuing to decline (O'Sullivan 1997). 'Farmability' of the Australian species had not previously been examined. In addition to assessment of glass eel availability, evaluation of growout potential and requirements was necessary to fully assess the aquaculture potential. Research had already begun in Victoria to assess growout of shortfin eel *Anguilla australis* (Gooley *et al.* 1999), but no information had been generated for the longfin eel *A. reinhardtii*. Accordingly, FRDC Project No. 97/312 entitled *Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture* was designed specifically to address this need (see Chapter 1, Section 1.31 for further details). Furthermore a supplementary project, FRDC No. 99/330, entitled *Validation of Longfin Eel Aquaculture Potential* was initiated to extend the term of the longfin eel aquaculture component of the original project by an additional 12 months. For convenience, final reporting for both projects has been consolidated into this single Chapter. All longfin eel aquaculture R&D for both projects (FRDC No. 97/312 and 99/330) was managed from the Freshwater Fisheries and Aquaculture Centre at Walkamin, north Queensland.

5.1.2 Research objectives

Little was known about the specific requirements of Australian longfin eel, and consequently initial culture procedures were based upon techniques which were developed elsewhere for species such as the Japanese eel, *A. japonicus* and the European eel, *A. anguilla* (Heinsbroek 1991; Usui 1991). The primary objective of the research was to apply best practice as defined for other established commercial species, and identify baseline production characteristics for longfin eel under semi-intensive management.

In addition to baseline production assessment, specific experiments were designed to investigate production parameters and husbandry requirements to achieve the following specific objectives.

- Determine suitable glass-eel handling procedures and weaning of glass eels to formulated diets
- Assess the efficacy of a variety of commercial fish and eels diets for the production of longfin eels, and as a consequence provide guidelines for future nutrition research
- Examine the effects of density on tank production of eels, and define optimal densities
- Investigate strategies for stocking eels to ponds to maximise their subsequent performance
- Determine the optimal temperature for growing longfin eels
- Assess the relative importance of artificial shelters on the production of longfin eels
- Examine impacts of size grading and relative performance of different size grades of eels
- Define baseline health management protocols for longfin eels in tanks and ponds

5.2 MATERIALS AND METHODS

This research was conducted at the Freshwater Fisheries and Aquaculture Centre at Walkamin (17.1°S, 145.5°E), approximately 70km west of Cairns in northeastern Australia.

Water temperatures in earthen ponds at Walkamin remain in the range of 25 to31°C for most of the year, and only fall below 20°C during a brief winter period of no more than 8 weeks. Consequently, the potential to achieve good growth rates for a tropically distributed species such as longfin eel, under semi-intensively managed pond conditions, was considered to be high. Although it was clear that early life stages from glass eel to small elver would be cultured in tanks, the thrust of the research was to assess and develop production technologies for the pond culture of longfin eels.

Industrial development of intensive culture of longfin eel in recirculation systems was occurring at the time of this research, providing an opportunity to compare the efficacy of this approach with pond culture. Such comparisons made during the course of this research were made on an informal basis and were qualitative. As the relative costs of establishment and operation would be significantly different, any formal comparison must be based on the economics of each approach. Economic analyses were not undertaken in this study, and the comparisons made must be considered indicative only.

The nature of eel aquaculture involves a reliance on supply of glass eels or elvers from the wild. For Australia, the resource assessment research and commercial catches over recent years indicated a limited and unpredictable supply of longfin glass eels. As eel aquaculture research is also reliant on such supply, experimentation for this study was necessarily

opportunistic, utilising eels when they were available. Longfin glass eels used for this study were supplied on two occasions as detailed in Table 5.1.

Table 5.1. Supply details for longfin glass eels used for this study.

Date	Source	Total weight	Number	Size
9/3/98	Albert River	16,773g	139,775	0.12
5/2/99	Albert River	3,060g	27,817	0.11

Although handling methods were improved with successive deliveries of eels, the procedures applied generally followed the sequence detailed below.

- Glass eels transported in 5ppt saline, oxygen saturated water, at approximately 1kg biomass per 20 L of water, in plastic bags housed in styrofoam boxes.
- On arrival, bags floated into 2000l round tanks of freshwater on flowthrough supply to allow temperature acclimation for 20 minutes. Directional flow established to generate a gentle circulating current around tank, and aeration supplied via several airstones.
- Bags opened and emptied into tank. Glass eels allowed to settle for 30 minutes.
- Water flow stopped, and salt added to tank to a concentration of 10ppt.
- Formalin added to tank to a concentration of 150ppm, left for 60 minutes.
- Water flow (20 L min^{-1}) turned on to allow progressive flushing of salt and formalin from system.
- No other intervention other than hourly observations made for following 24 hours.
- Feeding initiated using fish roe in combination with formulated diet (fish crumble)

Subsequent to this receival procedure, glass eels were introduced to experimental conditions as described in detail for each experiment. A proportion of each batch of glass eels received were not required for specific experimentation, and were reared as per documented commercial procedures as gleaned from the literature (Degani *et al.* 1984; Degani 1986; Degani and Levanon 1986; Degani *et al.* 1986; Degani *et al.* 1988a; Kamstra and Heinsbroek 1991; Ingram and Gooley 1996; Gooley *et al.* 1999) and local industry experience. These non-replicated assessment trials were secondary to the experiments performed, and were not rigorously quantified. Nevertheless, they provided useful information which is reflected in the discussions.

Unless otherwise stipulated, all tank based research was conducted using flow through water supplied from a bore. Basic water quality parameters were measured regularly by the following means; temperature, dissolved oxygen and pH by electronic probe (TPS FL90), nitrite and ammonia by spectrophotometer (Palintest).

Pond-based experiments were performed in a series of small research ponds of identical specification. They were 216m^2 (12m x 18m) in surface area, with a V-shaped cross section whose maximum depth was 1.0m at one end of the pond, falling to 1.6m at the deepest point. Pond volume (of water) at normal operating depth was 300,000 L (300 m^3). The ponds were lined with a synthetic (HDPE) liner, over which 250mm of top soil and clay was placed, in

the deepest 30% of the bottom surface area. This soil was included as a source for primary production of planktonic organisms, and as a buffer against water quality perturbations (particularly pH). Ponds were equipped with an inlet of water from a reservoir of irrigation-quality water, and outlet structures to facilitate either in-pond or external harvesting of pond stock. Aeration was provided by means of a single, 1hp electric aspirator (Eolo, Aquaculture Inc), operated for 12 hours per day from 4pm until 8am.

Unless otherwise specified, for pond experiments feeding of pellets was performed twice each day (am and pm) by hand broadcasting food around the inlet structure of the pond, over an area of approximately 10m².

Water quality was checked weekly, and when necessary, the ponds were flushed with new water to replace 5 to 10% of the pond volume within 24 hours. Occasionally higher exchange rates of up to 30% of pond volume within 24 hours were applied if conditions dictated.

Harvesting of ponds was performed by draining the pond and flushing all stock through the outlet to an external fish-out box equipped with a net. Eels were weighed (in total) and counted, and mean weights were determined by division of total biomass by number. Individual weights of eels were taken as specified for each experiment.

Standardised methods for quantifying the performance of eels under different management circumstances were confounded to some extent by the broad range in size of stock used (from glass eel to large 1kg + eels), the culture environment provided (from tanks to ponds) and the period of culture (from short experiments over several weeks to growout trials over many months). Eel biology further compounds the problem by virtue of extremely variable growth rates which diminish the interpretive value of statistics such as mean size at harvest. These difficulties were assessed through the progress of this project, and expression of results evolved. To standardise comparison of eel performance across all the experiments and variables applied, estimates of survival, specific growth rate and food conversion ratio were provided in addition to measures of harvest weight and biomass.

Specific growth rate (SGR) was measured as: $(\text{Ln}(Wt_t) - \text{Ln}(Wt_0)) / t \times 100$,

where,
- Ln is the natural logarithm
- Wt_t is the mean weight at time t
- Wt_0 is the mean weight at time 0
- t is the period of growth in days

SGR was expressed as percentage growth per day (% d^{-1}).

Food conversion ratio (FCR) was measured as: (Dry weight of food supplied) / (Increase in wet weight biomass).

Statistical analysis primarily involved analysis of variance using Genstat 5 Release 4.1 (Lawes Agricultural Trust). All ANOVA's were validated by examining residual plots. Means comparisons were performed for all significant ANOVA's ($P < 0.05$) by application of the Least Significant Difference test. Other data manipulations and calculations were performed using Microsoft Excel (97 SR-2).

5.3 GLASS EEL WEANING

5.3.1 Introduction

Early feeding experience of glass eels is clearly critical to the subsequent performance of elvers and eels through the growout process (Bronzi and Zaffignani 1990; Gooley *et al.* 1999). A variety of 'first feeds' have been successfully used for different eel species prior to their weaning to a formulated diet. An experiment was designed to assess the impact of four first feed types on growth and survival of longfin glass eels through the weaning process to a formulated diet.

5.3.2 Experiment 1. Assessment of pre-weaning diet.

5.3.2.1 Materials and Methods

A randomised block design was applied using four feeding treatments and four replicates. Sixteen, sixty litre round plastic tubs were used as the experimental units, each with 40 L of water. Four tubs were placed in each of four 2500 L fibreglass tanks (blocks), and equipped with water and air supply. Inlets and outlets of each tub were screened with 1.5mm mesh to prevent escape of stock. Water flow was adjusted to provide for a complete water exchange every hour.

Four feed treatments were i) live black worm (*Lumbriculus* sp.), ii) frozen mackerel roe, iii) frozen zooplankton (harvested from ponds) and iv) fresh *Artemia* nauplii. Formulated diet used was a commercial salmonid diet in fine crumble form.

Previously unfed glass eels (0.132g ± 0.002) were stocked at a rate of 200g per tub (equivalent to 3.3 kg m^{-3}, approximately 1,667 glass eels). Individual weight and length were measured for sample of 50 glass eels from each tank at the beginning of the experiment and at regular intervals thereafter until harvest.

After stocking the water flow was turned off and each tub was treated with formalin at a rate of 150ppm for 60 minutes. Water flow was then turned on to allow gradual flushing out of formalin. No food was provided during the first 24 hours. Feeding was commenced on day 2 at a rate of 18g (dry weight) of the treatment diet and 2g of formulated crumble per tub provided at 2 feeds (morning and afternoon). The formulated diet was provided from the outset, as this improves the effectiveness of weaning when the primary diet is removed. This ratio of treatment and formulated diet was maintained for each day through to day 8. On day 9 weaning was initiated by substituting 2g of the treatment diet with the formulated diet. For each subsequent day, a further 2g of the daily ration (on a dry weight basis) was provided as the formulated diet, until day 14 when the entire ration was formulated diet for every tub.

Maximum and minimum temperature, dissolved oxygen, pH and total ammonia nitrogen were measured once per week.

The experiment was initiated on March 13, 1998 and ran for 112 days.

5.3.2.2 Results

Water quality remained at acceptable levels throughout this experiment.

Statistics for the growth and survival of glass eels are presented in Table 5.2. The first sample of glass eels was taken at day 19, four days after weaning was completed. At this time a significant difference ($P < 0.05$) in weight was measured, such that weight for zooplankton and *Artemia* treatments were significantly less than for fish roe. By day 33, the difference in weight had disappeared, presumably due to the mortality of the smallest glass eels in the zooplankton and *Artemia* treatments. Figure 5.1 shows the mean size of glass eels during the first 33 days of the experiment. The difference in mean weight was not apparent at any subsequent sample including harvest ($P > 0.01$). Figure 5.2 depicts mean size for the entire experimental period.

Survival was significantly different ($P < 0.05$) between treatments. LSD analysis indicated a significantly lower survival for zooplankton treatment than all others (Figure 5.3).

5.3.2.3 Discussion

It is worthy of note that the mean weight at day 33 was not significantly different to that at day 0. It must be emphasised that the glass eel is initially a non-feeding stage (Usui 1991). During the first few weeks of feeding, as encompassed by this experiment, there are major physiological and morphological changes, including the development of the gut and other organs. The lack of any net increase in weight does not necessarily reflect inadequate feeding or development.

Although there was no significant difference in harvest weight between the treatments, the longterm impact of the pre-weaning diets on subsequent growth and survival may have been more significant. It was not possible to continue this experiment to determine the longterm performance of the eels, however, the negative growth experienced with the zooplankton and Artemia diets suggests that they should be avoided as pre-weaning diets. Fish roe and blackworms can be considered superior. Given the ease of sourcing fish roe relative to cultured black worms, fish roe will be the preferred choice of pre-weaning diet for longfin glass eels for all subsequent production.

Table 5.2. Summary statistics for glass eels weaned from four different pre-weaning diets to a formulated diet.

Treatment	Black worm	Fish roe	Zooplankton	*Artemia*
Weight @ day 19 (g)	0.1176 [a]	0.1273 [ab]	0.0967 [bc]	0.1105 [c]
Harvest weight (g ± se)	0.299±0.023[a]	0.272±0.012[a]	0.305±0.011[a]	0.289±0.017[a]
Harvest length (mm ± se)	62.42±1.18 [a]	61.15±0.81[a]	63.23±0.28 [a]	61.95±0.75 [a]
Survival (%)	96.4 [a]	96.4 [a]	89.5 [b]	94.5 [a]

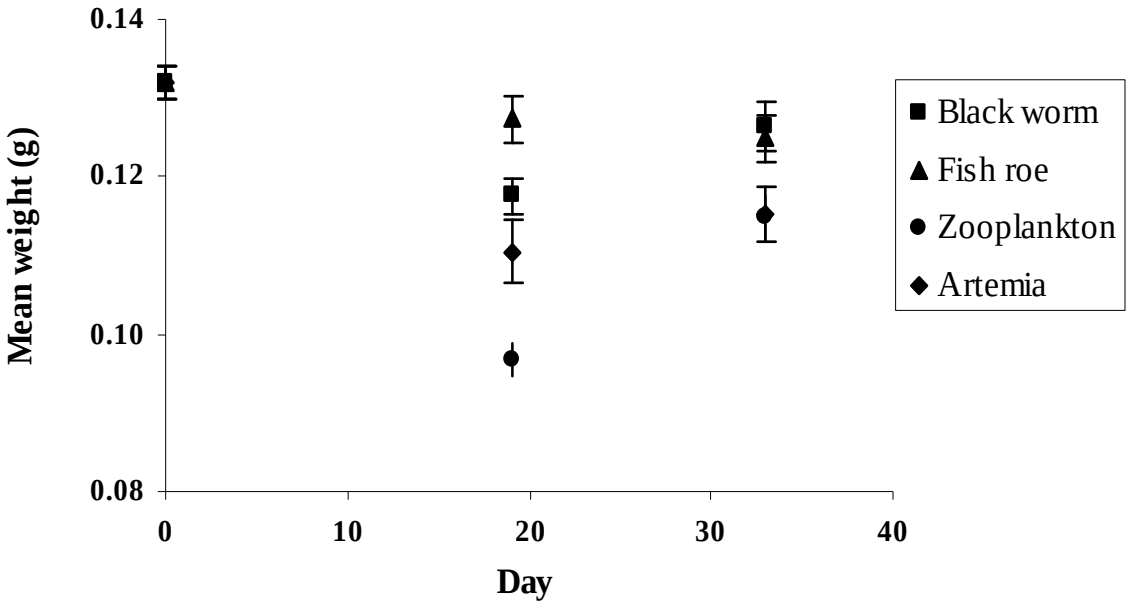

Figure 5.1 Mean weight (± s.e.) of longfin glass eels over 33 days during weaning from one of four pre-weaning diets to a formulated crumble**.**

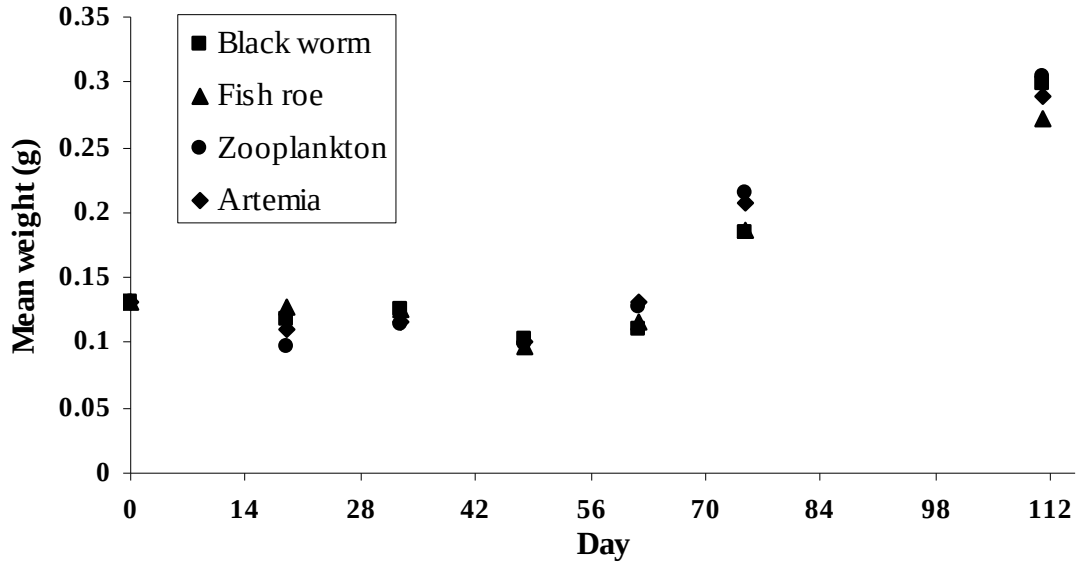

Figure 5.2 Mean weight of longfin eels for 70 days subsequent to that depicted in Figure 5.1.

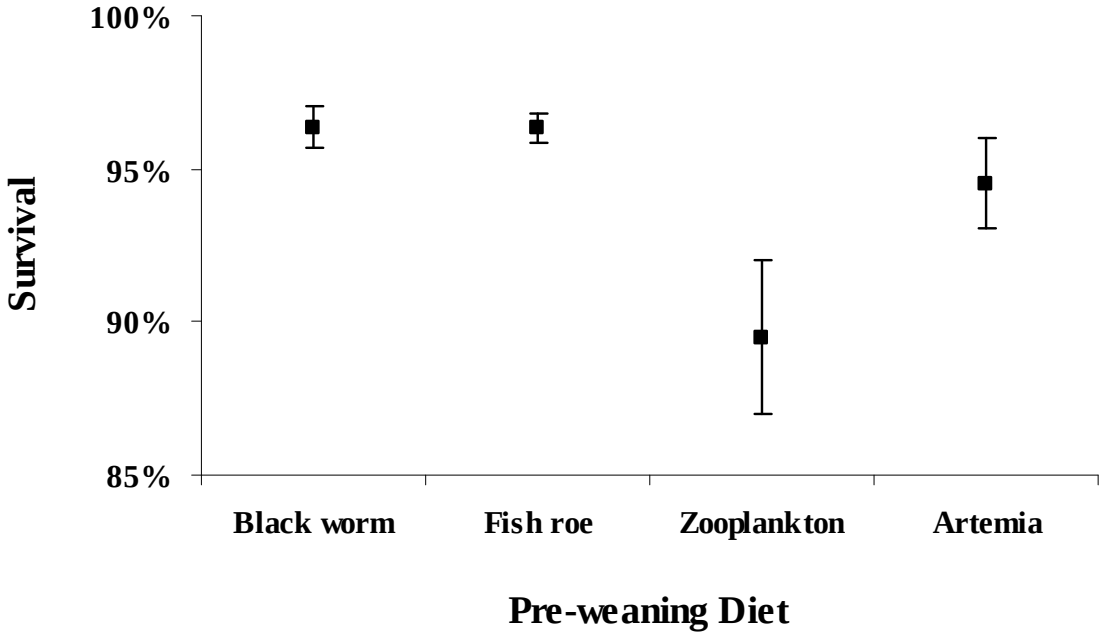

Figure 5.3 Survival (mean ± s.e.) of glass eels fed four different pre-weaning diets.

5.4 ELVER CULTURE

5.4.1 Introduction

Successful weaning of glass eels should result in actively feeding, rapidly growing eels. This transitionary stage after the glass eel stage is generally referred to as the elver. For our purposes, eels which had been successfully weaned on to a formulated diet, and which were in the size range of 0.13g to around 10g were referred to as elvers, and the specific husbandry applied to their production was referred to as elver culture. Once elvers reach approximately 10g they are suitable for stocking to growout.

It was clear from examination of the literature (Kastelein 1983; Degani *et al.* 1988b) that during the elver stage it is desirable to maintain active feeding and growth, to ensure subsequent rapid growth through to marketable sizes. It is common experience in the commercial cultivation of European and Japanese eels that a proportion of elvers do not perform well and their growth may stagnate for prolonged periods. This proportion of 'runts' varies in magnitude under different management practices and from one batch of eels to another, but it can be minimised if appropriate husbandry is applied.

By undertaking a series of experiments, it was aimed to define appropriate husbandry for the successful elver culture of longfin eels.

5.4.2 Experiment 1. Assessment of diet on growth and survival.

5.4.2.1 Materials and Methods

It was the aim of this experiment to determine the affect of diet on the survival, growth rate and size variability of longfin elvers, and generate further data for defining baseline production characteristics of longfin eels.

The scope of this study did not permit application of a nutrient-based approach to the development of a suitable diet for longfin eel. Although formulated diets specific to Australian eels were being investigated by some research agencies and feed manufacturers, there was an industry perception that commercial, formulated eel diets from overseas, or commercial fish diets from Australia may be the best option until formal nutrition research was undertaken. An additional factor was the form of the diet. Asian eel culture had traditionally used, with great success, a semi-moist dough for delivery of food, while the European approach used a conventional dry, steam-pressed pellet. These factors were considered in designing this initial experiment which examined three diets; i) a commercial Japanese eel dough diet, ii) a commercial salmonid pellet diet and iii) an experimental pellet diet designed for, and successfully tested on shortfin eel (De Silva, *pers. comm.*). Proximate composition of the diets is listed in Table 5.3.

A randomised block design was applied using the three treatment diets as described with four replicates. The experiment was performed in 12 x 500 L round fibreglass tanks (1.2m diameter), equipped with a flow-through water supply sourced from a bore. Each tank was plumbed to generate a circular current around the tank which at a delivery rate of 20 L min^{-1} created a current of approximately 10 cm s^{-1}. A central standpipe equipped with a removable 1mm mesh screen was used for the outlet. Two 25mm airstones were placed in each tank to provide aeration.

Table 5.3 Proximate composition (%) of diets fed to longfin elvers**.**

	Shortfin diet	Japanese Dough	Salmonid diet
Protein	52	48	51
Fat	12	7	14
Ash	10	15	12
Crude Fibre	3	1.2	4.1
Carbohydrate			13.7

A quantity of 784g (approximately 6,237) elvers (0.13g) which had been previously weaned to a commercial salmonid crumble diet from a pre-weaning diet of fish (mackerel) roe were stocked to each tank. Individual weight and length of 100 elvers from each tank was measured immediately after stocking and thereafter at approximately 14 day intervals.

Feeding was initially based on a fixed schedule of 8% of biomass per day, provided in two feeds in the morning and afternoon. This rate was adjusted according to observation, but kept consistent within each treatment. All feed measurements were on a dry weight basis. The dough diet was mixed with water at a rate of 10% water, after weighing. Tuna oil was added to the dough after mixing at a rate of 2%. To stimulate a strong feeding response, fish roe was provided at the time of feeding over the first 23 days. Initially, roe was provided at a rate of 10% of biomass (wet weight basis) per day, progressively reduced to 1% by day 23.

To provide estimates of food conversion, the quantity of uneaten food was estimated by visual assessment and subtracted off the quantity offered to provide a measure of food consumed. This was straightforward for the shortfin and salmonid diets for which uneaten food remained relatively intact. The dough however completely disintegrated after feeding and no estimate of the uneaten proportion could be made.

Maximum and minimum water temperature, dissolved oxygen, pH, total ammonia nitrogen and nitrite were measured weekly.

The experiment was commenced on March 17, 1998 and terminated after 99 days.

5.4.2.2 Results

Water quality remained at a high standard throughout the experimental period, and was consistent through all tanks. Water temperature ranged from 23.0 to 28.3°C with a mean of 25.2°C. Mean pH and dissolved oxygen were 6.8 and 6.3 ppm respectively.

It was necessary to discontinue the use of the experimental shortfin diet after 29 days (April 15) due to its clear inadequacy as a diet for longfin eels. Eels fed this diet lost condition progressively and quickly, and mortality became significant. At day 29 they were significantly smaller ($P < 0.001$) than those fed either of the other treatments (Figure 5.4) (Table 5.4), and 14% had died compared with 2.7% and 1.0% for the dough and salmonid diets respectively. Rather than lose the remaining stock for this treatment and gain no further information, the experimental shortfin diet was replaced with the salmonid diet (treatment ii) above) for the subsequent duration of the trial.

Table 5.4 Summary statistics (means ± s.e.) for elvers fed one of three diets over 99 days. Statistics for survival exclude data for tank 5 which sustained high mortality due to a parasitic infection (whitespot).

Treatment	Shortfin Diet	Japanese Dough Diet	Salmonid Diet
Weight @ day 29 (g)	0.0821 ± 0.0030 [a]	0.1271 ± 0.0063 [b]	0.1831 ± 0.0043 [c]
Condition @ day 29	0.1613 ± 0.0056 [a]	0.2379 ± 0.0099 [b]	0.3263 ± 0.0072 [c]
Survival at day 29	86.0 ± 1.2 [a]	97.3 ± 0.2 [b]	99.0 ± 0.1 [b]
Harvest weight (g)	0.3807 ± 0.0094 [a]	0.2210 ± 0.0072 [b]	0.4506 ± 0.0139 [c]
Harvest condition	0.5723 ± 0.0104 [a]	0.3752 ± 0.0096 [b]	0.6483 ± 0.0146 [c]
Survival (%)	63.0 ± 2.0 [a]	81.7 ± 1.1 [b]	93.0 ± 0.5 [c]

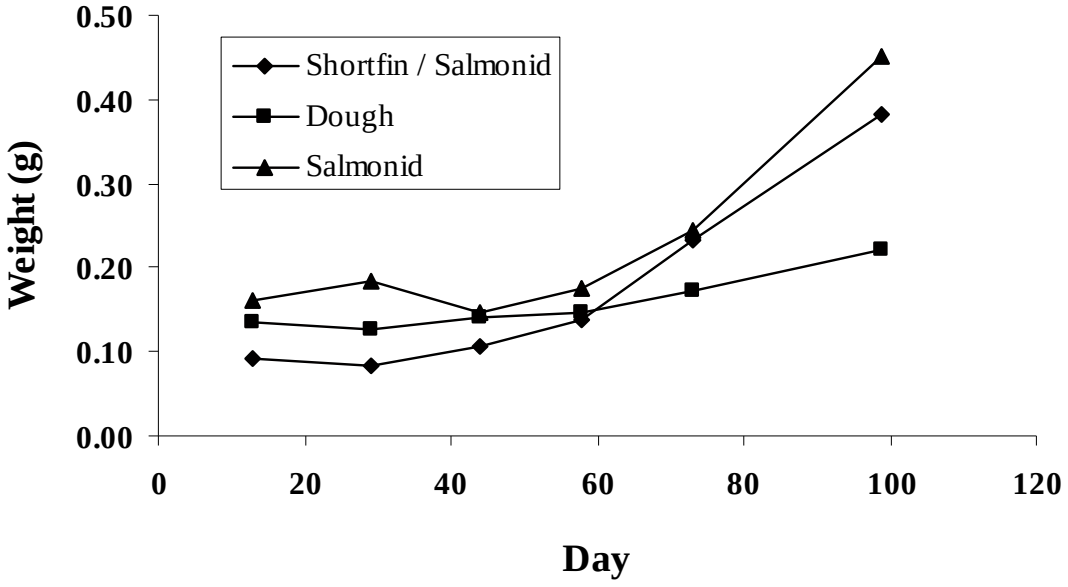

Figure 5.4 Mean weight of longfin eels over 99 days cultured in a flow through tank system and fed one of three diets. Note that the shortfin diet was replaced with the salmonid diet on day 28.

By day 29, 50% of eels in tank 5 had died due to heavy whitespot (*Ichthyophthirius multifiliis*) infection. Data from tank 5 were therefore excluded from all analyses. A low level infection of whitespot affected all tanks during a 20 day period of the experiment up to day 40. With the exception of tank 5, this led to low levels of mortality, and had a significant impact on appetite and growth. However, it was overcome with continuous salt bathing (10ppt) over two weeks (see section 1.6 Health and Disease).

At completion of the experiment after 99 days, a significant difference ($P < 0.001$) in weight was measured (Table 5.4). Eels fed the salmonid diet were 18% bigger than those which were initially fed the experimental shortfin diet, and 104% bigger than those on the Japanese dough diet. Survival was also significantly different between treatments ($P < 0.001$). Mortality was least for the salmonid treatment (7%), greater for the Japanese dough treatment (18.3%) and greatest at 37% for the experimental shortfin treatment (Figure 5.5).

Comparison of food conversion ratios (Figure 5.6) was confounded by the inaccuracy of consumption estimates due to the disintegration of the dough diet after feeding. The FCR of the dough diet is likely to be substantially lower than 9.46 ($\pm$ 0.99) as recorded, but still substantially higher than that of the salmonid diet (2.05 ± 0.07). The FCR of 4.05 ± 0.24 for the shortfin diet is somewhat meaningless. The shortfin diet was clearly deficient and would likely have generated a very high FCR over an extended period.

Figure 5.7 shows the size frequency distribution of elvers fed the three diets. The spread of size is equivalent for all diets. The high proportion of elvers in the smallest size classes (0.1 to 0.2g) for the dough diet provides a clearer illustration of the inadeqaucy of this diet, as most individuals were less than 0.3g at the completion of the experiment. Although the shortfin treatment eels were fed the shortfin diet for only one third of the culture period, their size distribution lagged well behind that of those exclusively fed the salmonid diet.

5.4.2.3 Discussion

A low level whitespot infection affected all eels in this experiment over a 20 day period during the initial few weeks (Figure 5.6). With the exception of tank 5 (Japanese dough diet treatment) where heavy mortality occurred, the infection rate and impact on the eels appeared to be relatively minor, and was controlled and eliminated through a series of salt baths. Growth and survival over the entire experimental period suggested that the infection had a short-term effect only and did not differentially influence the prosperity of eels exposed to different treatments.

The three diets offered to eels in this experiment generated markedly different results. The experimental shortfin eel diet, specifically formulated for *A. australis*, was clearly inadequate, to the extent that eels lost condition immediately, and mortality rose quickly. There is no doubt that all eels subjected to this treatment would have died within a few months if feeding of this diet had been continued. The decision to substitute the salmonid diet, which showed promising results from the outset, provided an opportunity to gauge the capacity of eels to recover from dietary deficiency and poor condition.

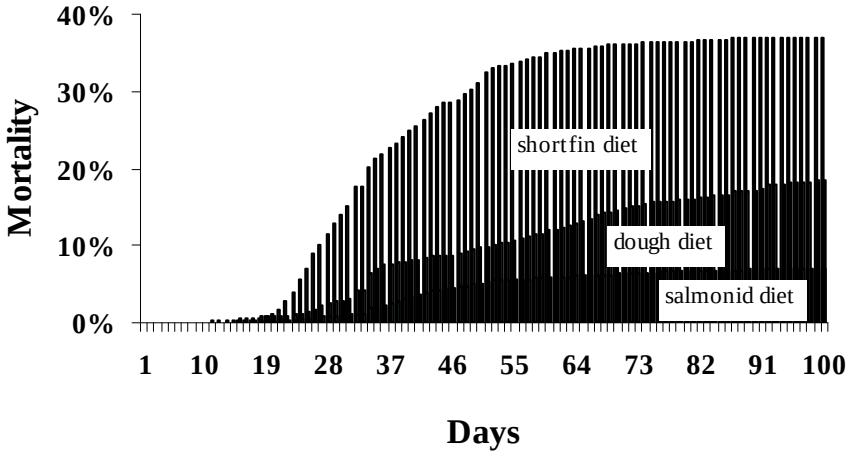

Figure 5.5 Cumulative mortality (%) of longfin eels fed one of three diets over 99 days. Note, shortfin diet was replaced with salmonid diet after day 29.

Figure 5.6 Food conversion ratios (+ s.e.) for longfin eels fed one of three diets over 99 days.

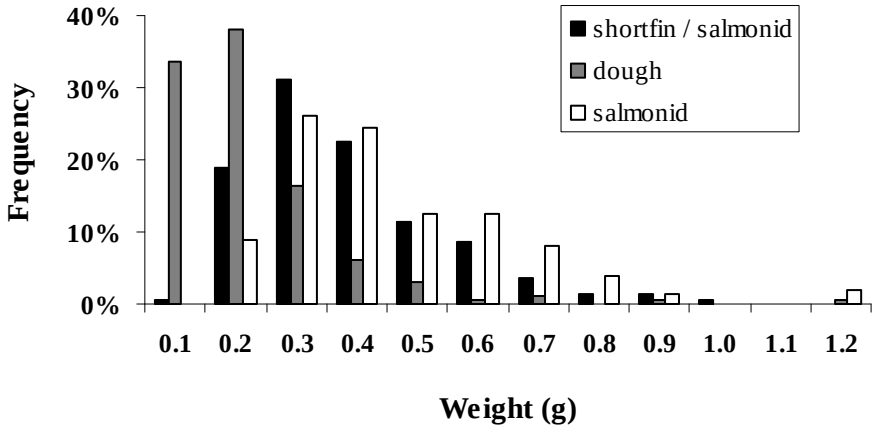

Figure 5.7 Size frequency distribution of longfin elvers after 99 days culture with three different diets.

Although reasonable growth and survival were achieved for eels fed the Japanese dough diet, their performance was significantly less than those fed the salmonid diet. Although the dough diet was a specifically formulated for *Anguilla japonicus* eels, like the experimental shortfin diet, it clearly was deficient for longfin eels. Marked differences in the nutritional requirements of different eel species have been suggested by Gooley *et al.* (1999). Furthermore, the dough diet represented a significantly different method of delivery of food to the eels. Notwithstanding the long history and success of dough as a food for commercial culture of *A. japonicus* in Asia, its application in this experiment indicated several disadvantages relative to dry, pelleted diets. These included the laboriousness of mixing the dough prior to feeding, the severe impact the dough had on water quality because of leaching and dispersion of food particles, and the build up of slime on the tank walls.

Of the three diets trialled, the salmonid diet was the only one which provided reasonable nutrition for longfin eels. The nutritional adequacy of the Japanese dough diet was confounded by its physical deficiencies. Notwithstanding the inefficiency of the moist dough delivery method, this diet appeared to fall well short of providing good nutrition.

Elvers under the shortfin diet treatment were fed the shortfin diet for 29% of the culture period, and the salmonid diet for the remaining 71%. Although their mean weight was significantly less than that of the salmonid treatment elvers at harvest, their growth (Figure 5.4) and size distribution (Figure 5.7) indicate that they recovered from the initial setback, and were performing well. This also confirms the nutritional adequacy of the salmonid diet in permitting recovery of animals that were in relatively poor condition at the time the diet was first administered.

5.4.3 Experiment 2. Further assessment of diet on growth and survival.

5.4.3.1 Materials and Methods

Having established that a standard salmonid grower diet was adequate for longfin elvers, further assessment of similar commercial fish diets was considered. Two diets were chosen that had similar proximate composition to the salmonid diet, an Australian manufactured eel diet (Diets B) and a commercial European eel diet (Diet C) and a third, Australian native fish diet which had a substantially lower fat content (Diet D). The salmonid diet (Diet A) was used as a control. Proximate composition of the diets is listed in Table 5.5.

Table 5.5 Proximate composition (%) of diets fed to longfin elvers.

Specified Diet	**Salmonid**	**Australian Eel**	**European Eel**	**Native Fish**
Label	**Diet A**	**Diet B**	**Diet C**	**Diet D**
Crude protein	55	47	60	56.4
Fat	15.4	13	13.5	7.6
Ash	11.8	10	12	10.7
Crude Fibre	4.1			1.9
Carbohydrate	13.7			23.4

A randomised block design was applied using four feeding treatments and four replicates. Sixteen, sixty litre round plastic tubs were used as the experimental units, each with 40 L of water. Four tubs were placed in each of four 2500 L fibreglass tanks (blocks), and equipped with water and air supply. Inlets and outlets of each tub were screened with 1.5mm mesh to prevent escape of stock. Water flow was adjusted to provide for a complete water exchange every hour.

Approximately 1,095 elvers (total weight 312g, mean weight 0.29g ± 0.02) which had been previously weaned to a commercial salmonid crumble diet from a pre-weaning diet of fish (mackerel) roe were stocked to each tub. Individual weight and length of 50 elvers from the pool of stock used was measured immediately prior to stocking and thereafter at approximately 2 week intervals. A saline treatment was applied to each tub after sampling as disease prophylactic. Water flow was stopped and salt was added to each tub to achieve a concentration of 10 ppt. The treatment was applied for 2 hours, after which water flow was resumed and saline was flushed from the system.

Feeding was initially based on a fixed schedule of 4% of biomass per day, provided in two feeds, morning and afternoon. This rate was adjusted according to observation, but kept consistent across all treatments. All feed measurements were on a dry weight basis. All feeds were sieved to ensure a maximum particle size range of 0.5 to 1.0mm.

To provide estimates of food conversion, the quantity of uneaten food was estimated by visual assessment and subtracted off the quantity offered to provide a measure of food consumed.

Maximum and minimum water temperature, dissolved oxygen, pH, total ammonia nitrogen and nitrite were measured weekly.

The experiment was commenced on July 3, 1998 and terminated after 62 days.

5.4.3.2 Results

Water quality remained at a high standard throughout the experimental period, and was consistent through all tubs. Mean water temperature, pH and dissolved oxygen were 24.4°C, 6.8 and 7.6 ppm respectively.

No significant difference ($P = 0.23$) was measured between diets for survival, which ranged from 99.7 to 99.9% for the experimental period. Growth however was affected by diet (Figure 5.8). Weight at harvest was significantly different ($P < 0.001$), and means comparison revealed that Diet D resulted in significantly less growth. Elvers fed this diet were 32% smaller than those fed the other diets.

Specific growth rates of around 1.3 % day^{-1} (Table 5.6 and Figure 5.9) indicated good growth was achieved for diets A, B and C. Similarly, these three diets provided reasonably good food conversion ratios (Table 5.6 and Figure 5.10) of between 2.1 and 2.3. A FCR of 4.43 for Diet D confirmed its nutritional deficiency.

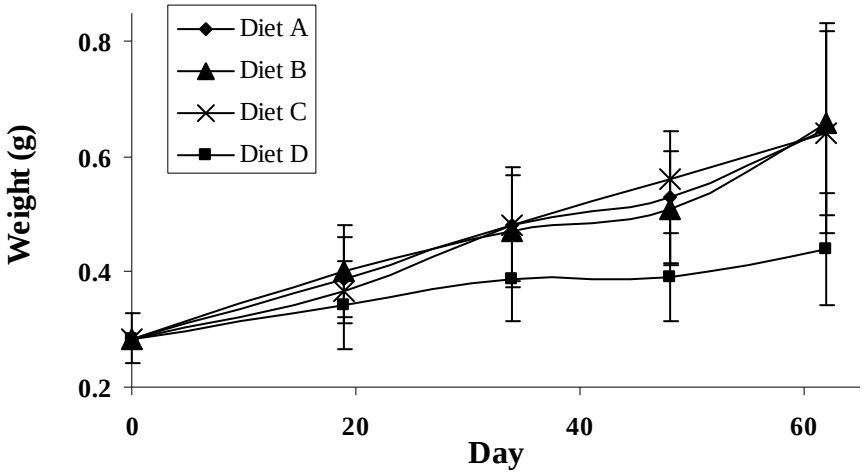

Figure 5.8 Weight (± s.e.) of longfin elvers fed 4 diets over 62 days.

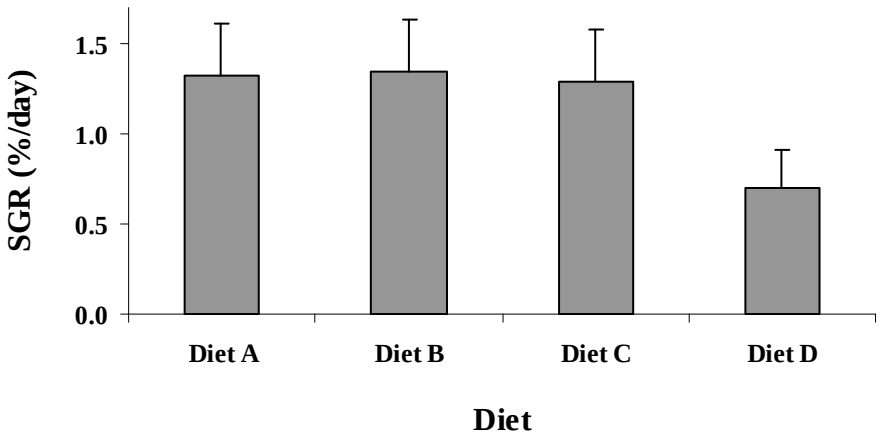

Figure 5.9 Specific growth rate (SGR)(% day^{-1} + s.e.) for longfin elvers fed 4 diets over 62 days.

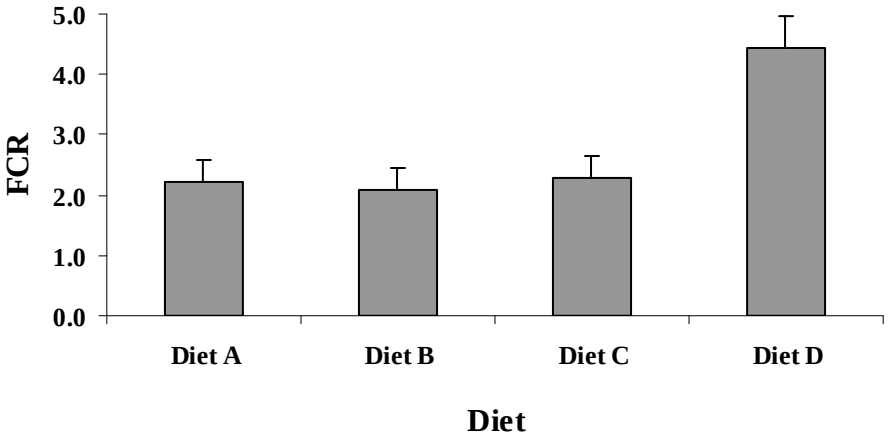

Figure 5.10 Food conversion ratio (FCR) (+ s.e.) for longfin elvers fed 4 diets over 62 days.

Table 5.6 Harvest statistics (means ± s.e.) for elvers fed 4 diets over 62 days. Statistics with the same superscript letter are not significantly different (P > 0.01).

Treatment	Diet A	Diet B	Diet C	Diet D
Harvest weight (g)	0.647 ± 0.092 [a]	0.656 ± 0.080 [a]	0.635 ± 0.087 [a]	0.442 ± 0.048 [b]
Survival (%)	99.8 ± 0.05 [a]	99.9 ± 0.0 [a]	99.9 ± 0.02 [a]	99.7 ± 0.05 [a]
SGR	1.32 ± 0.29 [a]	1.34 ± 0.29 [a]	1.29 ± 0.28 [a]	0.70 ± 0.21 [b]
FCR	2.22 ± 0.38 [a]	2.10 ± 0.36 [a]	2.28 ± 0.38 [a]	4.43 ± 0.52 [b]

5.4.3.3 Discussion

In comparison to the previous experiment, survival in this experiment was excellent due primarily to the abeyance of disease. Survival was unaffected by the treatment diets, and was uniformly high at over 99.3% for all experimental units. The high survival and uniform water quality conditions suggest that the growth results were uninfluenced by any factor other than the treatment diet.

Growth for diets A, B and C was excellent as expressed by specific growth rate values of around 1.3. This compares favourably for SGR values for *A. australis* (Gooley *et al.* 1999; Ingram *et al.* 2001). The deficiency of Diet D may be attributable to its relatively low fat content of 7.6% relative to the other diets whose fat content was 13% or greater. Protein level in diets A, B and C ranged from 47 to 60%. As there was no significant difference in growth for these diets, a protein level of under 50% may be sufficient to sustain good growth for longfin elvers.

5.4.4 Experiment 3. Further assessment of three commercial fish diets on growth and survival.

5.4.4.1 Materials and Methods

Given the relatively poor performance of elvers fed a native fish diet (Diet D, Table 5.6) in the previous experiment, and the relatively uniform performance of elvers fed the other three diets (Diets A, B and C, Table 5.6), an experiment was conceived to further assess these latter three diets over a longer period, and for larger sized elvers.

A randomised block design was applied using the three treatment diets (Diets A, B and C in Table 5.6) with four replicates. The experiment was performed in 12 x 500 L round fibreglass tanks (1.2m diameter), equipped with a flow-through water supply sourced from a bore. 250 L of water was maintained in each tank, leaving approximately 300mm of free-board to ensure elvers did not escape. Each tank was plumbed to generate a circular current around the tank which, at a delivery rate of 20 L min^{-1}, created a current of approximately 10 cm sec^{-1}. A central standpipe equipped with a removable 1mm mesh screen was used for the outlet. Two 25mm airstones were placed in each tank to provide aeration.

Elvers from the previous experiment (4.3) were translocated from their experimental tub to a tank. As survival and final weight from the previous experiment were not significantly different between treatments, no adjustments to the stock for each tank were made. Initial

stock number and mean weight were therefore as at the end of the previous experiment (Table 5.7).

Individual weight of 50 elvers from each tank was measured at approximately 14 day intervals.

To provide estimates of food conversion, the quantity of uneaten food was estimated by visual assessment and subtracted off the quantity offered to provide a measure of food consumed.

Maximum and minimum water temperature, dissolved oxygen, pH, total ammonia nitrogen and nitrite were measured weekly.

The experiment was commenced on September 2, 1998 and terminated after 91 days.

5.4.4.2 Results

No mortalities were observed in any tank over the experimental period. Elvers in each tank showed positive growth over the 91 day period, but there was no significant difference ($P > 0.05$) in weight of elvers between diet treatments at the end of the experiment. Statistics for elvers at harvest are presented in Table 5.8. Growth of elvers over the experimental period is presented in Figure 5.11. Growth was clearly not uniform over the period with several periods of negative growth expressed.

For comparative purposes, the growth of elvers in this experiment and the previous experiment were combined in Figure 5.12.

5.4.4.3 Discussion

Although survival was excellent for this experiment, suggesting conditions were amenable for good performance, growth was relatively poor, and several periods of apparent negative growth were observed. Specific growth rates and food conversion ratios were also poor further suggesting that conditions were not optimal. Given the reasonably good performance of the same diets in the previous experiment (see Figure 5.12), the diet may not be responsible for the poor performance recorded.

The apparent negative growth for elvers fed Diets A and B for the first 29 days relative to the apparent positive growth for the same period of elvers fed Diet C may be misleading. Mean weight of elvers at day 29 was not significantly different between diets, nor was it significantly different between this sample and initial weight, so the apparent change in weight is not supported statistically.

For the entire experimental period, elvers for all treatments increased in size, but at a rate that was substantially less than was measured in the previous experiment under equivalent conditions. With the exception of tank size (which was bigger), all other physical and biological factors were the same. The poor performance of the elvers in this experiment might therefore be attributed to latent handling stress. Given a longer experimental period, growth may have accelerated. Extended periods of low or no growth, mediated by stress associated with handling or changes in environment have been described elsewhere (Degani and Levanon 1983; Wickins 1983; Seymour 1984; Wickins 1985; Knights 1987; Kamstra 1993), and are a significant operational difficulty for commercial aquaculture.

Table 5.7 Statistics for elvers at commencement of feeding experiment. Values with same superscript letter are not significantly different (P > 0.05).

Parameter	Diet A	Diet B	Diet C
Biomass (g ± s.e.)	646.9 ± 16.0 [a]	647.5 ± 9.1 [a]	671.0 ± 8.5 [a]
Mean Weight (g ± s.e.)	0.647 ± 0.092 [a]	0.656 ± 0.080 [a]	0.635 ± 0.087 [a]
Mean number	1,000	987	1,057

Table 5.8 Statistics (means ± s.e.) for elvers after 91 days fed three different diets. Values with same superscript letter are not significantly different (P > 0.05).

Parameter	Diet A	Diet B	Diet C
Mean Weight (g ± s.e.)	0.904 ± 0.009 [a]	0.890 ± 0.025 [a]	0.968 ± 0.032 [a]
SGR (% d^{-1} ± s.e.)	0.37 ± 0.03 [a]	0.33 ± 0.02 [a]	0.46 ± 0.04 [a]
FCR (± s.e.)	8.12 ± 0.61 [a]	6.39 ± 0.38 [a]	7.13 ± 0.34 [a]

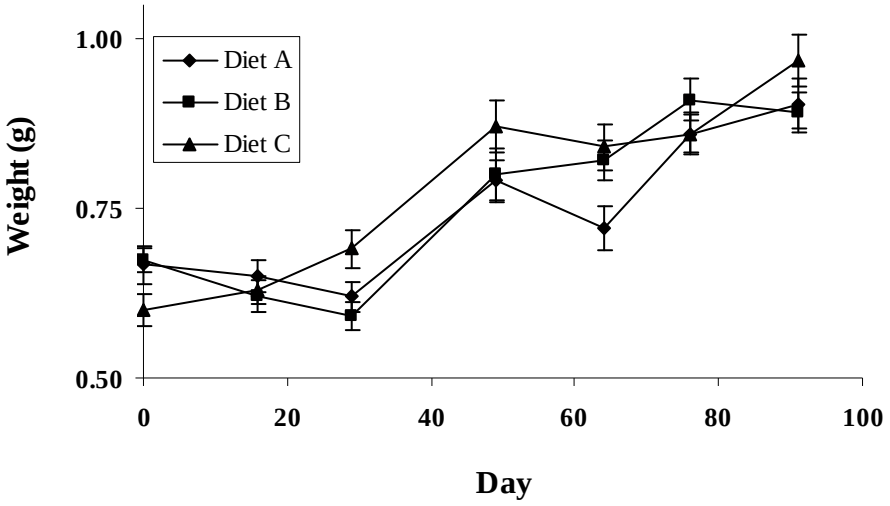

Figure 5.11 Weight (± s.e.) of elvers at times of sampling over 91 days, fed three diets.

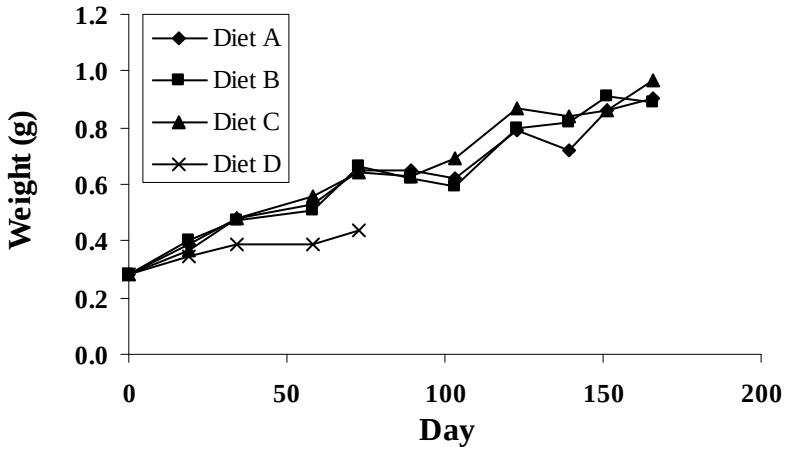

Figure 5.12 Growth data combined for Experiments 3 and 4.

Figure 5.12 shows the size frequency distribution of elvers at the beginning and end of this experiment. It clearly shows that most of the growth achieved over the experimental period can be attributed to the very smallest elvers (mean 0.25g) at the beginning, progressing to the 0.75g size class. There was no appreciably progression of elvers from 0.75g to larger sizes over the period. This suggests a growth barrier that may be nutritionally based. If so, the diets applied and the nutritional differences between them, provide no further insight into the nature of the barrier, as the performance of elvers on all three diets was essentially the same.

Clearly further detailed examination of growth during this phase is required to further define the importance of nutritional and non-nutritional factors. Water quality was thought not to be an issue as the system applied used flow-through bore water, and the quality measured was optimal at all times.

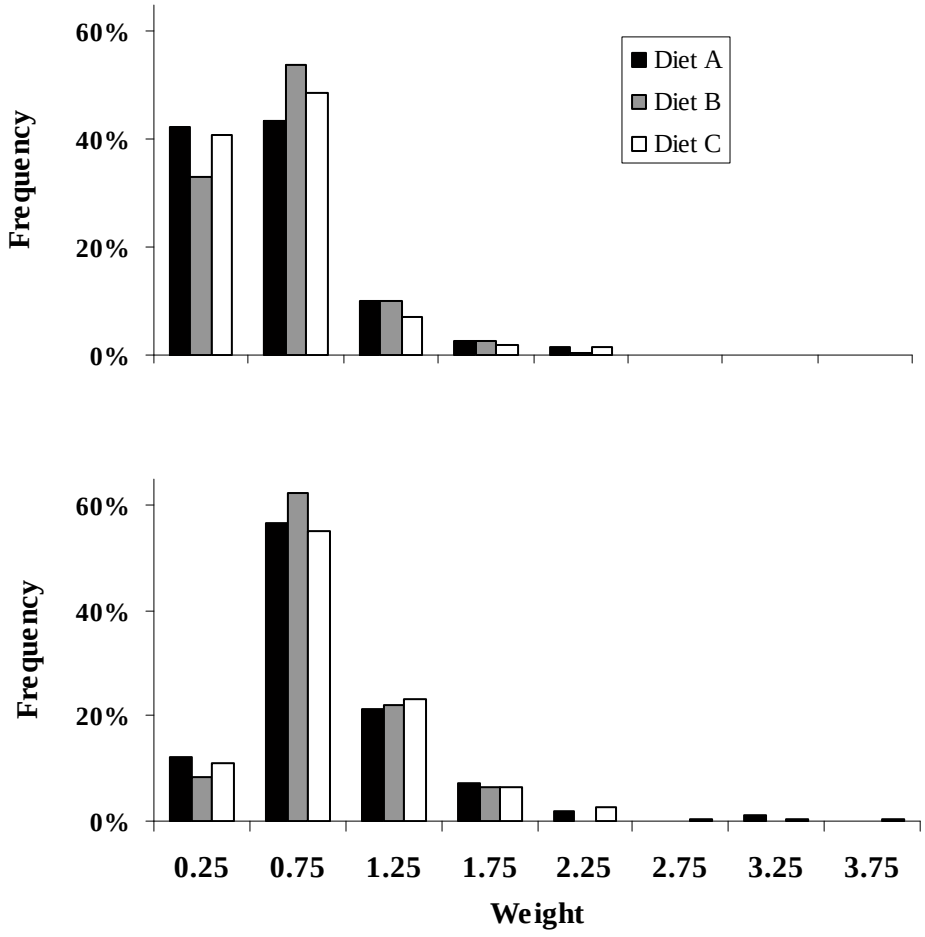

Figure 5.13 Size frequency distribution for elvers at beginning (above) and end (below) of feeding experiment.

5.4.5 Experiment 4. Effect of density on growth and survival.

5.4.5.1 Introduction

The commercial cultivation of longfin eels in Australia will likely involve components of both semi-intensive and super intensive technologies. Even where the growout of eels is to be performed in earthen ponds, there will be a requirement to manage some of the production in tank systems, specifically for glass eel and elver stages, up to a point where they are suitable for stocking to ponds. To maximise the productivity of the systems employed, identification of appropriate densities of stock in tanks will be necessary. Production technology from Asia and Europe suggests densities exceeding 50 kg m^{-3} may not be sustainable. To determine the best density for longfin eels in flow-through tanks, a range of experimental densities will be applied ranging from 15 to 60 kg m^{-3}.

5.4.5.2 Materials and Methods

A complete randomised design was applied using three density treatments with four replicates. The experiment was performed in 12 x 100 L round polyethylene tanks (0.7m diameter), equipped with a flow-through water supply sourced from a bore. 80 L of water was maintained in each tank, leaving approximately 300mm of free-board to ensure elvers did not escape. Each tank was plumbed to generate a circular current around the tank which, at a delivery rate of 20 L min^{-1}, created a current of approximately 10 cm sec^{-1}. Flow rates were increased through the experimental period in response to elevated ammonia levels to a maximum of 50 L min^{-1} . A central standpipe equipped with a removable 1mm mesh screen was used for the outlet. Two 25mm airstones were placed in each tank to provide aeration.

Experimental treatment densities applied were 15, 30 and 60 kg m^{-3}. These densities equated to numbers and biomasses as presented in Table 5.9.

Elvers of approximately 15g were stocked to each tank as per Table 5.10. Individual weight and length of 50 elvers from the pool of stock used was measured immediately after stocking and thereafter at approximately 2 week intervals. A saline treatment was applied to each tub after every sampling as a disease prophylactic. Water flow was stopped and salt was added to each tank to achieve a concentration of 10 ppm. The treatment was applied for 2 hours, after which water flow was resumed and saline was flushed from the system.

Feeding was initially based on a fixed schedule of 4% of biomass per day, provided in two feeds in the morning and afternoon. This rate was adjusted according to observation, but kept consistent across all treatments. All feed measurements were on a dry weight basis. All feeds were sieved to ensure a maximum particle size range of 1.5 to 2.0mm.

Table 5.9 Number and biomass of eels stocked to each tank to achieve specified densities.

	Density		
	15 kg m^{-3}	**30 kg m^{-3}**	**60 kg m^{-3}**
Number	80	160	320
Biomass	1200g	2400g	4800g

To provide estimates of food conversion, the quantity of uneaten food was estimated by visual assessment and subtracted off the quantity offered to provide a measure of food consumed.

Maximum and minimum water temperature, dissolved oxygen, pH, total ammonia nitrogen and nitrite were measured weekly.

The experiment was commenced on October 1, 1999 and terminated after 131 days.

5.4.5.3 Results

Due to heavy cannibalism of elvers in tank 1 (low density treatment) during the last few weeks of the experiment, data for this tank were excluded from the analyses. Between sampling on days 96 and 113 (harvest), 50 elvers (68.5%) in this tank were cannibalised, leaving 23 of the largest individuals. Mean harvest weight for this experimental unit was 172g, 137% larger than for the other three replicates of this treatment.

Key experimental statistics are presented in Table 5.10. Survival was not significantly different ($P > 0.05$) between densities, and remained high for the duration of the experiment.

Harvest weight was significantly different ($P < 0.05$) between densities (Figure 5.14). Means comparison revealed that elvers at the high density were significantly smaller than those at both medium and low density. Elvers stocked at medium and low densities were more than 45% larger than those grown at high density. A similar trend was observed for specific growth rate.

Biomass at harvest for each of the treatments represented 254, 288 and 268% increases over density at stocking for low, medium and high densities respectively.

No significant difference in FCR was measured between the density treatments.

All water quality parameters remained at acceptable levels for all tanks throughout the experiment, although there were indications of a treatment (stock density) effect on some parameters. Water quality data are summarised in Table 5.11.

Table 5.10 Statistics for each of three density treatments of elvers. Data at harvest excludes that of tank 1. Statistics with the same superscript are not significantly different ($P < 0.05$).

Density	low	medium	high
At stocking:			
Mean weight (g ± s.e.)	12.5 ± 1.62 [a]	12.94 ± 1.91 [a]	12.56 ± 1.52 [a]
At harvest:			
Mean weight (g ± s.e.)	72.78 ± 1.76 [a]	80.42 ± 2.55 [a]	50.11 ± 4.64 [b]
Survival (% ± s.e.)	98.9 [a]	99.1 [a]	99.9 [a]
Biomass (kg m^{-3} ± s.e.)	53.09 ± 1.03 [a]	116.30 ± 0.96 [a]	220.78 ± 5.10 [a]
FCR (± s.e.)	1.34 ± 0.03 [a]	1.18 ± 0.01 [a]	1.28 ± 0.04 [a]
SGR (% d^{-1} ±s.e.)	1.53 ± 0.01 [a]	1.63 ± 0.04 [a]	1.22 ± 0.05 [b]

Table 5.11 Water quality averaged across four tanks for each of three density treatments.

Density	low	medium	high
Dissolved oxygen (ppm ± s.e.)	7.04 ± 0.01	6.92 ± 0.02	6.81 ± 0.01
pH (± s.e.)	7.82 ± 0.02	7.77 ± 0.03	7.79 ± 0.02
Nitrite (ppm ± s.e.)	0.02 ± 0.002	0.03 ± 0.002	0.06 ± 0.006
Ammonia (ppm ± s.e.)	0.33 ± 0.01	0.67 ± 0.02	1.14 ± 0.03

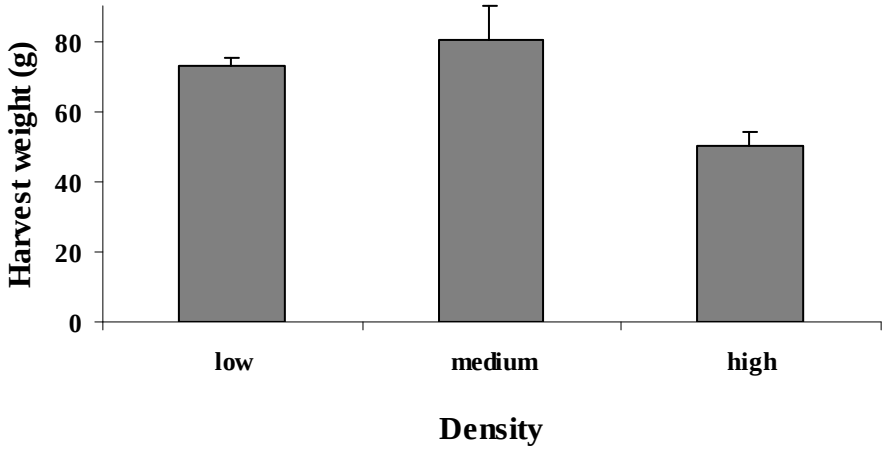

Figure 5.14 Harvest weight (g + s.e.) of elvers at three densities**.**

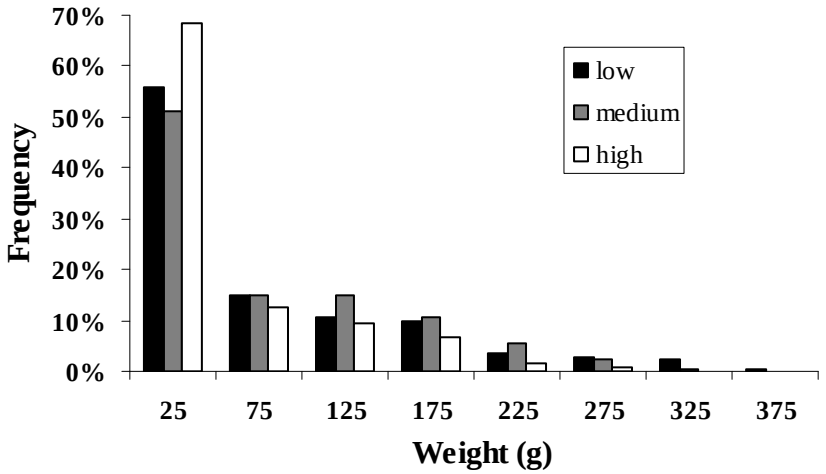

Figure 5.15 Size frequency of elvers after 131 days grown at three densities**.**

5.4.5.4 Discussion

This experiment confirmed that longfin elvers under intensive tank culture conditions can prosper at relatively high densities of over 200 kg m^{-3}. Although at the highest density, growth was less than at the other densities applied, a SGR of 1.22 % d^{-1} is likely to be commercially viable. The apparent superior growth of elvers at the medium density relative to the low density suggests that lower density may confer some disadvantage to the performance of elvers. Heirachical behaviours associated with dominance and subordinance in gregarious species can diminish when densities are sufficiently high (Degani and Levanon 1983; Seymour 1984; Degani *et al.* 1988a; Roncarati *et al.* 1997). This may allow energy otherwise expended on behavioural interactions to be diverted to growth. Naturally, an upper limit would apply to the advantages conferred by this, beyond which carrying capacity issues of the system would begin to dominate. Results of this experiment suggest that the optimal density range for longfin elvers may be in the order of 100 to 200 kg m^{-3}.

The likelihood of increased aggression amongst elvers at low density was supported by the excessive cannibalism experienced in tank 1. Size variation is also likely to be a contributing factor to aggression and cannibalism. Figure 5.15 indicated that for the medium density, greater proportions of elvers were evident for larger size classes, relatively to that of either low or high density.

Water quality was influenced by the density treatments applied. Although the system used was flow-through, the flow rate was insufficient to prevent some small rise in nitrite and ammonia. Both parameters were positively correlated with density, although levels did not exceed acceptable limits.

5.4.6 Experiment 5. Effect of artificial shelter on growth and survival.

5.4.6.1 Introduction

Many communal fish species whose behaviour and social structure are conducive to high density culture, can benefit from manipulations to their physical environment which further enhance their capacity to prosper under high density conditions. Provision of habitats or shelters has been demonstrated to provide significant advantage. Bronzi and Zaffignani (1990) showed the importance of shelter to *A. anguilla* elvers. To be applicable to commercial aquaculture, such shelter must provide some production enhancement, while not negatively impacting on operational procedures such as cleaning and harvesting of the culture environment. Two simple shelters were examined in this experiment to determine their impact on production of longfin elvers.

5.4.6.2 Materials and Methods

A complete randomised design was applied using three shelter treatments with four replicates. The experiment was performed in 12 x 2,500 L fibreglass tanks, plumbed to a recirculation system incorporating a simple biological filter consisting of a 5,000 L sump filled with Bioblocks (Leyton Industries ™). Each tank was filled with 1,000 L of water, leaving approximately 300mm of free-board to ensure elvers did not escape. Water inlets were arranged to generate a circular current around the tank which, at a delivery rate of 20 L min^{-1}, created a current of approximately 10 cm sec^{-1}. A central standpipe equipped with a removable 2mm mesh screen was used for the outlet. Four 250mm airstones were placed in each tank to provide aeration.

Experimental shelter treatments consisted of two artificial shelters (pipe stack and elevated platform) and a no shelter control. Pipe stack shelters were a fixed structure consisting of twenty-four 250mm lengths of 80mm diameter corrugated polythene pipe, placed in a stack 3 high by 8 wide. Stainless steel fencing clips were used to secure each pipe to adjacent pipes. One pipe on the bottom row was filled with concrete to facilitate sinking and to ensure that the habitat remained upright throughout the experiment. Four pipe stack shelters were provided to each tank.

Elevated platform shelters consisted of a flat sheet of PVC mesh (12mm x 12mm mesh size), 500mm x 900mm attached to an aluminium frame which held the platform 50mm off the floor. One such shelter was provided to each tank, providing an equivalent surface area of cover to the four pipe stacks.

4330g of elvers were weighed out for stocking to each tank. Individual weight of 50 elvers from each tank was measured immediately after stocking and the number of elvers in each tank was estimated by dividing the biomass by the mean tank weight. No further sampling was performed until the experiment was terminated at which time the total biomass, and individual weights of 50 elvers were recorded for each tank.

A saline treatment was applied to each tank after every stocking as a disease prophylactic. Water flow was stopped and salt was added to each tank to achieve a concentration of 10 ppm. The treatment was applied for 2 hours, after which water flow was resumed and saline was flushed from the system.

Feeding was initially based on a fixed schedule of 4% of biomass per day, provided in two feeds in the morning and afternoon. This rate was adjusted according to observation, but kept consistent across all treatments. All feed measurements were on a dry weight basis. All feeds were sieved to ensure a maximum particle size range of 1.0 to 1.5mm.

To provide estimates of food conversion, the quantity of uneaten food was estimated by visual assessment and subtracted off the quantity offered to provide a measure of food consumed.

Maximum and minimum water temperature, dissolved oxygen, pH, total ammonia nitrogen and nitrite were measured weekly.

The experiment was commenced on March 30, 2000 and terminated after 81 days.

5.4.6.3 Results

Water quality remained at acceptable levels throughout the experiment. Temperature ranged from 20.8 to 26.9°C with a mean of 24.5°C. All other parameters remained within acceptable limits.

No mortalities were observed throughout the experiment. Although cannibalism cannot be accurately accounted for, estimates of elver counts for the beginning and end of the experiment suggest few losses occurred.

Production statistics for each treatment are presented in Table 5.12. There was no significant difference ($P < 0.05$) in weight at harvest. Elvers in all treatments progressed from approximately 2 g at stocking to 3 g at harvest. Similarly, no significant differences ($P < 0.05$) in tank biomass, specific growth rate or FCR were evident.

Table 5.12 Statistics for each of three shelter treatments of elvers. Statistics with the same superscript are not significantly different ($P < 0.05$).

Shelter	No shelter	Pipe stack	Elevated platform
At stocking:			
Mean weight (g ± s.e.)	1.91 ± 0.22 [a]	1.88 ± 0.21 [a]	1.86 ± 0.20 [a]
At harvest:			
Mean weight (g ± s.e.)	2.98 ± 0.33 [a]	2.90 ± 0.29 [a]	2.95 ± 0.31 [a]
Biomass (kg m^{-3} ± s.e.)	6.33 ± 0.07 [a]	6.61 ± 0.04 [a]	6.40 ± 0.10 [a]
FCR (± s.e.)	2.84 ± 0.09 [a]	2.51 ± 0.05 [a]	2.84 ± 0.17 [a]
SGR (% d^{-1} ±s.e.)	0.55 ± 0.02 [a]	0.53 ± 0.02 [a]	0.57 ± 0.03 [a]

5.4.6.4 Discussion

This experiment did not fully clarify the importance of shelter to the production of longfin elvers. The experiment was terminated before sufficient growth was achieved to determine the potential impact of the shelter types provided. Specific growth rates were relatively low, suggesting the elvers had not fully recovered from the stress of handling and stocking. Given the relatively short experimental period (81 days), insufficient growth occurred to provide an opportunity to discern any differences between treatments. Over a longer period, and more substantial growth, some differences between treatments may have been evident.

The experiment did however demonstrate that the shelter types applied did not adversely impact on the elvers or the environment in which they lived. Further assessment of shelters as a productivity enhancement tool for longfin elvers is justified.

5.5 GROWOUT

5.5.1 Introduction

While the elver culture component of eel aquaculture is most effectively managed under tank conditions where tight control can be applied, the growout of eels to a desirable market size takes a considerably longer period, and may be cost effectively managed in less intensive conditions. Outdoor pond growout of longfin eels was considered to be potentially viable under tropical climatic conditions where ambient temperatures are likely to be close to optimal for most of the year. Ultimately, it will be economic considerations which determine the commercial viability of pond aquaculture of longfin eels relative to tank culture. This research aimed to assess the basic production requirements and protocols necessary to grow longfin eels in ponds.

Ponds used in these experiments were small (216m^2), but nonetheless equivalent to typical earthen ponds applied to semi-intensive aquaculture in Australia, which tend to be in the

range of 800m² to 2,000m². The transferability of the results is therefore considered to be very high.

Several of the experiments performed involved one pond only in response to the availability of eels of a similar size range, and there was no replication. This was intentional to make full use of the eels available to the project, and to generate maximum information. Nevertheless, results of these non-replicated experiments should be interpreted with caution.

5.5.2 Experiment 1. Preliminary pond growout of elvers with intermediate size grading.

5.5.2.1 Materials and Methods

This experiment was conceived to assess the production performance of elvers that had previously been weaned and grown successfully in tanks to sizes considered suitable for stocking to growout. Because of the implied importance of size grading of eels to maximise their performance, this experiment consisted of two phases with an intermediate grading and restocking. Two ponds were managed in this manner on separate occasions. The details of stocking are presented in Table 5.13.

Ponds C1 and C2 were used. Their specification and preparation were as described in Materials and Methods (Section 5.2).

Eels were fed daily with a commercial salmonid diet in 1 to 2mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

Water quality was checked weekly, and when necessary, the ponds were flushed with new water to replace 5 to 10% of the pond volume.

Harvesting was performed by draining the pond and flushing all stock through the outlet to an external fish-out box equipped with a net. Eels were weighed (in total) and counted, and mean weights were determined by division of total biomass by number.

This experiment involved two separate production runs. The first in pond C1 was commenced on November 10, 1998. First harvest and grading was performed after 118 days. Phase two commenced on March 9, 1999 and ran for 160 days. Production for pond C2 commenced on April 28, 1999. It was harvested after 68 days. Phase 2 then commenced on July 13, 1999 and ran for 93 days.

5.5.2.2 Results

Grading of eels at the first harvest separated two size grades. Statistics for eels at first harvest for each pond are presented in Table 5.14. Production results are summarised in Table 5.15.

For both phases of this experiment in both ponds, good production results were achieved. For pond C1 in phase 1, over 118 days, elvers grew from 11g to over 166g, representing a specific growth rate of 2.3% per day. During the second phase, when smaller eels had been graded out, and additional eels of the same mean size added, growth from 172g to 554g was achieved in 160d. Similarly attractive growth was achieved for eels in pond C2. Growth is illustrated in Figure 5.16.

Table 5.13 Stocking statistics for pond growout of longfin eels.

Pond	Date	Source	Eel statistics	
			Mean weight (g)	Number
C1	10/11/98	from tanks	11.0	963
C1	9/3/99	from ponds	171.9	650
C2	28/4/99	from tanks	9.2	3315
C2	13/7/99	from ponds	79.6	479

Table 5.14 Grading statistics for first harvest of longfin eels in pond culture.

Grade	Parameter	Pond C1	Pond C2
Small grade	Proportion of total (%)	46	75
	Mean weight (g)	101	11.5
Large grade	Proportion of total (%)	54	25
	Mean weight (g)	224	80

Table 5.15 Harvest results for longfin eels grown out in a pond with intermediate grading.

Parameter	Pond C1		Pond C2	
	1st phase	2nd phase	1st phase	2nd phase
Culture period (d)	118	160	68	93
Survival (%)	79.6	100	70.0	81.3
Mean harvest weight (g)	166.9	554	28.9	410
SGR (% d^{-1})	2.30	0.73	1.68	1.76
FCR	0.88	1.29	1.62	1.32
Yield (g m^{-3} d^{-1})	2.86	5.29	1.79	5.35
Mean water temperature	27.8	21.0	22.5	23.7

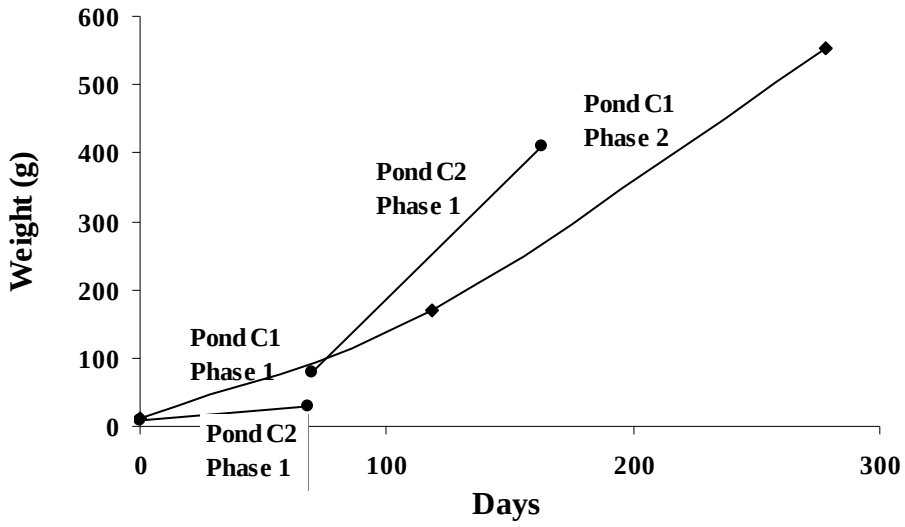

Figure 5.16 Growth of eels in a pond over 278 days. Size grading was applied at day 118, distinguishing phase 1 and 2.

5.5.2.3 Discussion

These were the first of the growout experiments performed within this project. The results were very encouraging for the commercial potential of longfin eels under semi-intensively managed, pond conditions. Survival during the first phase was acceptably high at over 70%. No health or disease problems were evident, and mortality was entirely attributed to cannibalism of the smallest eels by larger eels. Such cannibalism is commonly experienced in the earliest growth phase, and a loss of 20 to 30% matches industry standards for commercial culture of eels elsewhere (Heinsbroek 1991).

Variability in growth was as evident in this species as has been described for other commercially important eel species (Degani *et al.* 1988b; Kamstra 1993). The application of size grading after 2 to 4 months (118 and 68 days for C1 and C2) of culture is consistent with typical management practices applied to other eel species. The results achieved here represent the performance of the larger or faster growing grade only, and they must be interpreted in that context. The smaller grade were not subjected to formal growth trials, however, qualitative observation indicated that approximately 50% (by number) of elvers subsequently grew well over the subsequent 6 months. Of the original stock of elvers taken from tank culture and stocked to ponds, 50% grew to an acceptable market size (> 150g) within 6 months, and of the remainder, a further 50% grew to an acceptable market size within a further 6 months. The potential for acceptable performance of the remaining 25% of the original stock, i.e. the 'runts', is uncertain. Nevertheless, these growth performances and relative proportions are consistent with the typical performance of both European and Japanese eel under commercial culture.

5.5.3 Experiment 2. Pond growout.

5.5.3.1 Introduction

Small eels harvested from tank-based experiments were used to provide further assessment of their growth potential under semi-intensively managed pond conditions.

5.5.3.2 Materials and Methods

This experiment consisted of one pond only. Pond specifications were as described in Materials and Methods (Section 5.2).

On September 27, 1999, 814 eels (mean weight 23.6g) were stocked to pond C5. An additional stocking of 1,708 eels (mean weight 64.5g) was made on November 18, 52 days after the initial stocking.

Eels were fed daily with a commercial salmonid diet in 1.5 to 3mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

Water quality was checked weekly, and when necessary, the ponds were flushed with new water to replace 5 to 10% of the pond volume.

Harvesting was performed by draining the pond and flushing all stock through the outlet to an external fish-out box equipped with a net. The total pond stock was weighed and counted, and mean weights were determined by division of total biomass by number.

The experiment ran for a period of 169 days.

5.5.3.3 Results

313.2 kg of eels were harvested, with a mean weight of 400g. Biomass at harvest was equivalent to 1.04 kg m^{-3}. Quantification of growth in this experiment is complicated by the intermediate addition of more eels to the pond. However, given the similarity in size of those added, to the original stock in the pond, growth can be examined as a singular phase over the 169 days. Specific growth rate was 1.68% d^{-1}.

Survival was 31.0%, and all mortality was attributed to cannibalism of small eels by the larger size classes. Examination of gut contents of several larger eels during the course of the experiment confirmed the occurrence of cannibalism.

5.5.3.4 Discussion

Although cannibalism resulted in significant mortality, growth of surviving stock was very good. A specific growth rate of 1.68 % d^{-1}, is relatively high, particularly in the context that the growth phase represented growth to a substantial size, well above acceptable market minimum. This experiment confirmed the contention expressed from Experiment 1 (5.3) that pond growth of this species can be commercially viable.

The seriousness of the cannibalism that occurred in this experiment cannot be overlooked. It is likely however, that it can be managed to an acceptably lower level through improved feeding strategies, and particularly application of automated feeders which ensure availability of food which matched demand. In addition, the size range of eels in this experiment was relatively large, particularly after the additional stocking which involved a large proportion of runt eels from other trials. Minimisation of size range within any one crop should not be problematic given application of effective size grading at regular intervals through the pond growout phase.

5.5.4 Experiment 3. Growth of large eels.

5.5.4.1 Introduction

The previous experiment examined the growth of longfin eels for the phase representing elver to minimum market size. Given that preliminary market research (Ford and Roberts 1996; Zeller and Beumer 1996) suggests that longfin eels may have good potential into European markets in large size grades of 500g and above, the growth potential of large eels was examined.

5.5.4.2 Materials and Methods

For this experiment, large longfin eels were stocked to three ponds to assess their growth performance. Ponds used were as described in Materials and Methods (Section 5.2). Each was stocked as per Table 5.16.

Eels were fed daily with a commercial salmonid diet in 3mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

Water quality was checked weekly, and when necessary, the ponds were flushed with new water to replace 5 to 10% of the pond volume.

Harvesting was performed by draining the pond and flushing all stock through the outlet to an external fish-out box equipped with a net. The total pond stock was weighed and counted, and mean weights were determined by division of total biomass by number.

The experiment was started on October 29, 1999 and ran for 94 days.

5.5.4.3 Results

Water quality statistics for the experimental period are presented in Table 5.17.

Harvest statistics are presented in Table 5.18. Survival was 100% in all ponds for this experiment. Eels remained in good condition throughout, although feeding vigour fluctuated over the experimental period. Growth was only moderate over the 94 days, with specific growth rates of between 0.32 and 0.40 % d^{-1}. Standing stock of biomass in the ponds increased from 0.55 kg m^{-3} to between 0.73 and 0.79 kg m^{-3}. Food conversion ratios were between 1.86 and 2.39.

Table 5.16 Stocking statistics for pond growout of longfin eels.

Pond	C1	C2	C3
Number	373	381	370
Mean Weight (g)	438.3 ± 4.4	429.2 ± 3.9	441.8 ± 4.9
Biomass (kg m^{-3})	0.55	0.55	0.55

Table 5.17 Water quality statistics for pond growout of longfin eels.

Pond	C1	C2	C3
Temperature (°C, mean)	27.0	26.7	27.0
(range)	22.9-31.4	22.4-31.2	22.4-31.4
Dissolved oxygen (ppm, mean)	9.7	9.8	9.2
(range)	3.3-17.3	7.2-16.0	5.9-13.3
pH (mean)	8.5	8.7	8.4
(range)	7.2-10.3	7.2-10.2	7.3-9.4

Table 5.18 Harvest statistics for pond growout of longfin eels.

Pond	C1	C2	C3
Survival (%)	373	381	370
Mean Weight (g)	638	599	594
Biomass (kg m^{-3})	0.79	0.76	0.73
SGR (% d^{-1})	0.40	0.36	0.32
FCR	1.86	2.08	2.39

5.5.4.4 Discussion

Survival was excellent for this experiment, indicating acceptable environmental conditions. Eels fed vigorously on occasions, although observations indicated that feeding behaviour was particularly subdued during the first several weeks of the experiment, relative to the subsequent period.

Growth, in terms of specific growth rate, was less than for smaller eels as measured in Experiment 1. The culture period may have been to brief to provide an adequate assessment of growth for this phase. The apparent change in feeding behaviour and general vigour through the first several weeks of the experiment suggest that a reasonable recovery period after handling and stocking may be necessary.

Food conversion ratios were relatively high. This may also reflect post-stocking stress. Furthermore, the feeding strategy employed (i.e. hand feeding to excess) is unlikely to have been particularly efficient. More frequent, smaller feeds using automated feeders is likely to generate substantially better FCR's.

Notwithstanding these comments above, the potential for growth of longfin eels through to relatively large size grades of 500g and above appears good. Many of the eels harvested were over 2kg in size, after less than 18 months from weaning. Achieving more consistent, less variable growth will be a primary challenge that may be overcome with, in particular, improved feeding strategies and stock management practices.

5.5.5 Experiment 4. Production potential of runt elvers.

5.5.5.1 Introduction

One of the key management issues with the aquaculture of eels is the minimisation of size variability. Significant size variation within a stock of eels may present several problems including:

- enhancement of heirachical behaviour involving dominance / subordinance and increased levels of aggression
- inefficient feeding because of different requirements of small and large eels
- increased handling at harvest to separate size classes
- increased cannibalism and therefore decreased survival

Regular grading is therefore an essential component of eel stock management. Grading of longfin eels during the course of this project has commonly revealed three reasonably distinct categories; i) fast growing stock, ii) moderate growing stock and iii) slow or no growth stock. This last category, the 'runt' eels, applies to eels of all sizes. That is, within a group of eels stocked together and cultured over a reasonable period of time, there is always a proportion at harvest which have displayed no appreciable growth. This phenomenon appears to be common to all cultured eels species. The mechanisms that mediate this are unclear, but may involve some behavioural suppression of growth. It was hypothesised that runt eels may grow well when removed from the group they originated in. This experiment isolated a group of runt eels and stocked them separately to assess their production potential.

5.5.5.2 Materials and Methods

This experiment involved the stocking of one pond only. Pond specifications and management were as described in Materials and Methods (Section 5.2).

Runt eels were isolated from a stock of eels which had been previously stocked at mean weight 1.4g and harvested 52 days later. Fast growers had progressed to a mean weight of 60g, while the runts had achieved a mean weight of only 1.7g. 46,664 eels were stocked to the pond representing a biomass of 0.26 kg m^{-3}.

Eels were fed daily with a commercial salmonid diet in 1 to 2mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

Water quality was checked weekly, and when necessary, the ponds were flushed with new water to replace 5 to 10% of the pond volume.

Harvesting was performed by draining the pond and flushing all stock through the outlet to an external fish-out box equipped with a net. The total pond stock was weighed and counted, and mean weights were determined by division of total biomass by number.

The experiment commenced on November 18, 1999 and ran for a period of 224 days.

5.5.5.3 Results

At harvest, 384.9kg of eels were removed from the pond, representing an increase in biomass of 385%. Survival was estimated to be 8.6% due to excessive cannibalism of small eels, particularly over the final several weeks of the experiment, when a proportion of the stock had achieved large size. Approximately 1,000 eels at harvest had a mean weight of 300g.

5.5.5.4 Discussion

This experiment confirmed that runt eels do have potential for good growth. However, it also confirmed that within any one stock of eels, only a limited proportion will perform well, while the bulk of the stock (numerically) remains suppressed. In this experiment, high mortality due to cannibalism can be attributed to excessive size variation which in turn resulted from an excessive culture period without grading.

The result suggests that for elvers (<10g), culture periods of no longer than 2 to 3 months be applied before harvesting, grading and redistribution of stock occurs.

5.5.6 Experiment 5. Production potential of runt eels.

5.5.6.1 Introduction

The transition from tanks to ponds for the culture of eels can potentially be traumatic due to the significance of the change in environment. Elvers which had previously been cultured in tanks were stocked to a cage within a pond as part of a staged release. The performance of the elvers in the cage was very poor, as they failed to grow appreciably over a 1 year period. To determine if their suppressed growth was intrinsic, they were released to free-range in a pond. The hypothesis tested was that the change of environment would not have any impact on their subsequent performance.

5.5.6.2 Materials and Methods

This experiment consisted of one pond only. Pond specifications were as described in Materials and Methods (Section 5.2).

On December 9, 1999, 2868 eels (mean weight 15.0g) were stocked to pond C4, representing an initial biomass of 0.14 kg m^{-3}.

Eels were fed daily with a commercial salmonid diet in 1.5 to 2mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

Water quality was checked weekly, and when necessary, the ponds were flushed with new water to replace 5 to 10% of the pond volume.

Harvesting was performed by draining the pond and flushing all stock through the outlet to an external fish-out box equipped with a net. The total pond stock was weighed and counted, and mean weights were determined by division of total biomass by number.

The experiment ran for a period of 119 days.

5.5.6.3 Results

Although survival of eels in this experiment was relatively low at 35%, growth was good. At harvest, mean weight was 220g representing a specific growth rate of 2.26 % d^{-1}. Biomass at harvest was 0.73 kg m^{-3}, representing a 420% increase over the 119 days of the experiment. Food conversion ratio was 1.18.

5.5.6.4 Discussion

This experiment demonstrated that eels that had previously stunted, do have the potential for good growth. The relative importance of the spatial constraints of the cage versus the pond, or the change of environment in stimulating growth of these eels was not clear. Nevertheless, it is clear that stunted eels are not intrinsically growth suppressed, and given the appropriate circumstances can grow well.

This contention is supported by the common practice in northern European eel culture of transferring under-performing 'runt' eels from intensive tank systems to pond culture in Italy. A high proportion of these eels grow well under the changed environmental conditions, and commercially viable production can be achieved. There is no documented information on the underlying mechanisms of this phenomenon.

Cannibalism in this experiment was again significant. Reasons are likely to be as suggested previously, and similarly, minimisation of cannibalism is likely to be achievable with more effective feeding strategies and management of stock size through regular grading.

5.5.7 Experiment 6. Effect of staged release of elvers from tank to pond

5.5.7.1 Introduction

Transfer of elvers from tanks to ponds for growout to market size involves a significant change in environment for the stock. A host of spatial and physico-chemical factors are substantially different in a pond as compared with a tank. In addition there are biological factors including, for example the availability of alternative food items as a consequence of natural productivity within the pond. Release of small eels directly to a pond also involves a significant loss of managerial control, in that the stock can be lost from view, and visual assessment of health, feeding and general vigour is no longer guaranteed. This in essence is the primary disadvantage of pond culture compared with tank culture.

To allow increased control of eels being released to ponds, cages were constructed in which eels could be staged for a period of time prior to their release to 'free-range' in the pond. The perceived advantages of this included:

- allows for continued visual assessment of stock
- provides a spatially constrained environment to ensure food is sensed by the eels
- enables treatment of eels to be applied quickly and efficiently should a health problem arise
- potentially increased productivity

An experiment was designed to test the efficacy of staged release of eels to ponds via cages.

5.5.7.2 Materials and Methods

Elvers which had previously been weaned to a dry diet in tanks were used for this experiment.

A randomised design using two treatments and three replicates was applied. The treatments consisted of a with and without application of staged release of elvers to the pond environment. Staged release involved the stocking of elvers to a cage within the pond, and their maintenance there for 1 month prior to their release to free-range in the pond. The without staged release treatment involved release of elvers directly to the pond.

Ponds used were as specified in Materials and Methods (Section 5.2). Each cage consisted of a box made from PVC mesh (2mm), 1500mm x 1500mm, by 1500mm deep. The cage had a 300mm vinyl hem around the perimeter to prevent escape of eels. The cage was supported at the surface of the pond with a floating frame of 100mm diameter PVC pipe.

6.8kg of elvers were allocated to each pond as per Table 5.19. All eels were salt bathed prior to their release. This involved addition of salt to a tank of static water, to achieve a concentration of 10ppt. The salt bath was maintained for 2 hours and then gradually flushed. Eels were then hand netted and transported to their respective pond using a fibreglass fish transport tank.

Eels were fed daily with a commercial salmonid diet in 1 to 2mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

The experiment commenced on October 6, 1999 and ran for a period of 107 days.

5.5.7.3 Results

Water quality remained at acceptable levels for the duration of the experiment. Water quality statistics are summarised in Table 5.20.

At harvest, the mean weight of eels that had not been staged in cages was higher than that of eels which had been staged in cages, however, the difference was not significant ($P > 0.05$) (Table 5.21). Similarly, no significant differences ($P > 0.05$) were detected for the other production parameters of survival, specific growth rate and food conversion ratio.

5.5.7.4 Discussion

Although a non-significant difference between eels grown under the two stocking procedures was revealed, there appeared to be a trend which indicated that the staged release method had a negative impact on eel growth. This suggestion however could be an artefact of differences other than the staging alone. For the first half of the experimental period, the non-staged eels were clearly less interested in the pellet food provided. Examination of the gut content of sampled eels revealed that they were consuming large quantities of chironomid fly larvae from the pond sediment. The difference in diet between the treatments may have contributed to the larger size of the non-staged eels.

Table 5.19 Stocking statistics for elvers to staged release experiment.

Parameter	With staged release	Without staged release
Mean weight (g ± s.e.)	1.87 ± 0.03	1.93 ± 0.02
Mean number	3665	3553

Table 5.20 Summary of water quality statistics for experimental ponds. Figures represent averages for 3 ponds over 107 days.

Parameter	With staged release	Without staged release
Temperature	26.1	26.2
Dissolved oxygen	9.2	9.5
pH	8.8	8.8
Ammonia	0.17	0.18

Table 5.21 Harvest statistics for elvers. Statistics with the same superscript are not significantly different ($P > 0.05$).

Parameter	With staged release	Without staged release
Mean weight (g ± s.e.)	2.46 ± 0.23[a]	3.56 ± 0.31 [a]
Survival	90.7 ± 5.5 [a]	86.0 ± 6.3 [a]
SGR	0.24 ± 0.07 [a]	0.56 ± 0.09 [a]
FCR	22.6 ± 3.86 [a]	5.5 ± 0.41 [a]

The hypothesis that the staged release of eels through a transitionary period in cages prior to free-range release to the pond would provide no subsequent advantage to growth and survival was upheld. Use of such a management tool would appear not to be justified for the pond culture of longfin eels, unless the advantages as outlined above were perceived to outweigh the costs and effort of applying staged release.

5.5.8 Experiment 7. Identifying optimal temperature for production.

5.5.8.1 Introduction

To maximise the productivity of systems employed for the cultivation of longfin eels, identification of optimal culture temperature will be necessary. Further, knowledge of the temperature / growth relationship will enable more informed decisions to be made regarding site selection for pond-based eel aquaculture. To determine the best temperature for longfin eels, a range of temperatures extending beyond the likely optima will be applied ranging from 19°C to 31°C.

5.5.8.2 Materials and Methods

A randomised block design was applied using four temperatures and two size treatments with three replicates. The experiment was performed in 24 x 500 L round fibreglass tanks (1.2m diameter), equipped with a recirculating water supply within 4 separate systems. Each system consisted of six experimental tanks with independent outlets to a 3,000 L reservoir. Water from the reservoir was pumped via a series of in-line spa heaters (Stokes 3kw) through a bed of four 80l upflow sand filters, to a 50mm diameter delivery line to each tank. Each of the four systems was assigned a treatment temperature, and through a balance of thermostatically controlled room air conditioning and water heaters, the set temperature was maintained.

Each tank was plumbed to generate a circular current around the tank which at a delivery rate of 20 L min $^{-1}$ created a current of approximately 10 cm s $^{-1}$. A central standpipe facilitated removal of waste water which was lifted by airlift from the bottom and released onto a filter mat to collect solids. Two 25mm airstones were placed in each tank to provide aeration.

Small and large longfin eels were purchased from a commercial eel farm (Downunder Eels) and assigned to each tank as per Table 5.22.

Table 5.22 Stocking statistics for eels in temperature experiment.

Parameter	**Eel**	**Temperature (^{o}C)**			
	size	**19**	**23**	**27**	**31**
Mean weight (g ± s.e.)	Small	43.1 ± 3.4	40.7 ±0.7	38.4 ± 0.4	35.9 ± 1.3
	Large	113.0 ± 3.4	110.3 ± 1.2	113.4 ± 3.8	112.9 ± 1.8
Mean number	Small	19	20	21	23
	Large	13	14	13	13
Mean Biomass (kg m^{-3})	Small	4.1	4.1	4.1	4.1
	Large	7.5	7.5	7.5	7.5

Feeding was initially based on a fixed schedule of 2% of biomass per day, provided in two feeds, morning and afternoon. This rate was adjusted according to observation, but kept consistent within each treatment. All feed measurements were on a dry weight basis.

To provide estimates of food conversion, the quantity of uneaten food was estimated by visual assessment and subtracted off the quantity offered to provide a measure of food consumed.

Maximum and minimum water temperature, dissolved oxygen, pH, total ammonia nitrogen and nitrite were measured weekly.

The experiment was commenced on December 8, 1999 and terminated after 92 days.

5.5.8.3 Results

Water quality remained at acceptable levels for all tanks throughout the experiment. Water quality statistics are presented in Table 5.23.

Statistics for eels at harvest are presented in Table 5.24. Survival of eels in the experiment was very high, reflecting good culture conditions. Growth data are expressed as specific growth rates only. A significant difference in SGR was measured ($P < 0.05$) such that eels held at 19°C grew significantly less than those at the higher temperatures. Growth over the experimental period is illustrated in Figure 5.17.

5.5.8.4 Discussion

Results of this experiment were clear and unambiguous. Conditions remained stable in all treatment systems, and the results are a true indication of the effect of temperature on growth. While growth was not significantly different between 23 and 31°C, the lines of best fit depicted in Figure 5.17 suggest that optimal temperature is in the range of 24 to 28°C.

Table 5.23 Water quality statistics for temperature experiment. All values are means over 92 days.

Parameter	**Temperature (^{o}C)**			
	19	**23**	**27**	**31**
Temperature (°C)	19.2	23.0	27.5	30.8
Dissolved oxygen (ppm)	12.7	10.2	10.7	11.1
pH	8.48	8.50	8.40	8.51
Nitrite (ppm)	0.02	0.01	0.01	0.02
Ammonia (ppm)	0.08	0.07	0.15	0.15

Table 5.24 Harvest statistics for eels grown at four temperatures. Statistics with the same superscript letter are not significantly different (P > 0.05).

Parameter	Temperature (°C)			
	19	**23**	**27**	**31**
Survival (%)	92.3	92.1	95.4	96.6
SGR (% d^{-1} ± s.e.)	0.77 ± 0.06[a]	1.07 ± 0.01[b]	1.18 ± 0.03[b]	1.06 ± 0.03[b]
FCR (± s.e.)	2.40 ± 0.30[a]	1.34 ± 0.03[a]	1.50 ± 0.06[a]	1.73 ± 0.06[a]

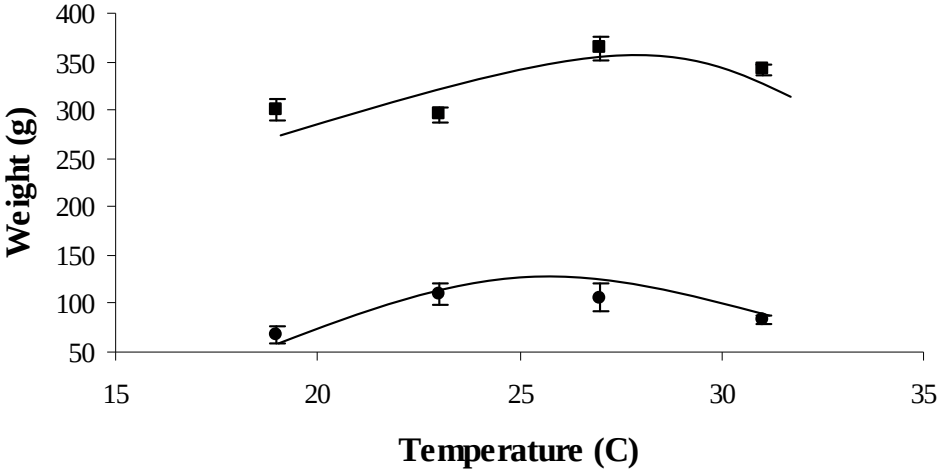

Figure 5.17 Weight (± s.e.) at harvest of eels (small and large) grown at four temperatures. Curves were fitted by eye and do not represent mathematical functions.

5.5.9 Experiment 8. Effect of size grading on production.

5.5.9.1 Introduction

The importance of minimising size variance within a stock of eels to maximise production is well documented (Kamstra 1993). To provide a measure of the relative importance of this management strategy and the biological factors which contribute to it, an experiment was designed to compare performance of eels with and without size grading.

5.5.9.2 Materials and Methods

Eels which had previously been grown under pond conditions were used for this experiment.

A randomised design using two treatments and three replicates was applied. The treatments consisted of with and without application of size grading of advanced eels prior to stocking to ponds. Graded eels were subjected to size culling using a mechanical bar grader to restrict the size range of individual eels to 250 to 450g. Ungraded eels ranged in size from 50g to 1,465g. Stocking statistics are presented in Table 5.25.

Ponds used were as specified in Materials and Methods (Section 5.2).

After grading and counting, eels were allocated to tanks where they were salt bathed (10 ppt) for 2 hours prior to their release to ponds. Eels were hand netted and transported to their respective pond using a fibreglass fish transport tank.

Eels were fed daily with an Australian commercial eel diet in 6mm pellet. Feeding rate was adjusted according to observed behaviour, and stopped only after eels clearly lost interest in the food. Food quantities were recorded.

The experiment commenced on April 12, 2000 and ran for a period of 70 days.

5.5.9.3 Results

Production results are summarised in Table 5.26.

Although survival for ungraded eels was less than that of graded, the difference was not significant ($P > 0.05$).

Because mean weight at stocking was significantly different ($P < 0.05$) between graded and ungraded treatments, for analysis of variance of final weight, initial weight was used as a covariate. No significant difference ($P > 0.05$) in final weight was measured.

Specific growth rate for ungraded eels was significantly greater than that of graded eels.

Food conversion ratio was not significantly different between treatments, and was economically attractive at between 1.1 and 1.3.

Size frequency of eels at stocking and harvest for each treatment are presented in Figure 5.18.

5.5.9.4 Discussion

Although the differences measured between the graded and ungraded eels appeared slight, they are nonetheless significant from a commercial aquaculture perspective. Furthermore, significantly greater differences are likely to have been evident if graded and ungraded eel stocks were followed through the entire production cycle from initial stocking to acceptable market size.

The small but insignificant difference in survival which suggested ungraded eels suffered greater mortality can be attributed to cannibalism of small eels by larger eels. Over the 70 day experimental period the difference was small, however, this factor alone over a longer period is likely to be more significant than any other, and is perhaps the primary reason why size grading should be applied regularly.

Differences in mean weight at harvest were confounded by the difference in initial mean weight. At harvest, mean weight of graded eels was approximately 100g greater than that of ungraded eels, reflecting the same size differential as at stocking. Specific growth rate was significantly greater for ungraded eels, however, this too would have been influenced by the smaller mean size at stocking.

Table 5.25 Stocking statistics for elvers. Statistics with the same superscript letter are not significantly different (P > 0.05).

Parameter	With grading	Without grading
Mean weight (g ± s.e.)	341.87 ± 0.10 [a]	241.28 ± 0.17 [b]
Minimum weight (g)	250.0	50.0
Maximum weight (g)	450.0	1465.0
Mean number	187 [a]	319 [b]
Mean biomass (kg m^{-3})	0.21 [a]	0.26 [b]

Table 5.26 Harvest statistics for eels grown in ponds, with and without size grading. Statistics with the same superscript letter are not significantly different (P > 0.05).

Parameter	With grading	Without grading
Mean weight (g ± s.e.)	497.21 ± 4.79 [a]	395.34 ± 7.14 [b]
Minimum weight (g)	285	45
Maximum weight (g)	885	1755
Survival	99.8 ± 0.2 [a]	90.6 ± 5.1 [a]
SGR	0.54 ± 0.02 [a]	0.70 ± 0.02 [b]
FCR	1.10 ± 0.05 [a]	1.28 ± 0.25 [a]
Mean biomass (kg m^{-3})	0.93 [a]	1.13 [a]

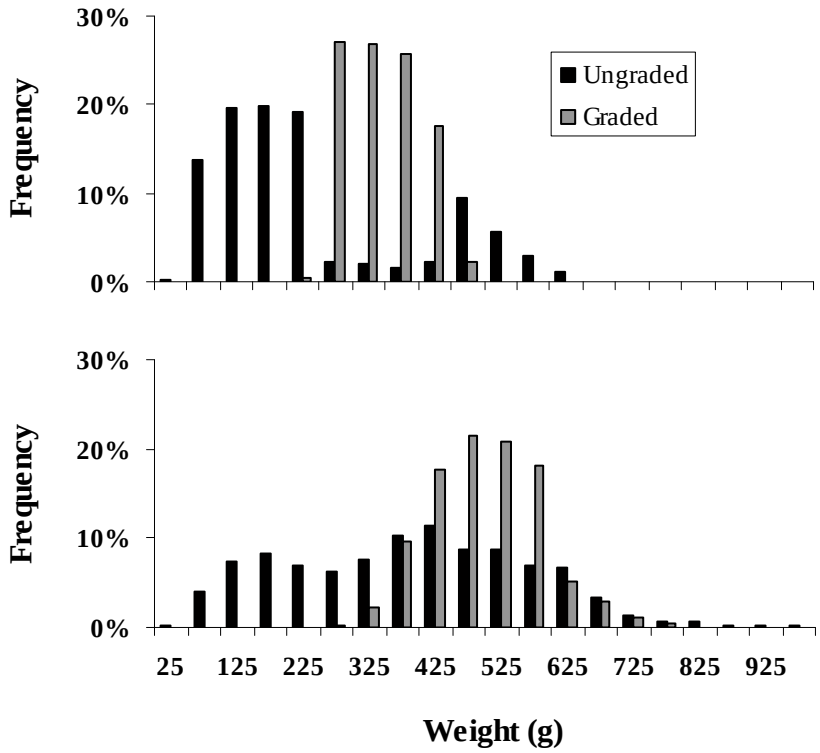

Figure 5.18 Size frequency of eels at stocking (above) and at harvest (below), grown with and without size grading.

The value of size grading is more clearly expressed in examination of the size distribution of eels at harvest, relative to that at stocking as depicted in Figure 5.18. This shows that all graded eels grew over the experimental period, with the singular mode of the distribution advancing from a mean of around 350g to around 500g. In contrast, the ungraded eels displayed much less uniform growth. Although the bimodal distribution at stocking became less pronounced at harvest, as the proportion of smaller eels diminished, a significant proportion (approximately 30%) of the population (from 0 to 300g) displayed no growth. It is likely that the wide size disparity in this population allowed heirachical behavioural mechanisms to operate whereby large eels suppressed the growth of the smallest eels in the population. It would be instructive in future experimentation to compare the performance of graded eels of several size classes against ungraded eels representing the same size range. This may more clearly demonstrate that the smallest eels, once graded, do perform well as suggested by earlier experiments.

5.6 HEALTH AND DISEASE

As aquacultured species, eels are susceptible to a broad range of health and disease problems (Mellegaard and Dalsgaard 1989; Gosper 1995, 1996). While the range of described pathogens of eels is relatively broad, disease prevention and control are based on conventional approaches, and need not be a major issue. During the course of this project a range of health and disease problems were faced, and all were managed quickly and effectively without major loss of stock. A summary of these health issues is provided.

A whitespot (*Ichthyophthirius multifiliis*) infection occurred in the first tank-based elver feeding experiment. Formalin (150 and 200ppm for 1 hour each) was applied with no affect. However continuous salt bathing over a two week period proved to be very effective. Salt was added to each tank with water flow stopped to achieve a concentration of 10ppt and left for 24 hrs static with ample aeration. Over the subsequent 24 hrs tanks were flushed with clean water. The procedure was repeated each 48hours for 14 days, eliminating the condition from the eel stocks.

Subsequent to the whitespot infection, salt bathing was applied as a prophylactic after every sampling or handling of eels. On all occasions, salt concentration was 10 ppt applied for 2 hours. This proved to be effective in minimising health and disease problems.

In September 1998, eels within a series of tanks were observed to have bulging eyes. Gas bubble disease was suspected, and measurement of dissolved oxygen confirmed that the water was supersaturated. The cause was identified as a faulty pump which was sucking air through a fractured pipe. Although a few eels died as a result of the condition, the majority recovered within 24 hours, and the swelling disappeared.

Approximately 300kg of large eels (>150g) held in tanks prior to allocation to further experimentation were diagnosed with a bacterial infection of the skin (including *Flavobacterium* spp. *Aeromonas hydrophila* and *A. sobria*). Within a week of diagnosis, some eels had died and all were displaying symptoms of morbidity. Oxytetracycline was administered at 20ppm on three occasions over 7 days, and the infection was controlled and eliminated. These eels had not been salt bathed when handled prior to their stocking to tanks.

On a number of unrelated occasions, unhealthy eels were observed with either poor feeding response, skin discolouration and/or ulcerations. On all occasions, diagnoses revealed low

level infections with various bacteria (as above), which were quickly controlled with salt bathing.

5.7 GENERAL DISCUSSION

Experimentation and experience through this project indicated that handling and weaning of longfin glass eels can be straight forward. Regular salt bathing is integral to effective health management, and feeding of fish roe as the initial diet is clearly recommended. Industry experience suggests that shorter weaning periods than applied in this project may be more effective in eliciting strong feeding response to formulated diets. Further research is justified in the areas of first feeding diets (i.e. roe of different fish species) and the timing of weaning.

While there may be some prospect of culturing weaned glass eels through the elver stage in ponds, the results of this project suggest this phase is best managed in a tank environment. Growth can be very rapid during this phase, but extremely variable, and the level of stock and environmental management control that a tank system confers is likely to provide significant benefit. Over the size range of glass eel (0.10g+) to elver (15g), substantial quantities of eels can be managed in relatively small volumes of water, and therefore small facilities that would be economically justified.

The production statistics generated by the various pond experiments through this project incorporated a wide range of stocking size, growth periods, ambient conditions and management procedures, and therefore give a representation of average baseline production potential for longfin eels for harvest sizes up to 3kg. Specific growth rate is perhaps the most universally useful statistic in summarising the performance of the eels, although it is clearly size dependent. For longfin elvers and smaller eels less than 100g, SGR's for those experiments where reasonable growth was achieved, were in the order of 1.5 to 2.3 % d^{-1}. For larger eels above 100g, SGR's were in the order of 0.36 to 1.0 % d^{-1}. While the application of these SGR's to estimate growth performance is confounded by the variability of growth in eels, they do serve as an indicator of the commercial potential of this species. Clearly, growth from weaned glass eel to 100g is achievable for a large proportion (>70%) of eels in 9 to 12 months. Subsequent growth to 300g can be achieved in a further 3 to 10 months. These results under ambient environmental conditions, averaged over all seasons, augur well for commercial growout of longfin eels in earth-based ponds in tropical Australia.

By way of comparison, the only experiment conducted in this project involving tank growth of larger eels, i.e. the temperature preference experiment, produced a maximum SGR of 1.18 % d^{-1} at the optimal temperature of 27°C. On this limited basis, there would appear to be no growth advantage conferred by the pristine tank environment. The major difference however between pond production in this project and tank production is the stock density. In no pond experiments did biomass exceed 1.2 kg m^{-3}. The carrying capacity of ponds was not specifically tested in this project, but is likely to be substantially greater than maximum that occurred. Indeed, the result of the tank-based density experiment suggests that growth in ponds at greater densities may be equivalent or superior to that at the densities that occurred due to behavioural factors. The limitation clearly would be the water quality of the pond environment. Nevertheless, even a modest increase in biomass beyond the 1.2 kg m^{-3} to say 10kg m^{-3} is not likely to exceed the carrying capacity of the pond.

Cannibalism of small eels by larger eels appeared to be the primary stock management issue in the pond environment. It is clearly more difficult to assess in ponds during culture as the

stock are less visible than they are in tanks. Regular size grading however would appear to be an effective management tool to minimise its impact. This is clearly the case for other eel species and there is no reason why it should be any different for *A. reinhardtii*.

Grading of longfin eels did not pose any particular difficulty. Standard procedures and equipment for separating specific size categories worked well for this species. Providing suitable prophylactic treatments were applied subsequent to grading, to minimise risk of health problems, grading of longfin eels was straight forward.

The assessment of different commercial fish and eel diets within this project provided useful guidance for industry and for future nutrition research. Good growth was achieved on a number of diets, suggesting that development of a specific and cost-effective longfin eel diet should not be problematic. Several experiments produced FCR's of between 1.1 and 1.5 for growth over substantial periods and size increase, suggesting diets were nutritionally adequate. Notwithstanding likely nutritional improvements through specific research, improvements in FCR and cost-effectiveness of feeding will likely come from further development of feeding strategies. Frequency of feeding, application of automated feeding devices and delivery strategies are all worthy of further investigation.

On the basis of these preliminary investigations of longfin eel aquaculture potential it is possible to make some qualitative assessment of the relative cost/benefit of pond –based culture and tank-based culture. Using documented establishment and operational costs for pond aquaculture of other species in the tropics it is likely that the cost of production (including depreciation of capital and all fixed and variable costs) for longfin eels using state-of-the art pond facilities would be in the order of $6 to $9 per kilogram. Industry advice indicates that this is directly comparable with the likely cost of production using 'turn-key', super-intensive, tank-based aquaculture technology. Given the significantly higher investment necessary for the tank approach, the pond-based approach may be more commercially attractive. These assessments are obviously qualitative and must be interpreted with caution. A comprehensive economic assessment of the two approaches would be necessary before a definitive recommendation could be made. What is clear, is the production of longfin eels in ponds under ambient conditions in tropical Australia does appear to be commercially feasible.

5.8 ACKNOWLEDGMENTS

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5.9 REFERENCES

Bronzi, P. and Zaffignani, P. (1990). Optimization of weaning elvers in a closed cycle system: Preliminary results. *Int. Rev. Gesamt. Hydrobiol.* 75(6): 883-885.

Degani, G. (1986). Dietary effects of lipid source, lipid level and temperature on growth of glass eel (*Anguilla anguilla*). *Aquaculture* 56(3-4): 207-214.

Degani, G. and Levanon, D. (1983). The influence of low density on food adaptation, cannibalism and growth of eels (*Anguilla anguilla* (L.)). *Bamidgeh* 35(2): 53-60.

Degani, G. and Levanon, D. (1986). The influence of different feeds on growth and body composition of glass eels (*Anguilla anguilla* L.). *Bamidgeh* 38(1): 13-22.

Degani, G., Levanon, D. and Meltzer, A. (1988a). Influence of high loading density on growth and survival of European glass eels. *The Progressive Fish-Culturist* 50(3): 178-181.

Degani, G., Levanon, D. and Trieger, G. (1984). Preliminary study on the influence of different feeds on mortality and growth of eels (*Anguilla anguilla* L.) in the initial period. *Bamidgeh* 36(2): 47-53.

Degani, G., Levanon, D., Trieger, G. and Mualem, J. (1986). Influence of two different feeds on food conversion, growth and survival of glass eels (*Anguilla anguilla* L.). *Journal of Applied Ichthyology* 2(2): 59-65.

Degani, G., Migal, D.L. and Gallagher, M.L. (1988b). Relationship between growth, food conversion, body size, body composition and temperature in the European eel, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 19(2): 139-143.

Ford, A. and Roberts, R. (1996). *Sensory profiles of eel species*. Department of Economic Development and Trade, Brisbane, Qld. Brisbane. 13 pp.

Gooley, G.J., McKinnon, L.J., Ingram, B.A., Larkin, B., Collins, R.O. and de Silva, S.S. (1999). *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production. Final Report FRDC Project No 94/067*. Marine and Freshwater Resources Institute, Alexandra, Australia. 124 pp.

Gosper, D. (1995). Some diseases and parasites that may affect the culture of eels. *Austasia Aquaculture* 9(5): 40-41.

Gosper, D. (1996). *A Guide to the Diseases and Parasites Occurring in Eels*. Aquaculture Source Book Publication, Turtle Press Pty Ltd.

Heinsbroek, L.T.N. (1991). A review of eel culture in Japan and Europe. *Aquaculture and Fisheries Management* 22: 57-72.

Ingram, B. and Gooley, G. (1996). Intensive tank and pond culture of Australian short finned glass eels in Victoria. *Austasia Aquaculture* 10(4): 74-75.

Ingram, B.A., Gooley, G.J., De Silva, S.S., Larkin, B.J. and Collins, R.A. (2001). Preliminary observations on the tank and pond culture of the glass eels of the Australian shortfin eel, *Anguilla australis* Richardson. *Aquaculture Research* 32: 833-848.

Kamstra, A. (1993). The effect of size grading on individual growth in eel, *Anguilla anguilla*, measured by individual marking. *Aquaculture*. 112(1): 67-77.

Kamstra, A. and Heinsbroek, L.T.N. (1991). Effects of attractants on start of feeding of glass eel, *Anguilla anguilla* L. *Aquaculture and Fisheries Management* 22(1): 47-56.

Kastelein, P. (1983). Survival and growth of elvers (*Anguilla anguilla* L.) reared on an expanded granulated diet. *Aquaculture* 30(1-4): 155-172.

Knights, B. (1987). Agonistic behaviour and growth in the European eel, *Anguilla anguilla* L., in relation to warm-water aquaculture. *Journal of Fish Biology* 31(2): 265-276.

Mellegaard, S. and Dalsgaard, I. (1989). *Handbook of Eel Diseases*. DF & H-RAPP No. 293. 47 pp.

O'Sullivan, D. (1997). Asian elver shortage sparks interest in eel farming. *Aust. Aquacult.* 11(1): 44-46.

Roncarati, A., Melotti, P., Mordenti, O. and Gennari, L. (1997). Influence of stocking density of European eel (*Anguilla anguilla*, L.) elvers on sex differentiation and zootechnical performances. *Journal of Applied Ichthyology* 13(3): 131-136.

Seymour, A. (1984). Eels: High stocking rates and moving water solve the grading problem. *Fish Farmer* 7(5): 12-14.

Usui, A. (1991). *Eel Culture*. Fishing News Books, Oxford. 148 pp.

Wickins, J. (1983). Speed up for slow eels. *Fish Farmer* 6(2): 24-25.

Wickins, J.F. (1985). Growth variability in individually confined elvers, *Anguilla anguilla* (L.). *Journal of Fish Biology* 27(4): 469-478.

Zeller, B.M. and Beumer, J.P. (1996). *Eel harvesting and culture in Queensland. A discussion paper*. Aquaculture Information Series. Department of Primary Industries, Queensland. Brisbane.

6 PRELIMINARY ECONOMIC ANALYSIS OF SELECTED AUSTRALIAN EEL AQUACULTURE SYSTEMS

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CONTENTS

6.1 INTRODUCTION

High-density eel aquaculture in Australia is a relatively new development, with industry investment still limited and very much in the early stages. Reliable benchmark financial indicators and quantitative measures of the overall economic feasibility of this new and developing sector therefore do not exist presently. To do such analyses effectively, it is necessary to have a good understanding of key production parameters determining growth, survival and marketability of the target species, and in turn the associated production cost and revenue structure for each specific enterprise in question.

In Australia presently there are insufficient commercial eel aquaculture operations to determine actual Best Practice production parameters and associated reliable benchmark financial indicators. However, in the present study various aspects of system design, husbandry, diet and general operational procedures have been preliminarily investigated in an attempt to develop optimal Best Practice management guidelines for aquaculture of the Australian shortfin eel, *Anguilla australis*, and longfin eel, *A. reinhardtii*, albeit with an emphasis on juvenile eel stages (see Chapters 4 and 6). Other major global eel aquaculture sectors have also been reviewed (see Chapters 1 and 4), specifically the production of *A. anguilla* in Europe and *A. japonica* in Asia, for the purpose of extrapolating relevant production parameters and applying these, at least conceptually, to Australian eel culture practices and systems.

The combination of this new information specific to the culture of Australian anguillids generated from the present study, together with relevant information extracted from the literature and other reliable sources (eg. internet and personal communication with industry practitioners), has therefore provided sufficient data to enable a preliminary economic analysis of selected "conceptual" Australian eel culture systems in the present study.

6.1.1 The present study

For the purposes of this study, two culture systems have nominally been identified as having potential for the commercial production of Australian eels. These are:

- Super-intensive tank culture of *A. australis* in controlled environment recirculation aquaculture systems; perhaps most relevant in the more temperate climate of south-eastern Australia where glass eels of this species are generally more commonly available
- Semi-intensive pond culture of *A. reinhardtii* under ambient conditions with supplementary aeration and water exchange; perhaps most relevant in the more tropical/sub-tropical climate of northern Australia where glass eels of this species are generally more commonly available

Clearly the opportunity exists to culture both species in systems other than those described in the present study. Indeed, commercial opportunities exist for both the super intensive tank culture of *A. reinhardtii* and the semi-intensive pond culture of *A. australis*, as is presently being practiced to a limited degree by industry. However, it is intended that this analysis be used as a guide only for existing and new eel aquaculture investors, to assist in the business planning process of both existing and planned commercial ventures for the most likely industry choice of potential species/system combinations. Furthermore, the analysis is not intended to be definitive or exhaustive, rather indicative, and designed to enable some generalised comparison of the different options in a relative, but not necessarily absolute way. In so doing, it is also intended that eel aquaculture investors will be able to gain some insight, in broad terms at least, to the economic feasibility of proposed new developments, as well as to get some idea of the relative merits of different production options and/or market scenarios and associated pricing sensitivities, before fully committing themselves.

The specific objectives of the present study therefore are to:

1. Compare the relative economic feasibility of growing *A. australis* under intensive conditions in a controlled-environment, recirculating, tank-based system, and *A. reinhardtii* under semi-intensive, ambient conditions in a pond-based system.
2. Compare the relative economic feasibility of growing these two species to 300g and 1kg market size under such conditions.
3. Provide an indication of Best Practice management requirements for economically viable aquaculture production of Australian anguillids under such conditions.

6.1.2 Limitations of the study

It should be recognised that such analyses, which are typically based on a combination of actual data and a suite of intuitive and generalised assumptions, are limited, particularly in the case of new and developing sectors such as eel aquaculture, in which:

- Key production parameters are either not known or typically are changing rapidly as new and innovative technologies and associated improvements become available.
- Market dynamics are such that new opportunities may open up which have not previously been identified, or existing markets may change due to global circumstances beyond any immediate control.

- The risk of industry and/or market failure may impact in a way that was not initially anticipated, including at a "catastrophic" scale.
- The aquaculture and/or business skills base of proponents may be insufficient at some key point in the development of the business that it becomes a limiting factor not previously anticipated.

In addition, many external factors such as currency exchange, interest and inflation rate fluctuations will also have a major bearing on financial analysis of all possible farming systems for all species.

6.2 MATERIALS & METHODS

The analysis is based on the development of two separate eel aquaculture bio-economic models, each then run for a range of different "product" and "market" scenarios (all dollars quoted are in Australian currency, unless otherwise stated), viz.:

- Models
  - #1: Tank-based *A. australis* production.
  - #2: Pond-based *A. reinhardtii* production.
- Product scenarios
  - 300g fish in 15 months.
  - 1kg fish in 24 months.
- Market scenarios
  - $10, 15 and 20/kg farm-gate price.
  - Various combinations of 0, 25, 50, 75 and 100% of product sold at each of the three nominal farm-gate prices.

For the purposes of this study, the models assume that growth and survival rates and FCRs are identical for the two species, that the systems are designed to accommodate a 50kg annual glass eel intake, either as glass eels directly (for Model #1) or as a subsequent relative quantity of weaned 1g elvers (for Model #2). Given that stocking densities and operational requirements for the two systems will vary according to system design, this means that a relative cost comparison can be made for getting each batch of glass eels through to market size under the different scenarios outlined above. It is also assumed for this study that the choice of system is geographically limited, such that pond culture of eels under ambient conditions is unlikely to be viable in temperate regions of Australia, and that there is likely to be limited competitive advantage in tank culturing eels under controlled environment conditions in tropical/sub-tropical regions of Australia.

6.2.1 Production and Cost Assumptions.

At the present time, Best Practice aquaculture production of *Anguilla* spp. is estimated to be in the order of 500kg production of 150-200g eels in 12-15 months from each 1kg intake of glass eels. This is based on intensive, tank-based production of *A. anguilla* in recirculating systems in Europe (G.Gooley, unpublished data). For the purposes of this study it is also assumed that:

- such production is possible for other anguillids under similar conditions, although this is not yet the case in practice.
- a similar (Best Practice) glass eel:marketable eel biomass ratio is possible (at least as good) for larger 300g Australia eels produced over 15 months (see above).

- growth, FCR and survival rates would remain consistent over a further 9 months under the same production conditions in order to achieve a larger final market size of 1kg after 24 months
- both Australian anguillid species are equally suitable for both intensive and semi-intensive production in tanks and ponds respectively (subject to previously mentioned geographic limitations on system choice) and that largely similar production parameters will apply to each species.

Based on these assumptions, the different scenarios for the two models have been designed to be as similar as possible so that they are interchangeable, and therefore broadly comparable, between the two eel species under consideration. As previously stated, the ability to grow larger 1kg fish of either species in either intensive or semi-intensive conditions, is designed to identify whether this is a viable economic option for farmers. This is despite the fact that this is presently not industry practice, and despite the likely increased production costs and associated risk. However, it also recognises the apparent opportunity to meet the relatively high demand for export quality, larger eels at or greater than 1kg in the Asian market place.

In the present study, the models make a number of further assumptions about other key system design, production and market parameters which are then fixed throughout the analysis for each of the above-mentioned scenarios. In summary, these include:

Model #1 - Capital costs

- Land value – nominal cost & area ie 5ha @ $10,000/ha.
- Miscellaneous – nominal cost of $150k to fit out with non-aquaculture specific infrastructure and equipment (eg. office, store, workshop, fencing, vehicle etc).
- Recirculation aquaculture system (RAS), tanks and miscellaneous aquaculture infrastructure and equipment – based on current industry investment benchmark (*AQUAfarmer*™) and proportional to projected production levels (see Model #1 & 2 Returns).
- RAS #1 (valued at current industry prices) for a maximum production level of approximately 70 tonnes priced at $750,000 plus requisite number of tanks at current market prices (suitable for production of 300g eels).
- RAS #2 (valued at current industry prices) for a maximum production level of approximately 200 tonnes, priced at $1,500,0000, plus requisite number of tanks at current market prices (suitable for production of 1kg eels).
- Aquaculture specific building to house RAS @ nominal $50k for RAS #1 and $200k for RAS #2.

Model #1 - Operating costs

- All initial capital set-up costs and first year operating costs are borrowed at a commercial interest rate of 8% per annum (assuming the borrower has sufficient collateral); annual loan repayments are based on principle and interest, with the loan paid off after ten years.
- Seedstock is based on annual 50kg glass eel intake directly to the grow-out farm @ nominal $250/kg with 75% survival to 1g elvers, 80% survival rate for 1g seedstock to 300g market size, and 75% survival for 1g seedstock to 1kg market size.
- Labour costs based on 2.5 x 'full-time equivalent persons' (FTEs) for 300g production scenario which includes a full time manager and 1.5 FTE assistants, and 5 x FTEs for 1kg production scenario, which includes 2.5 extra FTE assistants.
- Transport and packaging combined based on nominal $4/kg cost to the farmer to land live fish in Asian export markets.

- Depreciation is treated as an annual fixed cost. It is calculated according to the straight line method which uses the initial value of the goods being depreciated (iv), the life of the asset (L) and the residual value (rv) expressed as a %. Annual depreciation is then equal to (iv-(iv*rv))/L.
- Feed costs based on final production (tonnage) estimates (see *Returns*) @ nominal FCR of 2.5 and price of AUD$1.50/kg for growout of 1g seedstock.
- Water based on 10% daily exchange @ $650/ML for domestic supply.
- Energy primarily electricity/other for pumps, aerators, heating, oxygen generation etc @ nominal $0.60/kg of final production.
- Other operating based on nominal estimates for administration, maintenance, rates, insurance etc @ AUD$0.50/kg of final production.

Model #2 - Capital costs

- Land value – nominal cost & area ie 50ha @ $1,000/ha.
- Miscellaneous – nominal cost of $150k to fit out with non-aquaculture specific infrastructure and equipment (eg. office, store, workshop, fencing, vehicle etc).
- Pond and aerator costs based on projected production levels (see *Returns*) @ nominal AUD$10,000/1000m^3 pond and AUD$750/aerator (2 aerators per pond) respectively.

Model #2 – Operating costs

- All capital costs and first year operating costs are borrowed at commercial rate of interest @ nominal 8% per annum for capital and 10% for year 1 operating (assume that the borrower has sufficient collateral); annual loan repayments are based on principle and interest, with the loan paid off after ten years.
- Seedstock is based on annual 50kg glass eel "allocation", weaned and grown out with 75% survival to 1g elvers by a third party and on-sold to the growout farmer @ nominal $500/kg, with 80% survival rate for 1g seedstock to 300g market size, and 75% survival for 1g seedstock to 1kg market size.
- Labour costs based on 2.5 x FTEs for 300g production scenario which includes a full time manager and 1.5 FTE assistants, and 5 x FTEs for 1kg production scenario, which includes extra assistants.
- Transport and packaging combined based on nominal AUD$4/kg cost to the farmer to land live fish in Asian export markets.
- Depreciation is treated as an annual fixed cost. It is calculated according to the straight line method which uses the initial value of the goods being depreciated (iv), the life of the asset (L) and the residual value (rv) expressed as a %. Annual depreciation is then equal to (iv-(iv*rv))/L.
- Feed costs based on final production (tonnage) estimates (see *Returns*) @ nominal FCR of 2.5 and price of AUD$1.50/kg.
- Water based on 50% weekly exchange @ AUD$200/ML for commercial irrigation supply
- Energy primarily electricity for pumps and aerators @ nominal AUD$0.20/kg of final production.
- Other operating based on nominal estimates for administration, maintenance, rates, insurance etc @ AUD$0.50/kg.

Model #1 & 2 - Returns

- All fish produced are sold as live product with prices quoted to the farmer inclusive of packaging and freight costs landed in Asian markets.
- Annual production is based on a 50kg annual glass eel intake provided directly to the farmer in Model #1, and as the equivalent quantity of 1g elvers in Model #2, both

purchased at market rates (@ $250/kg for glass eels and @ $500/kg for weaned 1g elvers) from commercial suppliers.

- Annual production is based on a nominal 75% survival rate for glass eels to 1g size, 80% survival rate for 1g seedstock to 300g market size and 75% survival rate for 1g seedstock to 1kg market size.
- Annual production is based on growout stocking densities at maximum standing crop of 75kg/m^3 and 25kg/m^3 for Model #1 and 2 respectively, each of which then determine specific production infrastructure needs (including tanks and ponds) and associated capital costs.
- Value of annual production for different scenarios are based on nominal combinations of set (farm gate) market price ($10,15,20/kg) and proportion of production (0,25,50,75,100%) at each nominated price.
- Both models assume that in practice glass eels will be available each year (50kg annual intake – see previous assumptions for Model #1 & 2) and that seasonality restrictions on glass eel numbers will not affect production and therefore projected financial returns.

6.2.2 Profitability Indicators and Risk

In the present study, the profitability indicators for the two models are identical and include the use of discounting at a rate of 10% in order to convert future value (FV) statements. Discounting uses the following relationship expressing the ratio of present value (PV) to future value in terms of the discount rate r, and time difference n,

$$PV/FV_{(year\ n)} = 1/(1+r)^n$$

For each of the models, economic viability invariably has its costs and benefits spread over a number of years and subsequently requires that time stream's of costs and benefits be reduced to a single number.

Using a modification of an existing proprietary, spreadsheet-based, economic software package (*AQUAfarmer*™ - developed by Fisheries Victoria (Department of Natural Resources and Environment) (DNRE 1999), various combinations of capital (fixed) and operating (variable) fish production and system design costs and market price scenarios, as summarised above, were tested to estimate Profit Margin (PM), Net Present Value (NPV) and Internal Rate of Return (IRR) for each of the specified models (see Appendix for definition of PM, NPV and IRR as used in the present study).

For the purposes of this study, estimates of NPV and IRR include a residual (salvage) value of 25% of capital equipment and infrastructure and 100% of land, as well as a proportionate value of partly grown stock on hand at the end of the tenth year. Nominal risk (eg. catastrophic crop failure through disease, system malfunction etc) has been included for all scenarios and associated financial indicators. This risk is based on a nominal 25% and 75% "extraordinary" medium stage mortality every 5 years for 300g and 1kg production respectively. In these years, the revenue loss is partly offset by 25% of the value of the lost production being recouped through an insurance payout along with a nominal 50% reduction in operating costs due to the reduced production level. Tax benefits are made available to alleviate annual operating losses through income averaging over two year cycles, otherwise tax rates are set at a nominal 29% per annum.

6.3 RESULTS

Summaries of NPV, IRR and PM for the different market price scenarios for each model are provided in Table 6.1, Table 6.2, Table 6.3 and Table 6.4 with the percentage of final marketable product sold at each of AUD$10, 15 and 20/kg in that order denoted on the left hand side of each table (eg. Price of 50/25/25 = 50% sold @ $10/kg, 25% @ $15/kg and 25% @ $20/kg). Negative IRRs are not shown. The break even point in NPV for each model (based on 100% of sales of marketable product) is between $10-15/kg (Fig. 6.1, Fig. 6.2, Fig. 6.3 and Fig. 6.4).

The major annual (operating) cost items are feed (at about the normal industry standard of 30% of total costs), packaging/freight and loan repayments, the latter of which is most relevant to the Model #1 scenarios which are having to service debt on substantial capital costs for the recirculation system.

As expected, profitability increases in all cases with increased proportion of sales being at the higher prices. More specifically, in most scenarios the tested models do not become economically viable until at least 50% of the production is sold at prices of $15/kg or better. For this study, viability is defined as being achieved when one or more of the key profitability indicators meets or exceeds specified benchmarks as follows:

- NPV – positive value
- IRR – minimum 10-15% > commercial interest rates (presently at around 6-7%)
- PM – ≥ Australian agribusiness (agriculture, forestry, fisheries) industry benchmark (presently about 14%)

6.4 DISCUSSION

The results of the present study suggest that there is relatively little difference in profitability of growing Australian anguillid eels intensively in tanks (Model #1) compared with semi-intensively in ponds (Model #2) up to 300g market size, but that profitability of the latter exceeds the former for production of larger, 1kg eels. The apparent profitability differential in favour of the larger eels in Model #2 is likely due to the increased production costs for 1 kg eels in Model #1. These include increased capital costs for infrastructure and equipment (eg. for water treatment), as well as operating costs (eg. energy, water etc), most of which are unique to recirculating aquaculture systems.

The results also suggest that there is no obvious economic disadvantage overall in having to pay a higher price for seedstock as weaned elvers, as is the case for Model #2, compared with purchasing seedstock directly as pre-weaned glass eels (as for Model #1). Any initial price disadvantage for the increased cost of the larger seedstock is largely compensated for by the relatively cheaper production costs for pond farmers operating under ambient conditions, although it is assumed that such production is consistent with industry Best Practice management standards.

Table 6.1 Summary of price structure (% sold at $10/$15/$20 per kg) and associated NPV, IRR and PM for intensive tank production of 300g *A. australis*.

	SF Eel 300g		
Price	NPV	IRR	PM
100/00/00	-$734,465	3.00%	-29.56%
75/25/00	-$451,630	8.00%	-15.14%
50/50/00	-$169,453	13.00%	-3.63%
50/25/25	$112,725	17.00%	5.79%
25/75/00	$112,725	17.00%	5.79%
00/100/00	$394,902	21.00%	13.64%
00/75/25	$677,079	25.00%	20.29%
00/00/100	$1,523,611	36.00%	35.23%

Table 6.2 Summary of price structure (% sold at $10/$15/$20 per kg) and associated NPV, IRR and PM for intensive tank production of 1kg *A. australis*.

	SF Eel 1Kg		
Price	NPV	IRR	PM
100/00/00	-$1,123,437		-19.82%
75/25/00	-$307,579	7.00%	-6.50%
50/50/00	$508,279	15.00%	4.15%
50/25/25	$1,324,136	21.00%	15.65%
25/75/00	$1,324,136	21.00%	15.65%
00/100/00	$2,139,994	27.00%	20.26%
00/75/25	$2,955,852	33.00%	24.17%
00/00/100	$5,403,425	47.00%	32.95%

Table 6.3 Summary of price structure (% sold at $10/$15/$20 per kg) and associated NPV, IRR and PM for semi-intensive pond production of 300g *A. reinhardtii*.

	LF Eel 300g		
Price	NPV	IRR	PM
100/00/00	-$720,912		-34.57%
75/25/00	-$438,735		-19.62%
50/50/00	-$156,558	5.00%	-7.65%
50/25/25	$125,620	14.00%	2.13%
25/75/00	$125,620	14.00%	2.13%
00/100/00	$407,797	22.00%	10.29%
00/75/25	$689,974	29.00%	17.19%
00/00/100	$1,536,506	49.00%	32.72%

Table 6.4 Summary of price structure (% sold at $10/$15/$20 per kg) and associated NPV, IRR and PM for semi-intensive pond production of 1kg *A. reinhardtii*.

	LF Eel 1Kg		
Price	NPV	IRR	PM
100/00/00	-$744,945		-9.72%
75/25/00	$67,032	11.00%	8.51%
50/50/00	$875,996	25.00%	14.70%
50/25/25	$1,698,678	38.00%	19.87%
25/75/00	$1,698,678	38.00%	19.87%
00/100/00	$2,514,605	49.00%	24.13%
00/75/25	$3,330,462	59.00%	27.74%
00/00/100	$5,778,036	84.00%	35.85%

Fig. 6.1 NPV break even point for intensive, tank-cultured 300g *A. australis* with 100% of production sold at $10, $15 and $20/kg.

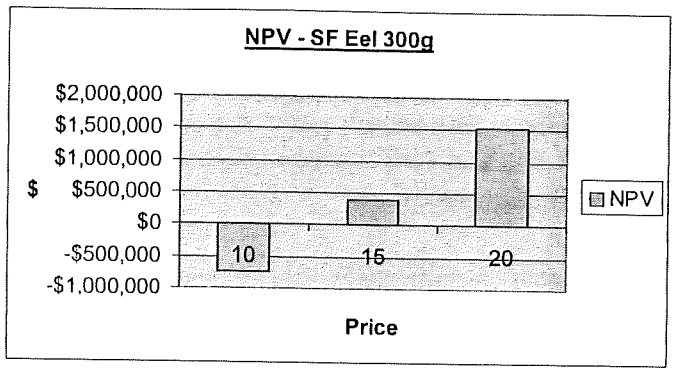


Fig. 6.2 NPV break even point for intensive, tank-cultured 1kg *A. australis* with 100% of production sold at $10, $15 and $20/kg.

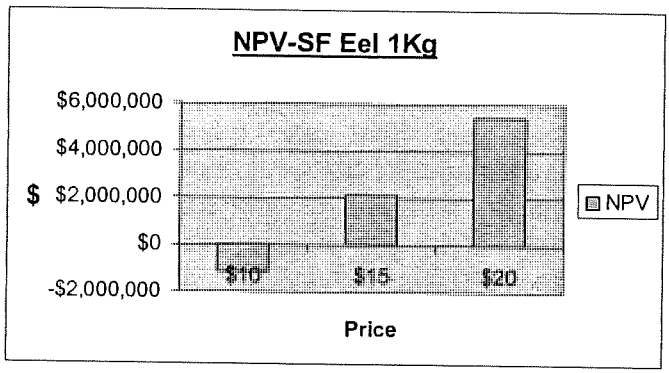


Fig. 6.3 NPV break even point for semi-intensive, pond cultured 300g *A. reinhardtii* with 100% of production sold at $10, $15 and $20/kg.

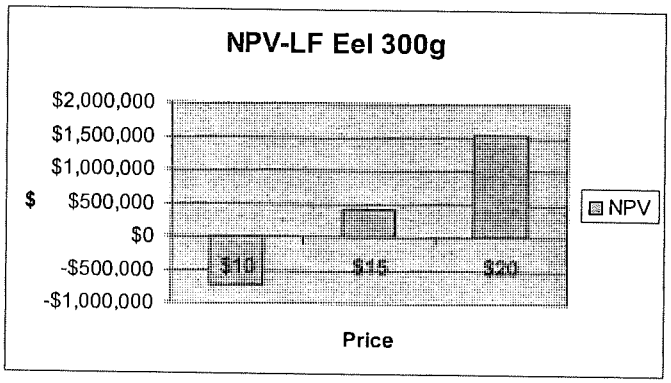
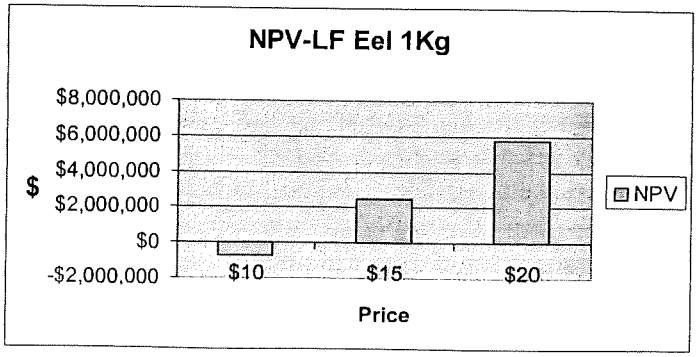


Fig. 6.4 NPV break even point for semi-intensive, pond cultured 1kg *A. reinhardtii* with 100% of production sold at $10, $15 and $20/kg.



Overall, the study suggests that production of larger, 1kg eels also appears to be relatively more profitable than production of 300g sized eels, independent of choice of production system. This is due to the proportionately increased biomass of marketable product and the associated economies of scale (costs per unit decrease over time) for the larger fish scenario, despite the increased risk associated with holding the fish for a much longer production period. Indeed, in this comparison, the production costs actually reduce on a per kg basis for both models (approximately 7.5% and 19% for Model #s 1 and 2 respectively) in going from 300g to 1 kg market size production scenarios.

Although production of 1kg eels in such systems, as described in the present study, is not being practiced presently by the industry *per se*, it is suggested that this should be considered as a potentially commercially viable option. To be economically viable however, such an option will need to adopt Best Practice management and target high value markets at a minimum live price of about $15/kg for larger eels and $15-20/kg for smaller eels. At the present time, industry sources suggest that export markets exist at these prices for the former but not the latter.

A cost comparison between conventional, semi-intensive channel catfish production in ponds under under ambient conditions and "best case" production of tilapia under intensive conditions in a recirculating aquaculture facility, at similar scales of production and economic parameter inputs, suggests that the latter is slightly more cost-efficient than the former (Timmons and Henehan 1995). This study also notes the potential risks specifically associated with intensive recirculation aquaculture production by such systems not performing to technical specification. However, the cost-comparison assumes identical levels of risk, as determined by assigned mortality rates, between the two systems (Timmons and Henehan 1995). In the present study, the cost comparison between pond and tank eel production assumes a much higher level of risk associated with the latter.

Although some assumptions in the present study may be somewhat ambitious, in reality, eel production costs may actually be less than described in the present study due to the introduction of various technical, operational and business efficiencies on an enterprise specific basis. For example, the model assumes that all eels reach market size at the same time, whereas in practice this will occur over a period of several months after which a small proportion of eels will probably be discarded due to poor growth. On the other hand, the model also assumes that all eels are sold live and exported, which incurs a substantial freight and packaging cost (estimated at $4/kg; approximately 34.1-44.3% of the production costs for all systems/scenarios). In practice, any eels sold into the domestic market or exported non-live will have reduced freight costs. Also, in practice, Australian producers would have the option of value-adding through smoking, portion control and packaging in order to increase profitability.

Another example may be in relation to glass eel intake, which in the present study is fixed at 50kg/annum. Indeed if larger quantities of glass eels are available, and if market demand exceeds supply, the specified farming systems could well have the capacity to increase productivity by simply increasing stocking densities and associated standing crop. Stocking densities in the present study are assumed to be fixed at very conservative levels, which in practice could easily be increased significantly without incurring any further capital costs. Best Practice intensive eel farming in Europe is known to routinely reach stocking densities in excess of 200kg/m^3, more than double the densities assumed in the present study for comparable systems.

In 1999-2000, a total of about 44 tonnes of (predominantly farmed) eels worth approximately $0.43 million were imported into Australia as fresh, chilled and frozen product (Brown and Connell 2001). Much of this product is then substantially value-added, with 100g smoked and packaged fillet portions retailing for >$9/piece. Furthermore, there is thought to be a substantial latent demand in Australia for farmed eel produce from certain European ethnic groups, particularly the Australian Dutch, Asian and middle European (eg. Latvian) communities, which routinely harvest large quantities of eels (estimated several hundred kg/week Australian-wide) on a non-commercial basis from inland waters for their own consumption. At least some of this demand could be met via local aquaculture production. The opportunity also exists for eel farmers to supplement wild fisheries production by various means, at a time when market prices for wild eels, particularly at the 1kg or greater size, are priced at a premium in both Asian and European markets.

In relation to technical efficiencies, the models assume relatively conservative FCRs and maximum stocking densities, each of which are presently being exceeded in practice in both Australia and overseas for commercial anguillid species (see Chapter 4). It is therefore considered technically feasible that cost-effective production of Australian anguillid eels could be achieved through adoption and/or development of Best Practice management guidelines as described in the present study.

In conclusion, under Australian conditions it is likely that the final determinant as to the target species and associated aquaculture system to use for anguillid eel production will have as much to do with various practical considerations such as the suitability of ambient climatic conditions, access to markets, glass eel seedstock, sites and finance, as it will be to do with cost-benefit analysis of alternative system design characteristics and performance.

6.5 ACKNOWLEDGMENTS

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6.6 REFERENCES

Brown, D. and Connell, P. (2001). *Market Demand for Australian Aquaculture Products. Report to the Fisheries Resources Research Fund.* Project No. 1529. Australian Bureau of Agricultural and Resource Economics. Canberra. 46 pp.

DNRE. (1999). *AQUAfarmer Ver 1.1 for Recirculation Aquaculture.* Department of Natural Resources and Environment, Melbourne, Victoria.

Milon, J.W. and Shogren, J.F. (1995). Integrating economic and ecological indicators. In: *Practical Methods for Environmental Policy Analysis.* Praeger, London.

Sassone, P.G. and Schaffer, W.A. (1978). *Cost-Benefit Analysis. A Handbook.* Academic Press, London.

Snell, M. (1997). *Cost Benefit for Engineers and Planners.* Thomas Telford Publishing, London. 306 pp.

Timmons, M.B. and Henehan, B. (1995). *Engineering Economic Analysis of Indoor Versus Pond Aquaculture. Unpublished Data.* Department of Agriculture and Biological Engineering, Cornell University. USA.

6.7 APPENDIX

Key Economic Indicators Used In Bio-Economic Model In The Present Study

- after Sassone and Schaffer (1978), Snell (1997) and Milon and Shogren (1995).

Nett Present Value (NPV)

The NPV method of evaluating investment is the preferred way of measuring economic activity through time. The NPV takes account of the time value of money. This method allows us to compare alternative multi-year investments on a uniform basis. If a NPV of an investment is greater than the initial investment then the project is deemed viable. It essentially tells the investor/operator what the net present value of his investment should be over time. After taking into account parameters such as, cash flows over a period, loan requirements (if any), discount rate of interest, capital required and the effects of any sensitivity parameters over time, such as feed price and sale price, this method can produce a present evaluation through time. Discount rates usually reflect the riskiness of the project, the riskier the project the larger the discount rate.

NPV = The total or net present value of an investment's worth discounted through a period of time taking into account future cash payments and income. Can also be represented as the excess of present value over cost.

Given a stream of net benefits, $\beta_0,\beta_1,\beta_2,\ldots\ldots\ldots\ldots\beta_n$ where the β's are positive, zero or negative ie. Benefits – Costs (B-C), or initial set-up cost, the NPV is given by

$$\beta_0 + \beta_1/(1+r) + \beta_2/(1+r)^2 + \ldots\ldots\ldots \beta_n/(1+r)^n$$

or more briefly,

$$\Sigma\ \beta_t/(1+r)^t$$

where r is the discount rate, and t is time.

Internal Rate of Return (IRR)

The Internal Rate of Return (IRR), is the discount rate applicable to where NPV minus initial investment is equal to zero. Taking account of time also the IRR is a more respectable form of the average rate of return which merely sums the net benefits over the life of a project and divides them by the number of years in which they occur. Using the discounting methodology it is a measure popularized by John Meynard Keynes and is currently used as a key evaluative tool within the banking and finance sector. It is defined as that rate of discounting the future that equates the initial cost and the sum of the future discounted net benefits.

Put otherwise, the IRR is that rate of discount, which makes the present value of the entire stream – benefits and costs – exactly equal to zero ie. That is, the IRR is some value of r such that;

$$\beta_0/(1+r)+\beta_1/(1+r)^2+\beta_2/(1+r)^3+\ldots\ldots\ldots\beta_n/(1+r)^n = 0$$

or more briefly,

$$\sum\ \beta_t/(1+r)^t = 0$$

Profit Margin (PM)

It is helpful to compare one specific dollar amount with another dollar amount on the same statement. This sort of comparison results in a ratio analysis that helps analyse an operations * strength and solvency and * earning power and growth potential. A Profit Margin relates profit to sales revenue to give the reader an exact margin, in percentage form, for profits made. Essentially it is the margin in relation to sales and can either be compared with gross profit or net profit before tax or after tax.

7 OUTCOMES OF FRDC-FUNDED AUSTRALIAN ANGUILLID GLASS EEL R&D (1997/8-1999/2000) (FRDC PROJECT NO. 97/312 & NO. 99/330)

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Gooley, G.J. (2002). Outcomes of FRDC-funded Australian anguillid glass eel R&D (1997/8-1999/2000) (FRDC Project No. 97/312 & No. 99/330). In: *Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture* (ed. G.J. Gooley and B.A. Ingram), pp 197-203. Final Report to Fisheries Research and Development Corporation (Project No. 97/312 and No. 99/330). Marine and Freshwater Resources Institute, Alexandra, Victoria, Australia.

CONTENTS

7.1 INTRODUCTION

The research into Australian anguillid glass eel assessment and aquaculture utilisation funded by the Fisheries Research and Development Corporation (FRDC), as part of FRDC Project No. 97/312 (1997/8-1999/2000), has addressed a number of information gaps relevant to eel aquaculture industry development in Australia. Although much of the information provided in this report is of a preliminary nature, it does build considerably on the previous FRDC-funded work (FRDC Project No. 94/067) reported by Gooley *et al.* (1999) specifically for shortfin glass eels, *Anguilla australis*. In conjunction with FRDC Project No. 99/330 (1999/2000), this study also provides significant, new glass eel assessment and aquaculture information on the longfin eel, *A. reinhardtii*.

The outcomes and associated management and industry development implications of this work can be effectively summarised in relation to three distinct stakeholder sectors, *viz*. wild fishery industry, aquaculture industry and resource management (government and industry combined). Details regarding project conclusions, benefits and further developments specific for each of the major sub-project components (assessment and aquaculture) have been documented to a large extent as part of the respective Results/Discussion sections in the preceding chapters of this report. However an overall project summary of such outcomes is also provided in this chapter for convenience and to meet standard, Final Report formatting requirements for FRDC.

7.2 R&D CONCLUSIONS AND BENEFITS

The most immediate beneficiaries of the research outcomes of this project are the commercial eel fishing and aquaculture industry sectors in Australia, as well as the relevant state fisheries agencies in Queensland, New South Wales, Victoria and Tasmania. Indeed, as a direct, cumulative result of recent FRDC-funded glass eel R&D (this and related projects as previously mentioned), either wholly or in part, commercial glass eel fishing and aquaculture utilisation is now being practised to varying degrees by industry in Victoria, NSW and Queensland. Further glass eel-based eel industry development is also pending in all states, including Tasmania, although constraints do exist with respect to industry access to the resource and appropriate expertise and technology, and presently in relation to market demand/production cost dynamics.

The conclusions drawn from this project are therefore highly relevant, and the associated flow of benefits (both real and potential) to the key stakeholders are described for each of the previously mentioned sectors in the following sections of this chapter.

7.2.1 Wild Fishery Sector

Ready and ongoing access to sustainable, commercial quantities of suitable, endemic glass eel resources is crucial to the viability of an expanded eel aquaculture industry in Australia. To this end suitable sites and fishing techniques have been identified and/or further elucidated in the present study for harvesting of longfin and shortfin glass eels in Victoria (Snowy River) and Queensland (Albert River), albeit in the absence of any absolute estimate of the total size of the resource. Nonetheless, sufficient information exists at the present time to initiate, or continue (as the case may be) commercial harvesting of glass eels of both species at these sites under a precautionary, risk management approach, and subject to market demand.

Quantities of glass eels in the order of 100-200 kg per species per site are considered reasonable to be harvested in the first instance on an annual basis. In the longer term, and subject to appropriate site specific and fishery-wide guidelines, it is suggested that up to 500kg of at least shortfin glass eels could be harvested annually on a sustainable basis from the Snowy River. The potential for increased harvesting of longfin glass eels in the Snowy River, beyond the above-mentioned levels, is presently unclear due to the limited data available. The potential for increased harvesting of either species in the Albert River appears to be limited due to the risks of impacting on standing crop in the catchment. This risk in turn is due to the relatively high fishing efficiency associated with harvesting glass eels in the Albert River using the preferred sites and collection methods as described in this study. Glass eel fishing in the Albert River is also complicated by the mix of species in the catch, with both species often being taken at the same time and place. However, it is likely that there are a number of other potentially more suitable glass eel collection sites/waters which need to be evaluated in Queensland, particularly for longfin glass eels, given the known natural distribution of the species in this area.

Clearly much of the risk associated with glass eel harvesting in Australia, for whatever species, needs to be managed within a ‘precautionary approach’, as the underpinning principles of formal fisheries management plans. A new eel management plan, designed to facilitate such harvesting in Victoria in a manner consistent with Environment Australia’s ESD imperatives, is presently in final draft format by Fisheries Victoria prior to receiving final endorsement by government and industry in this state (McKinnon 2001). In part, this plan is specifically intended to facilitate regulated access to glass eel harvesting in the Snowy

River, and in other suitable waters within Victoria which are presently subject to limited access licensing provisions relevant only to existing licensed eel fishers. Subject to the provisions of the proposed management plan, the potential exists therefore to harvest at least as many glass eels again collectively from these other waters as could potentially be harvested from the Snowy alone.

Although suitable sites for harvesting of commercial quantities of glass eels at similar scales have not yet been confirmed in NSW and Tasmania, both species were collected in the present study at port Hacking in NSW and at least shortfin glass eels were taken in the Prosser River in Tasmania. Anecdotal information and previous studies by Sloane (1984), Beumer and Sloane (1990) and Gooley *et al.* (1999) have also collected glass eels from other waters in these states, particularly shortfin eels in the Tamar River in Tasmania. This suggests therefore that a significant glass eel resource may be accessible in these areas, if in fact suitable collection sites and/or associated fishing techniques can be subsequently identified.

High quality Australian glass eels are estimated to have a minimum commercial 'beach' value in the order of AUD$150-250/kg in the domestic market place, inclusive of initial sorting, storage, and aquaculture acclimation and weaning. Subsequent aquaculture-based 'nursery' costs associated with feeding and general maintenance are likely to proportionately increase the costs of larger, weaned, pigmented glass eels and/or elvers up to an estimated cost of AUD$200-500/kg (subject to size, stage of development, general condition etc). Such a 'product' would then be suitable for domestic use as either seedstock for intensive aquaculture or re-stock for open water stock enhancement (also referred to as extensive culture). By comparison, it is useful to note that this scenario has some broad similarities to the prevailing circumstances in the European glass eel industry.

The adoption by industry of efficient and environmentally sustainable Best Practice glass eel fishing and aquaculture standards will be critical to achieving significant productivity gains in the Australian eel industry. Although experience with other juvenile and sub-adult development stages is relatively common place in the Australian eel industry, at the present time there are few experienced glass eel operators available. Accordingly, industry extension and training will be of paramount importance in order to realise many of the commercial benefits flowing from this study. To this end, *Preliminary Best Practice Glass Eel Fishing and Aquaculture Guidelines* have been prepared as a key extension output of the present study (McKinnon *et al.* 2001) (see Appendix I). These guidelines are in the form of a brief technical report and are intended to be used by industry as a practical extension tool.

Actual prices for glass eels and elvers however will ultimately be determined also by industry demand and associated availability as much as anything else. This demand in turn is impacted by market forces and, in the case of the stock-enhanced wild fishery at least, access to suitable 'open' waters for extensive production. Historically, the major eel fishery production from stock enhanced waters has been in Victoria using wild caught elvers from Tasmania as seedstock, although natural recruitment also occurs to varying degrees in some of these waters. In practice, several successive years of drought in this area has limited the number of suitable waters (mostly lakes, swamps and farm dams etc) available for this activity and production has declined to an estimated 10-20% of capacity. Subject to the availability of suitable waters, the use of glass eel seedstock has the potential to supplement and/or ultimately fully replace wild elver seedstock for wild fishery enhancement purposes in Victoria at least to the point where production can be fully recovered to previous estimated levels in the order of 100-200 tonnes pa.

Glass eel-based seedstock is considered to offer distinct advantages over wild caught juveniles for stock enhancement and aquaculture, including the fact that they are of a single size and age cohort, can be to some extent selected for specific characteristics (eg. size, development stage), and can be reasonably assured to be disease-free. They are also thought to be more conducive to rapid, 'compensatory' growth spurts under optimal production conditions, although this has yet to be tested in other than intensive, tank-based culture systems. Financial cost-benefit and environmental sustainability imperatives will ultimately determine industry preference for the eel seedstock of choice.

At this stage it is not envisaged that Australian glass eel seedstock would have any direct export potential of any consequence, largely due to the availability of relatively limited quantities by global industry standards.

7.2.2 Aquaculture Sector

The flow of benefits of the present study to the aquaculture sector relate directly to the increased access by industry to larger quantities of better quality glass eel seedstock for high density production purposes, along with improved technology, husbandry and feed formulations to facilitate increased productivity of such culture systems. Glass eels of both shortfin and longfin species have proven to be readily adaptable to a variety of culture system designs, broadly summarised as semi-intensive, pond-based systems and intensive, tank-based systems. Although still not widely practised in Australia, the present study clearly shows that the use of glass eel seedstock for semi and fully intensive production of both species can be quite profitable under Best Practice conditions.

The actual choice of system for commercial operators typically has as much, if not more, to do with location of the farm than it does with target species. This is given that both species are presently being successfully farmed commercially in Australia in such ways, including specific examples of large-scale pond production under semi-intensive, ambient conditions in Queensland, and tank production under intensive, controlled environment conditions in Victoria. Based on commercial experiences and outcomes from the present study, both options appear to be commercially viable, albeit to varying degrees of profitability.

It is presently unclear to what extent Australian industry experiences to date reflect adequate Best Practice production standards, and therefore the extent of the productivity gains that industry can expect as a direct consequence from this study. For instance, not all farms use glass eel seedstock exclusively, with some operators still utilising wild caught elvers and sub-adults when available. This is partly because the availability of high quality, acclimated and weaned glass eels in sufficient quantity is still problematic in Australia, further aggravated by the limited availability of glass eel expertise in the Australian industry, and the perception in some cases that glass eels are relatively more expensive than the alternative. Moreover, the limited expertise available in Australia for designing and operating eel specific culture systems has also been a constraint, however this is changing rapidly as a result of the importation of European and Asian eel farming technologies and experiences gained by industry and researchers involved in the present study. As previously mentioned, *Preliminary Best Practice Glass Eels Fishing and Aquaculture Guidelines* produced as an output of this study are also intended in part to facilitate industry extension in this area (McKinnon *et al.* 2001) (see Appendix I).

As evaluated in the present study, the use of fish roe from species such as carp, *Cyprinus carpio*, warehou, *Seriolella brama*, and mackerel (Scomberomorini and Scombrini) for initial weaning of Australian anguillid glass eels, appears to offer great advantages to local

producers. Roe of these species is a readily available and relatively cheap resource in Australia presently. The selection of which roe to use in practice will be dictated by cost and accessibility, given the geographic distribution and seasonality of abundance of the target species presently under consideration. It is further noted that the use of fish roe as a weaning feed for other juvenile, Australian native finfish species with commercial value and/or potential is also now being employed more routinely in Australian aquaculture following the successful application in glass eel systems.

Conversely, there are still no specifically formulated, commercial pelleted feeds for Australian anguillids during the post-weaning/nursery and grow-out stages, meaning that in many cases industry is using sub-optimal feeds designed for other species, such as coldwater salmonids and barramundi. Some specific *A. japonica* formulated feeds have at times been imported into Australia from Asia, however these are thought to be of dubious quality and usefulness for Australian anguillids, and may not adequately satisfy Australia's import quarantine standards. As a result of the present study, species specific diet formulations, which are more nutritionally complete than presently available commercial alternatives, are now available to aquafeed companies for shortfin and longfin eels, if and when aquaculture industry demand in Australia dictates the need. In practice however it is unlikely that these formulations will be commercialised in the short term until the present scale of eel production in Australia increases significantly.

The cost-benefit analysis in this study clearly suggests that either purchasing acclimated and weaned glass eels and/or larger, pigmented elvers (collected initially as glass eels) is likely to be cost-effective, and that growing eels out to a larger size (up to 1kg) over a longer growing period (up to 24 months total) is potentially more profitable than producing smaller fish (up to 300g) over shorter production cycles (up to 15 months). Additionally, all production scenarios are sensitive to market prices, with farm-gates prices at less than $15/kg being only marginally profitable at best, and with higher prices unlikely to be realised for anything other than the larger fish. In practice, to profitably produce larger fish it will be necessary to have access to affordable feeds with an appropriate nutritional regime (as developed in the present study) and used under Best Practice conditions.

7.2.3 Government Sector (Resource Management)

The Federal Government in Australia is progressively adopting a structured framework for managing commercial fisheries and aquaculture according to the principles of Ecologically Sustainable Development (ESD). Moreover, all export fisheries, including anguillid eels, must demonstrate that they are being managed sustainably, in accordance with Environment Australia ESD-based guidelines, in order to retain export permit requirements under Schedule 4 of the Wildlife Protection (Regulation of Exports and Imports) Act 1982 (McKinnon 2001). Accordingly, with the opportunity to increase the productivity and value of the Australian eel industry through innovative utilisation of the glass eel resource, comes the need to better understand the resource and to prescribe appropriate management guidelines. In this context therefore, the outcomes of the present study will greatly benefit fisheries managers in the respective state agencies through providing more accurate and comprehensive life history and fisheries assessment information.

Given the likelihood that Australian anguillid species represent single, genetically panmictic stocks, there is also a need for a degree of coordination of management arrangements across state boundaries in Australia, and possibly even including New Zealand in the case of shortfin eels. This places an additional premium on managers having access to reliable information on Australian eel resources, and to enable them to better understand all aspects of the differing

and very complex life history stages, from marine (oceanic and inshore) through to freshwater. Furthermore, the extensive range, complex life history, relatively long life span, age at first maturity/spawning, and associated spatial and temporal variability of recruitment in glass eels of all species dictates the need for establishment and maintenance of long term databases (> 10-20 years?) to be at all effective. These databases should include key recruitment indices across a broad spatial scale (multiple sites) throughout the range of the respective species. The outcomes of this project provide the basis for some of these databases, particularly in relation to CPUE in the Snowy River in Victoria, which is likely to be a key monitoring site for the Victorian/south-eastern Australian extent of the shortfin eel distribution. The Australia New Zealand Eel Reference Group (ANZERG), which has provided an informal Steering Committee role for this study, is a logical forum in which cross boundary eel management issues can be addressed using this type of information at a national level, and therefore will be a key stakeholder in future eel management developments in Australia.

7.3 FURTHER DEVELOPMENTS

As previously mentioned, the Fisheries R&D Corporation of recent years has invested significant funds into the development of the commercial eel fishery and aquaculture sector within Australia. Most notably the FRDC has funded two major projects managed by the Marine and Freshwater Resources Institute in Victoria, Australia, which have investigated aspects of glass eel stock assessment and aquaculture. These projects (FRDC Project No's 94/067 and 97/312) have involved extensive collaboration between MAFRI, Deakin University and the Queensland Department of Primary Industries, NSW Fisheries and the Inland Fisheries Service Tasmania. The FRDC has also recently funded projects investigating aspects of the wild eel fishery in Queensland and NSW.

As a consequence of much of this work, clearly the opportunity now exists through utilisation of the Australian glass eel resource to provide sustainable access to an additional eel seedstock supply for commercial purposes in the order of several million 'pieces' (individuals) of each species. Subject to market dynamics, this has the potential to more than double the present levels of industry productivity and profitability, if in fact various bureaucratic impediments (management planning, licensing etc) can be resolved and industry investment and associated development can be achieved on a nationally strategic basis.

Given the ongoing level of industry support for R&D in this area, the FRDC has more recently adopted a strategic approach to investing in this sector through the development of a national eel fishery & aquaculture R&D strategic plan. This plan emphasises national R&D priorities for the eel sector (eastern Australian states) and has engaged all relevant stakeholders including industry, Government and researchers.

Before proceeding to implementation of the R&D plan, FRDC has now identified the logical next step in addressing the strategic needs of the eel aquaculture industry sector. Indeed the FRDC has determined that the R&D Plan in itself is insufficient to determine an appropriate level of R&D investment in eel aquaculture in the absence of key business and economic information. Such a nexus is consistent with the vagaries of many new and developing aquaculture species. Furthermore, there are few examples/templates of such information databases to support R&D investment decisions for such new commercial entrants.

Specifically, the need to describe an appropriate industry development strategy, together with an analysis of the investment potential for eel aquaculture in Australia, is now apparent. This

strategy should complement the R&D strategy and effectively provide the commercial rationale for further investment in eel R&D and associated industry development in Australia.

Although intended to focus on the new and developing eel aquaculture sector in Australia, any subsequent analysis is expected to also address attendant issues relevant to the wild glass eel and elver fishery, recognising the need for wild seedstock to support eel aquaculture at the present time. Furthermore, such an analysis should consider both existing commercially significant eel species in Australia, viz., shortfin and longfin eels. Based on these imperatives, a new FRDC project (No. 2000/264), entitled *Australian Eel Aquaculture Industry Development Strategy & Associated Investment Analysis* with the following broad objectives is now in progress:

1. To analyse shortfin and longfin eel aquaculture investment potential in Australia, including development of an appropriate Decision Support Information database for Government and industry
2. To determine strategic guidelines for development of the Australian shortfin and longfin eel aquaculture industry, including evaluation of national R&D priorities.

7.4 REFERENCES

Beumer, J. and Sloane, R. (1990). Distribution and abundance of glass-eels *Anguilla* spp. in East Australian waters. *Int. Rev. Gesamt. Hydrobiol.* 75(6): 721-736.

Gooley, G.J., McKinnon, L.J., Ingram, B.A., Larkin, B., Collins, R.O. and de Silva, S.S. (1999). *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production. Final Report FRDC Project No 94/067.* Marine and Freshwater Resources Institute, Alexandra, Australia. 124 pp.

McKinnon, L. (2001). *Victorian Eel Fishery Management Plan*. Marine and Freshwater Resources Institute. Queenscliff. 37 pp.

McKinnon, L.J., Ingram, B.A., Larkin, B. and Gasior, R.J. (2001). *Best Practice Guidelines for Australian Glass Eel Fishing and Aquaculture*. Report No. 48. Marine and Freshwater Resources Institute. Alexandra. 21 pp.

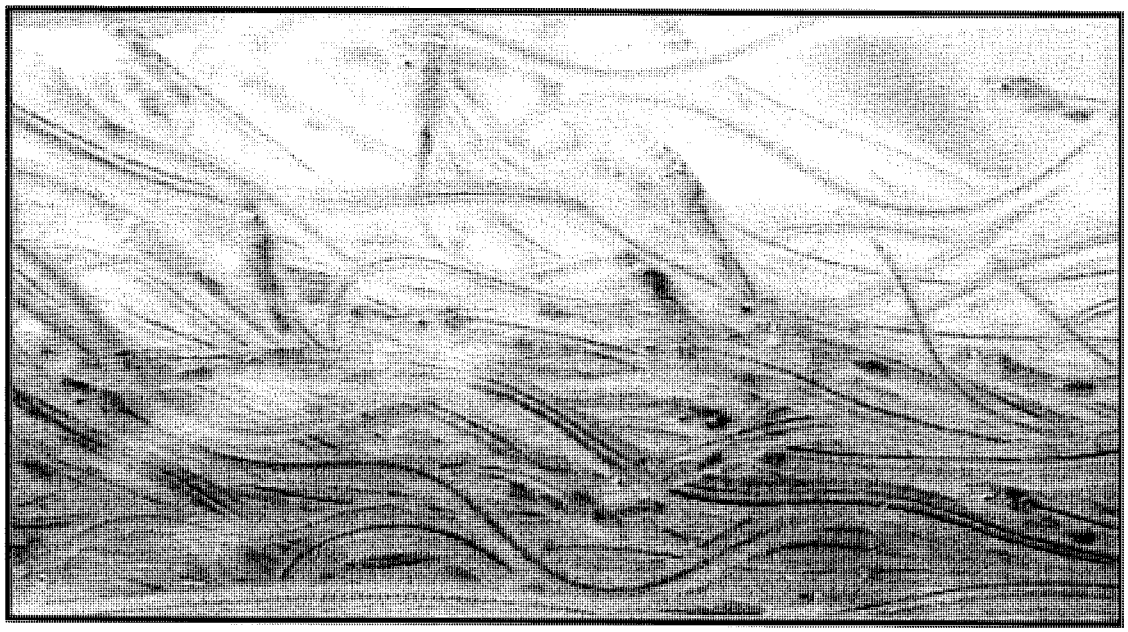
Sloane, R.D. (1984). Invasion and upstream migration by glass-eels of *Anguilla australis australis* Richardson and *A. reinhardtii* Steindachner in Tasmanian freshwater streams. *Australian Journal of Marine and Freshwater Research* 35(1): 47-59.

APPENDIX I

Marine and Freshwater Resources Institute

Report No. 48

Best Practice Guidelines for Australian Glass Eel Fishing and Aquaculture



L.J. McKinnon, B.A. Ingram, B. Larkin and R.J. Gasior

November 2001

State Government Victoria Department of Natural Resources and Environment

FISHERIES RESEARCH & DEVELOPMENT CORPORATION

Victoria The Place To Be

Marine and Freshwater Resources Institute

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Best Practice Guidelines for Australian Glass Eel Fishing and Aquaculture

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Table of contents

1 Background

Eel culture in Victoria has historically been an extension of the commercial eel fishery. Australian shortfinned, *Anguilla australis,* elvers taken from Victorian and Tasmanian coastal streams have been stocked in public waters for ongrowing. However, eel culture has considerable scope for further growth through adaptation of intensive farming techniques using glass eel and elver seedstock.

As part of the Fisheries Victoria/FRDC funded studies, "Assessment of Juvenile Resources in South-eastern Australia and Associated Development of Intensive Eel Farming For Local Production" (FRDC Project N^{o} 94/067), and "Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture" (Project N^{o} 97/312), preliminary techniques for the harvest, transport and culture of *A. australis* and *A. reinhardtii* glass eels and elvers have been developed. These techniques and some of those developed by Australian and international commercial eel farmers are discussed here.

This document is intended to be used by eel fishers and farmers as a preliminary guide only, and will be updated from time to time as relevant new information on glass eel capture and culture techniques becomes available. This document focuses on collection and holding techniques for both Australian shortfinned and longfinned glass eels, and weaning and early rearing techniques for shortfinned glass eels. Much of the information on the latter section could, however, be equally applied to Australian longfinned glass eels (*Anguilla reinhardtii*). Readers should refer to the included list of references (see Section 5 Further Reading) for more detailed aquaculture information on eel and other species.

2 Glass eel harvesting and transport

2.1 Harvesting Guidelines

2.1.1 Suitable conditions

It is considered best to set fishing gear at the harvesting site at low slack water on or after sunset. In general, the minimum productive period to fish for glass eels is 2-5 days following new and full moons. Broadly speaking, the peak fishing period for shortfinned glass eels is winter/spring; that for longfinned glass eels is summer/autumn, however considerable variation in seasonality may occur for both species, including seasonal overlap in abundance of both species, depending on geographic location within the species' range. For example, the most productive fishing for shortfinned glass eels in Victoria occurs from the new moon in June to the full moon in October, while glass eels of both species may be equally abundant in late summer/early autumn in northern NSW and southern Queensland.

2.1.2 Select harvesting site

When planning glass eel harvesting, ease of access to launching ramps, jetties and access to transport tanks and equipment should be considered.

The substrate at the fishing site should be clear of debris that may snag nets and other equipment, or prevent anchors/poles from holding, Suitable harvesting sites are dependent on several considerations, including:

- River volume and flow
- Size and depth of the river
- Gear type used.
- Substrate type

It is generally advisable to fish within the tidal zone at a suitable site between the mouth of the river and the freshwater interface, at the first riffle or confluence with a major tributary, or barrier upstream from the mouth (within the tidal zone). Site selection will also be dependent on whether glass eels or pigmented glass eels or elvers are being targeted. The latter developmental stages are more likely to be taken nearer to or at the saline/freshwater interface.

2.1.3 Select gear and boat type

Gear type depends partly on the site fished (which also depends partly on the gear type available). For example:

- In waters less than 4m deep and less than 100m wide, glass eel nets (Figure 1), dipnets from the bank, stow nets, hell nets (Japanese glass eel nets) (Figure 2), and trawls can all be utilised.
- In waters from about 4-7m in depth and/or greater than 100m wide, dipnets, trawls, plankton purse-seines and possibly stow nets may be utilised.
- In waters where tidal bore exceeds 0.4m/s, gear is restricted to dipnets, trawls and plankton purse-seines.

Passive gear (hell nets, glass eel nets, stow nets) require poles or anchors (or both, depending on tidal velocity) for fixing wings, with buoys attached, floated headline and weighted leadline; mesh size 2mm diamond mesh or less, with a detachable codend of mesh size ~0.5-1.0mm (Figure 1, Figure 2). Active gear (nets which utilise some form of energy to be propelled through the water column) should be robust enough to cope with the rigours associated with heavy catches and strong water flows without breakage. Mesh coloured white is preferable, allowing clear observation in the water, and easier detection of glass eels in the net.

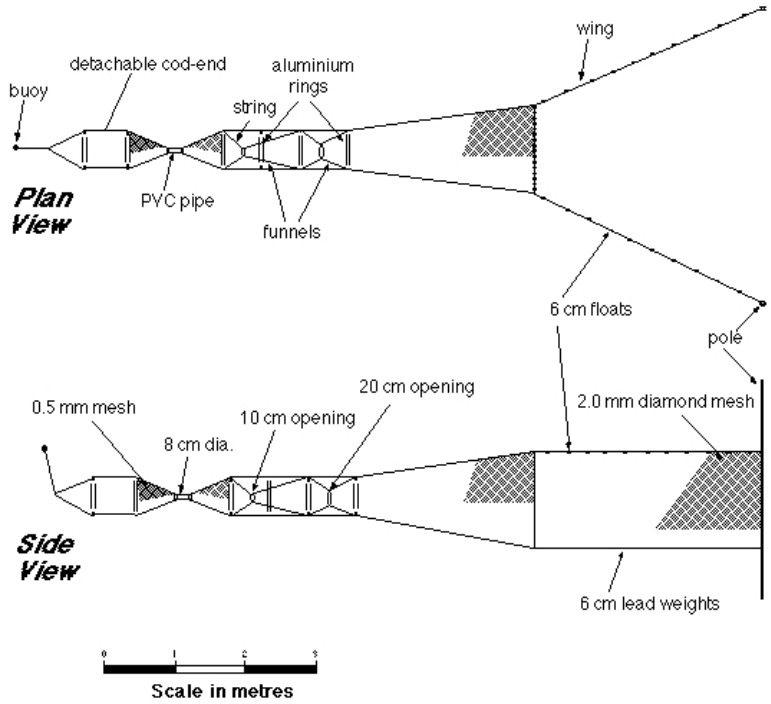

Figure 1 Schematic diagram of a glass eel net.

The type and size of boat required depend largely on the gear type to be utilised, which in turn is dictated by the site to be fished (See 2.1.2 Select harvesting site). Large nets eg. hell nets and stow nets, and associated "open" water sites require a larger boat (typically ~5-6m v-bottom boat with a powerful (75-100 hp motor), whereas smaller streams and smaller gear eg. glass eel net and dipnets may require no boat at all or a small punt (3-5m) and outboard motor (10-25 hp). Safety is paramount in any type of boat, and normal safety procedures for working in boats should be followed as a minimum requirement, particularly given the often difficult prevailing conditions. In most cases glass eel fishing operations should be undertaken by two persons for both operational efficiency and safety.

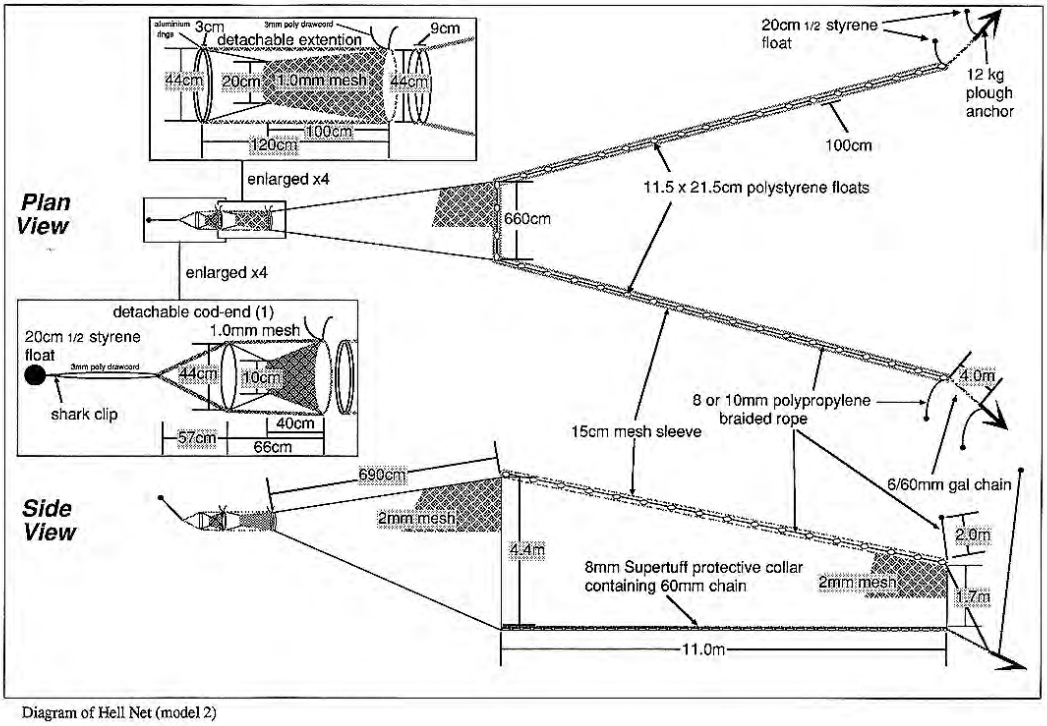

Figure 2. Schematic diagram of hell net

2.1.4 Equipment to hold and sort catch

Glass eels are generally sorted immediately from bycatch using a series of plastic crate-based sieves fitted with 10mm, 3.5mm and fine (≤1mm) mesh to retain glass eels in bottom crate (Figure 3). The speed with which glass eels separate depends on the quantity and composition of bycatch. For example, early in the glass eel season in eastern Victoria, most of the bycatch consists of small fish such as sandy sprat, also with some larger individual fish, such as mullet, bream, and estuary perch. Glass eels are quite vigorous and separation is generally not too difficult with up to 90% of glass eels separating easily. Later in the season, small opossum shrimp become more prevalent and present problems. Opossum shrimp are small, and generally pass through screens with the glass eels, making them difficult to separate. Multiple handling of the catch (sieving and screening) may be necessary to adequately remove glass eels from opossum shrimp. All bycatch should be returned to the water quickly after separating from glass eels to minimise mortality.

Glass eels can be held in fish bins of sea water aerated via 12V or 3V air pump or an oxygen cylinder, with airline and airstones (Figure 4). In the field, densities of glass eels should be kept low, but up to 5kg/50L is acceptable for short term holding with regular water exchange. Alternatively, 1-2 kg of glass eels can be held in fine-mesh bottomed crates without water for 1-2 hrs at night ("dry crates") (Figure 5). That is glass eels need to remain wet, but do not require immersion in water. The use of stacked crates allows transport of large numbers of glass eels, over short periods of time, without the need for large volumes of water. Note that the mesh in dry crates should not be made of heat-conductive material such as stainless steel, but of insulating material such as nylon or plastic. Transfer of glass eels from the field to holding facilities should be done slowly to prevent temperature shock.

It should be noted that when large quantities of glass eels and/or bycatch is anticipated, more frequent net clearing should be undertaken to reduce stress and damage to the catch. More frequent net hauls of smaller catches are also generally easier on the operator, and will reduce the strain on the nets.

An effective alternate means of separating glass eels from bycatch is the use of a stainless steel (3.25mm mesh) basket (450mm diam. X 340mm deep) contained in a 100L cylindrical (600mm diam. X 435mm deep) polyethylene tank filled with water and aerated. The codend of the net is emptied into the basket, and glass eels swim through the mesh, whilst bycatch is generally retained alive within the basket (Figure 6).

Figure 3 Glass eel sorting trays

Figure 4. Holding glass eels on board. Note oxygen cylinder.

Figure 5. "Dry" crates, each containing 1-2kg glass eels.

Figure 6. Woven stainless steel basket glass eel separator (12mm frame, 3.25mm mesh).

Figure 7 Land based short-term recirculating glass eel holding facility

2.1.5 Maintenance of equipment

Simple maintenance of all equipment should be undertaken, and all equipment should be kept clean prior to use. Wash nets with fresh water after use, dry, and store away from direct sunlight if possible.

2.1.6 Short-medium term glass eel holding requirements

In any system where fresh tap water from a town supply is used to hold glass eels, any chlorine in the water must be removed by aerating the water for at least 24 hours prior to stocking with glass eels. A mixture of tap water and river or estuary water may be used to reduce the chlorine content of the holding water. In static or recirculating holding systems where chlorinated tap water is used, a daily exchange of up to one-third of the total volume using chlorinated tap water is acceptable, provided the water in the holding system has been dechlorinated by aeration previously. Any mortalities and miscellaneous bycatch remaining in the holding facility should to be removed as required.

Glass eels may be held in 100L tubs containing approximately 70L of constantly aerated de-chlorinated tap water, river or estuary water. No apparent effect on survival has been observed on glass eels transferred from brackish estuary water (20-25ppt), directly into fresh water. Holding densities up to approx. 0.5kg of glass eels per litre of water for extended periods of time (up to 1 week) are possible. However, water in these tubs needs to be well aerated and exchanged regularly. 12V aerators may maintain adequate levels of oxygen in the holding system or industrial grade oxygen may be utilised in conjunction with fine-bubble airstones or "leaky pipe". Water temperature should be maintained below 15^{o}C (use ice if necessary).

Sorted glass eels may be held in one of three ways:

- In a flow through system with constant water exchange
- In a static water system with a minimum 1/3 water exchange each day
- In a recirculating system which pumps water through filters eg. activated carbon and exchanges water at 10-20 % each day (Figure 7).

2.1.7 Fish health and stress reduction

Glass eels will die if left in small volumes of water without aeration. Once removed from the net, glass eels should be sorted and placed in holding/transport containers as described above as soon as possible.

Stress is defined as the response beyond the "normal" range of responses to normal environmental stimuli. Stressors include physical and chemical factors that cause bodily reactions that may contribute to disease and death. More specifically, the capture, harvest and transport operations for glass eels causing stress include:

- Increased fish density and poor water quality ie. low dissolved oxygen, undesirable temperature or pH, increased concentrations of carbon dioxide, ammonia, hydrogen sulphide and organic matter in the water.
- Injury during handling (including capture, sorting and transport).
- Poor sanitation.

These conditions can result in decreased resistance to disease by the fish, which in turn results in the spread of disease, parasitic infestation and eventual mortalities. Some methods of reducing stress during the capture, harvest and transport operations include:

- Provision of "hides" in containers for glass eels eg. rolled up parcels of plastic mesh, (see Figure 8). Mesh size for hides should be determined by the size of the eels. Hides also allow glass eels to rest, thereby conserving energy, and may assist in harvesting glass eels from tanks, as well as provide for easier removal of mortalities and bycatch.
- Keep holding tanks in subdued light or darkness as much as possible.
- Minimise dramatic movement of tubs and tanks containing glass eels.
- Maintenance of constant and optimal environmental conditions for glass eels, particularly oxygen and ammonia levels and water temperature ie. sudden changes in such parameters can stress fish.

Figure 8. Rolled up oyster mesh providing shelter for glass eels.

2.2 Transport guidelines

2.2.1 Equipment and techniques

Glass eels are typically transported over long distances in double plastic bags filled 1/3 with water and 2/3 with industrial grade oxygen. These bags are non-porous heavy grade polyethylene plastic bags, of around 20L capacity, and may be sealed with rubber bands or rubber elastrator rings, then placed in cardboard or polystyrene boxes and taped closed (Figure 9). Up to 2kg of glass eels per bag may be transported for up to 6-12 hours, either by boat, road or air. However the containers must be kept cool and insulated from extreme temperature change during transit eg. polystyrene containers and in air-conditioned vehicles. As soon as water and glass eels are added, bags should be immediately inflated with pure oxygen and goose-necked, or tied in such a way to prevent any leakage of oxygen over the course of the trip. Glass eels must not remain in unoxygenated water in the transport container for more than one or two minutes.

Purpose built transport tanks may also be used for long term/large scale transport needs (Figure 9). Fibreglass and poly tanks of 1000L capacity have successfully carried 0.2-0.5kg glass eels per litre. At these densities, glass eels will survive well overnight, provided constant aeration is supplied. Ensure the transport tank is always filled to capacity with water, regardless of quantity of glass eels being transported, to reduce physical injury to the glass eels from excessive water turbulence.

Other equipment which may be necessary includes: scales to weigh glass eels, fine mesh dipnets, small buckets (1-2L), plastic bags, marking "Elastrator" rings, rubber bands, oxygen bottles, aerators, airstones, packing tape, aquarium airline, and oyster mesh hides.

2.2.2 Water quality

Water should be thoroughly oxygenated prior to and during transport of glass eels. High concentrations of ammonia in transport water should be avoided, as should high concentrations of iron ,which may be an issue if water is sourced from bores or a subterranean source.

For long trips (eg 3-4 hours or greater) and/or transporting large quantities (>10kg) of glass eels, the use of continuously oxygenated transport tanks, as described above, is recommended. Water quality should be monitored every 2-3 hours in cooler weather, and more frequently in warmer conditions. Glass eels have been successfully transported in heavy gauge plastic bags for periods of over five hours in cool conditions (eg. insulated containers, and in air-conditioned vehicles).

Figure 9. Packing and transporting glass eels. Note oxygen cylinders mounted to transport trailer.

3 Glass eel aquaculture, quarantine and husbandry

3.1 Acclimation to hatchery conditions

3.1.1 Water quality and acclimation

In Victoria, *A. australis* glass eels are captured in the wild during the period from June to October when ambient temperatures range from 10-17^{o}C (approximate mean of 12^{o}C) (see Section 2 Glass eel harvesting and transport). Since weaning and rearing of eels is generally conducted in fresh water at temperatures between 20^{o}C and 25^{o}C, a protocol has been adopted for the acclimation of newly-caught glass eels to aquaculture conditions. This includes a period of up to 5 days during which the temperature of the holding water is slowly increased, and the salinity is slowly decreased. During this time the glass eels are not fed, and water quality is maintained at premium levels (see Table 1). It has been suggested that this non-feeding or "fasting" stage also occurs in the wild when glass eels invade fresh water from the sea. Specifically it is the time during which the larval leptocephali metamorphose into the typical glass eel post-larval form and develop functioning mouth parts used for feeding in the estuarine, and later freshwater, environment. In intensive culture, this initial acclimation phase may occur in flat-bottomed trays or circular tanks.

The first offering of feed at the end of the acclimation period effectively "breaks the fast" and is the commencement at the active feeding phase of glass eel growth. Current practice in the Dutch intensive eel farming industry does not include an acclimation period to freshwater for newly-caught glass eels, however, emphasis is placed on obtaining glass eels of a high quality. Japanese eel farmers originally included an acclimation period during which salinity was slowly decreased, but now prefer to transfer glass eels directly into freshwater, then allow them to rest for up to one week before feeding.

In natural conditions (estuaries and rivers) *Anguilla australis* glass eels increase in pigmentation stage as the season progresses. The advancement in pigmentation also occurs in tanks or aquaculture ponds as *A. australis* glass eels acclimate and begin to feed. This pigmentation phase continues until full pigmentation is achieved

3.1.2 Fish Health: Sanitation, Disinfection and Stress

Historically, diseases such as branchio-nephritis, bacterial and fungal infections have caused serious problems in eel culture overseas. The only diseases and parasites encountered to date during *A. australis* culture trials at MAFRI have been protozoan infestations of *Ichthyobodo* and *Trichodina*, both relatively ubiquitous and cosmopolitan pathogens affecting a wide range of cultured Australian finfish species. These ecto-parasites are routinely treated by standard therapeutic and/or prophylactic methods, namely 5-10 g/l salt (sea salt of the type normally used in saline swimming pools is suitable) for up to 1hr. Other disease organisms have been observed in experimental *A. reinhardtii* culture, including whitespot (*Ichthyopthirius mulitfiliis*), and the bacteria *Flavobacterium* spp., *Aeromonas hydrophila* and *A. sobria* (Jones 2001).

Personnel traffic should be restricted to reduce the possibility of disease being inadvertently brought into the hatchery. A disinfectant footbath just inside doorways is a good preventative measure. Do not move nets or other equipment from the hatchery. All equipment used in the hatchery should be reserved for hatchery use only. Clean and disinfect the hatchery and equipment regularly with a hypochlorite solution, or an approved quaternary ammonium disinfectant. Tanks and floors should also be disinfected between groups of fish. As an

additional safeguard against the spread of disease microorganisms, keep the hatchery well ventilated to prevent condensation forming on walls or the ceiling.

All transportable equipment (eg. nets) should be stored off the floor in a dry area when not in use. Sun drying of nets and equipment between uses is also beneficial. Alternatively dip-nets may be stored in a weak disinfectant (eg. 3% formalin solution) and thoroughly rinsed in freshwater before use.

If the glass eels are transported in tanks separate to the acclimation troughs they should be transferred with minimal stress to the fish. High quality, healthy glass eels will survive the necessary rigours associated with acclimation better than weak or stressed fish. Always minimise the time out of water when handling small fish.

3.2 Weaning and early feeding techniques

3.2.1 Basic tank design and husbandry techniques

Tank size and shape are important factors to consider when weaning and growing glass eels. Several tank sizes will be required to grow eels from the glass eel size to an acceptable market size, at the same time as maintaining suitable densities for culture. Good quality tanks of varying sizes are available from commercial suppliers, or may be custom made to suit a particular circumstance (eg. Figure 10). A slope on the floor of the tank toward the centre screen is desirable (Figure 10), as it aids in the self, and manual cleaning processes. Other practical considerations for tank design include:

- Smooth, hard wearing surfaces to facilitate cleaning and reduce scratching (eg. fibreglass, high density polyethylene plastic).
- The height of the tank should be accessible for cleaning and observation of eels.
- No sharp surfaces to help prevent injury to eels and culturists.
- Non-transparent tanks are preferable, to reduce stress on eels which may be instigated by activity near the tank

To help prevent eels from escaping, water levels should be kept well below the upper lip of the tank. Eels can climb steep, damp surfaces, and have been observed at least one full body length from the water surface. Circular tanks are generally recommended for the weaning and growth stages for several reasons, including:

- There are fewer points of low flow, or “dead spots”, than in rectangular or square tanks
- The centre draining pipe aids in self-cleaning
- Water levels can be raised and lowered easily to aid the cleaning process

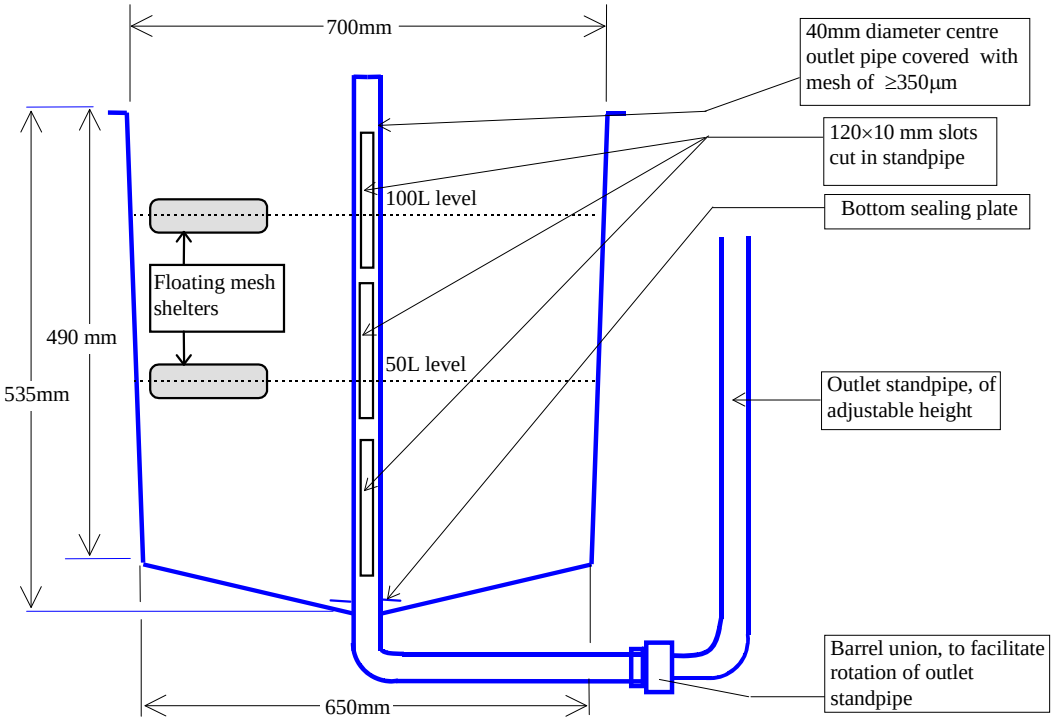

Figure 10 Design of tanks utilised to wean and grow glass eels at Marine and Freshwater Resources Institute, Snobs Creek.

3.2.2 Feeding techniques

A preweaning diet to break the fast is generally offered manually as a wet biomass on a floating platform (Figure 11). After the eels are fully weaned they may then be fed either by hand several times a day, or by automated feeders. Automated feeders are usually of the belt type, or some other type of automated unit delivering known quantities of feed (typically pelleted and/or paste) on a regular basis (eg. see Figure 12).

It appears that neither growth nor survival of weaned, captive eels, is affected by light intensity. However it is highly recommended that disturbances and traffic near rearing tanks be kept to a minimum to avoid undue stress on the eels, and that whatever lighting is used, it should be of a consistent intensity with sudden change minimised.

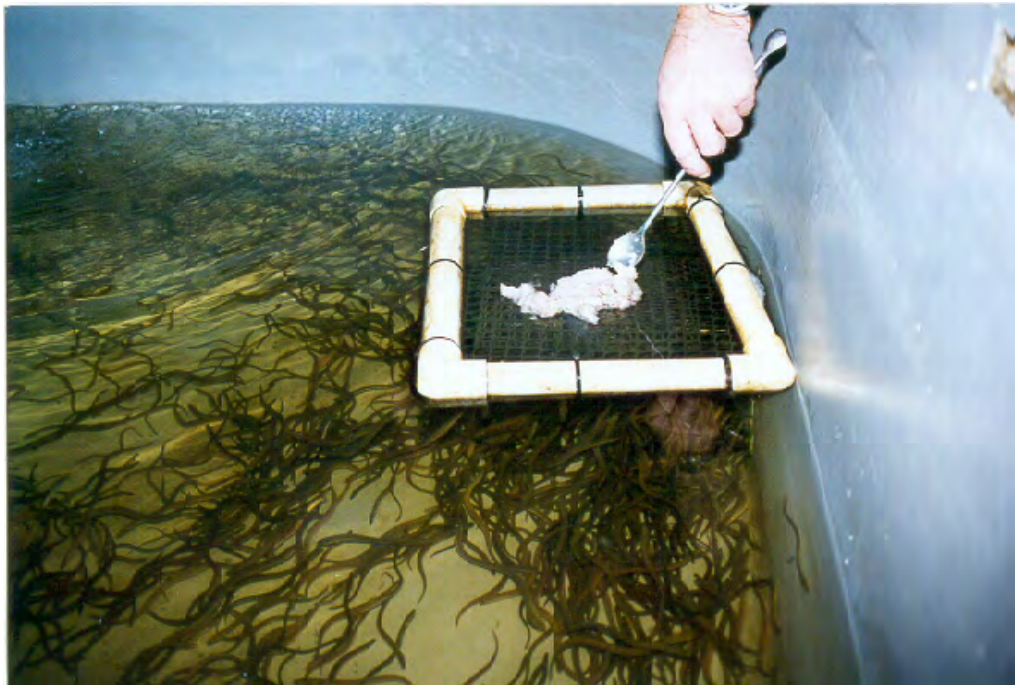

Figure 11 Floating mesh platform utilised for initial feeding and resting eels.

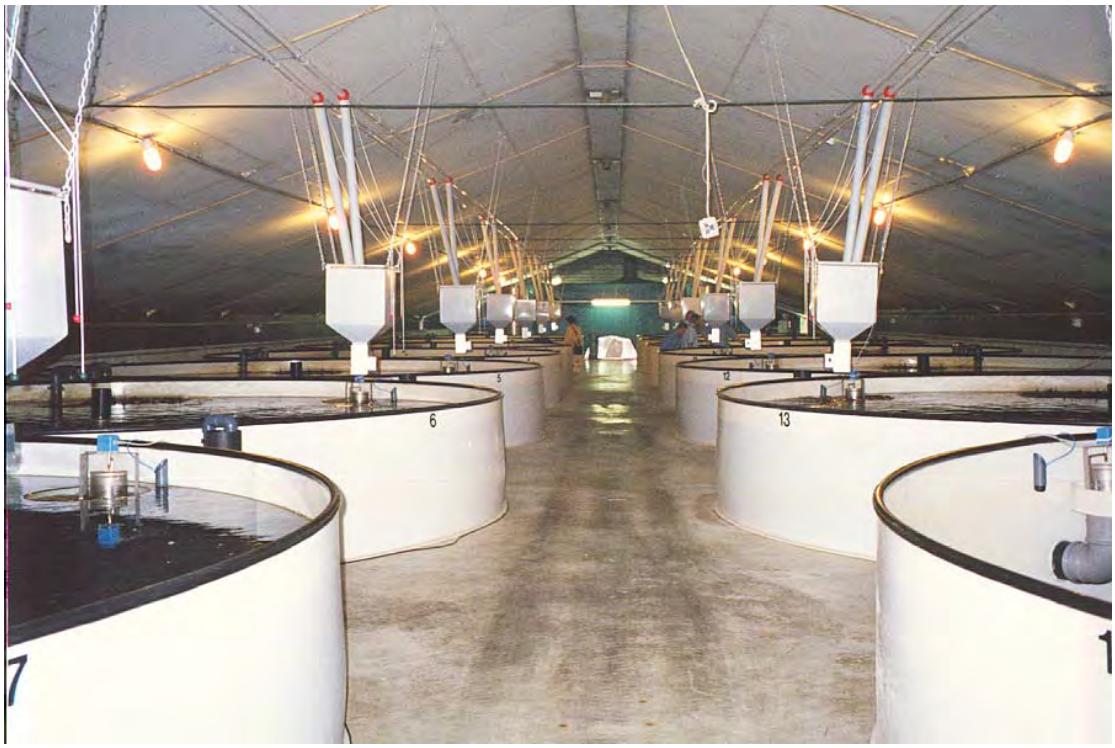

Figure 12 Eel growout tanks with pendulum feeders

3.2.3 Glass eel feed types

During its life history, the dietary requirement of the eel changes. The leptocephalus (larval phase) feed on zooplankton in the sea, but after metamorphosis, a more varied diet is observed. Following metamorphosis from leptocephalus to glass eel, and prior to entering fresh water, apparently no feeding occurs during a "fasting stage". The glass eel still has an empty gut, and little food is found even in those eels with first pigmentation at capture. Once in freshwater, active feeding re-commences, and more strongly pigmented eels are found to have food in their stomachs. The prey of later stage elvers include: copepods, polychaetes, oligochaetes, amphipods and aquatic insect larvae.

A. australis glass eels will commence feeding on "natural" diets of either live, newly hatched brine shrimp (*Artemia*), common carp (*Cyprinus carpio*) roe, and/or freshly minced fish flesh of different species (eg. rainbow trout, carp). Carp roe is presently considered to be the most suitable first feed for glass eels, although roe of other commonly available marine and freshwater species may also be suitable. In practice, glass eels should not be fed until acclimation and quarantine is complete; typically 5-7 days from capture (see section 3 Glass eel aquaculture, quarantine and husbandry). Commencement of feeding may be facilitated by providing a floating mesh tray in each tank which acts both as a resting station for eels as well as a feeding platform on which the preweaning diet is placed. Glass eels are typically not placed directly onto an artificial diet without first breaking the fast using a "natural" diet. Glass eels are best fed to satiation four or five times a day at this stage.

3.3 Pigmented glass eel weaning and production techniques

3.3.1 Weaning techniques

Weaning is critical to the successful adaptation of eels to aquaculture conditions. Several factors are critical to successful weaning once glass eels are accepting a first-feeding or pre-weaning diet (see 3.2.3 Glass eel feed types). These factors include:

- **Rate of weaning.** Survival and growth of *A. australis* glass eels and elvers are affected by rate of weaning. In trials, glass eels weaned at a slow rate (ie. 20% increment change from "natural" diet to artificial diet every 3 days; total weaning period is 15 days) had higher growth rates than those weaned at a faster rate (ie. 20% change from "natural" diet to "artificial" diet every day; total weaning period of 5 days).
- **Feeding rate.** Increasing feed rates up to 12% of body weight per day increased growth rates of weaned glass eels significantly above that of lower feed rates. A maximum feeding rate has not yet been identified other than to say that feed rates up to 12% of body weight per day are effectively feeding eels to satiation. However, in general production, juveniles are being feed at rates of 2-5%/day, following weaning (Table 2)
- **Weaning diet.** Artificial diets have several advantages over natural diets in the weaning and growth of eels including:
  - More convenient to use as cold storage is not required and less space is needed
  - Readily available from commercial suppliers.
  - Relatively easy to refine nutrition and incorporate additives such as antibiotics and appetite stimulants.
  - Attractiveness is equal to, if not higher than, natural diets once accepted.

Commercially available pastes and pellets have been accepted by *A. australis* glass eels and elvers, with reasonable growth rates recorded for both forms of food. Most commercial farms have adopted the particulate (pellets and crumbles) form of diets, as it is relatively easy to store and use, and is readily accepted at all stages of eel growth. Pellets are also more environmentally manageable in that water quality is less affected and residual feed wastes are easier to remove mechanically from the culture system.

3.3.2 Production techniques

3.3.2.1 Size grading

In intensive culture of the Japanese eel *A. japonica* and European eels *A. anguilla*, size grading is employed at least every 6-8 weeks after weaning is complete. Grading is generally believed to improve the growth rate of smaller individuals by removing the suppressive, or intimidatory effect of larger, more aggressive feeding individuals. Grading is usually preformed by means of mechanical graders. Smaller graders may be operated using hand-held dip-nets (Figure 13), or by specially designed, commercially available fish pumps in larger scale units.

Figure 13 Mechanical grading of eels.

3.3.2.2 Glass eel stocking

Densities as high as 40 kg/m^3 do not significantly affect growth or survival. It is recommended that glass eels be stocked at these levels to avoid natural aggressive hierarchical and territorial tendencies. Such densities are also conducive to rapid weaning to artificial diets, assist in the self-cleaning of wastes from the culture tank and generally provide the fish with a degree of security which reduces stress. It is assumed however that at higher stocking densities suitable water quality is maintained. For example, in intensive recirculation systems, juvenile *A. australis* have been reared at densities up to 115kg/m^3 (Table 2)

3.3.2.3 Water quality

In relation to temperature this study has shown that the glass eels of *A. australis* grew significantly faster at 25^{o}C than at lower temperatures. Water temperatures in culture systems for other species of eel have been reported to be in the range of 20-32^{o}C for *A. japonica* and 23-25^{o}C for *A. anguilla* (See Table 1). The effects of temperatures higher than 25^{o}C on the growth and survival, are not known for *A. australis*.

Table 1 Preferred range of selected water quality parameters for eel (after Brusle 1990; Usui 1991; Gooley *et al*. 1999; Gousset 1992).

Parameter	Acceptable Range	Comments
Temperature (^{o}C)	22-28	Growth will be optimised within this range.
Dissolved oxygen (mg/l)	>5	Eels can tolerate short periods of lower concentrations.
pH	7.0-9.2	Waters should be well buffered. Some commercial farms are known to operate as low as 5.5 on a consistent basis.
Salinity (ppt)	0-10	Eels can be cultured in slightly saline waters.
Light	Intense light to be avoided	Eels prefer shaded or subdued light (including dark) conditions.
Total hardness (mg/l as $CaCO_3$)	>50 - <500	
Total Nitrogen (mg/l)	<0.5	Ammonia toxicity increases with rising pH and temperature.
TAN (mg/l)		
Suspended Solids (mg/l)	<40	Eels are adaptable to a wide turbidity range.
Iron (mg/l)	<0.1	
Hydrogen sulphide (mg/l)	<0.002	

3.3.2.4 Fish health

Historically, diseases such as branchio-nephritis, bacterial and fungal infections have caused serious problems in eel culture overseas. Under culture conditions at MAFRI, the only diseases or parasites encountered to date on *A. australis* glass eels and elvers were infestations of the protozoan ectoparasites *Ichthyobodo* and *Trichodina* while other disease organisms, including some bacterial infections, have been observed in experimental *A. reinhardtii* culture (see 3.1.2 Fish Health: Sanitation, Disinfection and Stress).

Good husbandry practices to ensure optimum fish health is maintained include:

- Recording of daily mortalities.
- Monitoring of any parasite load or presence by routine gill and skin smears.
- Quarantine and sanitisation of influent water supply.
- Recording of daily water quality parameters such as nitrates, dissolved oxygen, temperature and pH.
- Ensure feed is fresh, stored correctly and that uneaten food is removed from the tank

3.3.2.5 Growth rates and survival.

Growth rates of *Anguilla australis* glass eels have been found to be highly variable, ranging from -2.1%/day to 3.6 %/day. The wide range in growth rates is a reflection of many contributing factors such as:

- Growth conditions the eels were exposed to during the trials (eg. water temperature, feed rate).
- A wide size range of seedstock and genetic variability within the seedstock.
- Initial weight of the glass eels to be cultured.

Growth rates of glass eels (< 0.5 g weight) have been found to be generally higher and more variable than for larger eels (>0.5 g weight). In the first 3-5 months following weaning juvenile eels may grow at rates of 10 - 15% per week, but in later months growth may slow to 5 - 10% per week. At these rates, eels reach a minimum weight of 200 g within as early as 10 months (average of 14 months).

Survival rates may also be highly variable, and ranged from less than 40% to 100% in trials on *A. australis* glass eels. The wide range in survival rates, like growth rates, reflected conditions the eels were exposed to during the trials (eg. diet type etc.). Survival rates of glass eels (< 0.5 g weight) was generally lower and more variable than for larger eels (>0.5 g weight). After three months, survival is typically 75% or greater. The majority of mortalities occur within the first few months. Very few eels die during growout.

A comparison of the production potential for *A. australis*, *A. japonica* and *A. anguilla* is presented in Table 2.

The importance of having good quality glass eels for weaning cannot be emphasised enough. Further, the efficient use of these eels through maximising survival during weaning and adaptation to captivity has been identified as a critical phase of eel culture for other species of eel in addition to *A. australis*.

Table 2 Comparison of the production performance of *A. australis* and other species of farmed *Anguilla* (from Ingram 2001).

Parameter		*A. australis*	*A. reinhardtii*	*A. japonica*	*A. anguilla*
Culture temperature (^{o}C)		23-25	24-28	20-30	25
Initial size (g)		0.15-0.18	0.13-0.17	0.2	0.25
Pieces per kg		6,000-8,000	5,900-7,700	5,000-6,000	2,500-4,000
Starter diet		fish, fish roe	fish roe, blackworms	*Tubifex*, squid, krill, fish	Cod roe
Grow-out diet		Artificial dry	Artificial dry	Artificial wet & dry	Artificial dry
Culture method	- Nursery	Tanks	Tanks	Ponds	Tanks
	- Growout	Tanks	Ponds	Ponds	Tanks
Feed rates (%/day)	- Nursery	3-5	3-8	3-8	2-5
	- Growout	1-2	2	1-3	1-2.5
Growth rates (%/day)	- Nursery	0.5-3.5	1.5-2.3	2-4	0.5-3.5
	- Growout	0.5-1.5	0.4-1.0	0.8-2.0	0.4-2.0
FCR		0.9-8.0	0.9-5.0	1.4-1.9	1.2-4.0
Densities (kg/m^{3})	- Nursery	6-8	6-8	0.15-0.5	Up to 20
	- Growout	Up to 115	Up to 50	0.5-30	Up to 330
Size after 2-3 months (g)		1.4-2.6	1.0-3.0	2-3	NA
Survival after2-3 months (%)		75	75->90	80-90	80-90
% to market size (180-200g) after 6 months		10	10-20	10-20	NA
Months to min. Market size (180-200g)		9-18	6-18	12-18	8-15
Kg marketable eels per kg glass eels		500-600	500-1000	600-900	200-400

4 Acknowledgements

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5 Further Reading

Beumer, J.P. (1983a). Suitability of *Anguilla australis* for intensive culture. *Austasia Aquaculture* **4**: 13-18.

Beumer, J.P. and Harrington, D.J. (1980). Techniques for collecting glass eels and brown elvers. *Australian Fisheries* **39** (8): 16-22.

Beumer, J. and Sloane, R. (1990). Distribution and abundance of glass eels *Anguilla* spp. in east Australian waters. *Int. Revue ges. Hydrobiol.* **75** (6): 721-736.

Boyd, C.E. (1990). *Water Quality in Ponds for Aquaculture.* Alabama Agricultural Experimental Station, Auburn University, Alabama. 482 pp.

Brusle, J. (1990). Eels and eel farming. In: G. Barnabé (ed.), *Aquaculture Volume 2*. West Sussex: Ellis Horwood Ltd. Pp 756-785.

Copland, J.W. (1981). Intensive eel culture - The problem of diseases. *Aust. Aquacult.* **4**: 18-21.

Degani, G. and Gallagher, M.L. (1995). *Growth and Nutrition of eels*. Jerusalem: Laser Pages Publishing Ltd. 119 pp.

FAO (1984). *Catches and landings*, FAO (Food and Agriculture Organisation of the United Nations). Year-book of Fishery Statistics 56.

Gosper, D. (1996). *A Guide to the Diseases and Parasites Occurring in Eels*. Aquaculture Source Book Publication, Turtle Press Pty Ltd.

Gooley, G. J., McKinnon L. J., Ingram B. A., Larkin, B. J., Collins R. O., and S. S. deSilva. (1999) *Assessment of Juvenile Eel Resources in South Eastern Australia and Associated Development of Intensive Eel Farming for Local Production*. Final Report FRDC Project N^{o} 94/067

Gousset, B. (1992). *Eel Culture in Japan*. Bulletin de l'Institut océanographique, Monaco, n^{o} spécial 10.

Hall, D.N., Harrington, D.J. and Fairbrother, P.S. (1990). *The Commercial Eel Fishery in Victoria*. Arthur Rylah Institute for Environmental Research Technical Report Series No. 100. Department of Conservation, Forests and Lands, Victoria. 41 pp.

Heinsbroek, L.T.N. (1991). A review of eel culture in Japan and Europe. *Aquaculture and Fisheries Management* 22: 57-72.

Ingram, B. and Gooley, G. (1996). Intensive tank and pond culture of Australian shortfinned eel in Victoria. *Austasia Aquaculture* **10:** 74-75.

Ingram, B.A., Hawking, J.H., and Shiel, R.J. (1997). *Aquatic life in freshwater ponds. A guide to the identification and ecology of life in aquaculture ponds and farm dams in south eastern Australia*. Cooperative Research Centre for Freshwater Ecology Identification Guide No. 9. 105 pp.

Ingram, B.A. (2001). Advances in the weaning and rearing of juvenile Australian shortfin eels (*Anguilla australis*). **In:** "Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture". G.J. Gooley and B.A. Ingram (eds), pp75-109. Final Report to the Fisheries Research and Development Corporation (Project No. 97/312). Marine and Freshwater Resources Institute, Alexandra, Victoria, Australia.

Jones, C. (2001). Preliminary assessment of the aquaculture potential of the Australian longfin eel (*Anguilla reinhardtii*). **In:** "Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture". G.J. Gooley and B.A. Ingram (eds), pp 135-181. Final Report to the Fisheries Research and Development Corporation (Project No. 97/312). Marine and Freshwater Resources Institute, Alexandra, Victoria, Australia.

Matsui, I. (1980). *Theory and Practice of Eel Culture*. A. A. Balkema: Rotterdam.

McKinnon, L.J. and Gooley, G.J. (1998). Key environmental criteria associated with the invasion of *Anguilla australis* glass eels into estuaries of south-eastern Australia. *Bulletin Français de la Pêche et de la Pisciculture*. **349**: 117-128.

McKinnon, L.J., Gasior, R.J., Collins, A., Pease, B. and Ruwald, F. (2001). Assessment of eastern Australian *Anguilla australis* and *A. reinhardtii* glass eel stocks. **In:** "Assessment of Eastern Australian Glass Eel Stocks and Associated Eel Aquaculture". G.J. Gooley and B.A. Ingram (eds), pp11-72. Final Report to the Fisheries Research and Development Corporation (Project No. 97/312). Marine and Freshwater Resources Institute, Alexandra, Victoria, Australia.

O'Sullivan, D. (1997) Asian elver shortage sparks interest in eel farming. *Austasia Aquaculture* **11:** 44-46.

Pillay, T.V.R. (1993). *Aquaculture Principle and Practices*. Fishing News Books, Oxford.

Tesch, F.-W. (1977). "The Eel. Biology and Management of Anguillid Eels". Chapman and Hall, London, 434pp.

Rowland, S.J., and Ingram, B.A. (1991). *Diseases of Australian native freshwater fishes with particular emphasis on the ectoparasitic and fungal diseases of Murray cod (Maccullochella peeli), golden perch (Macquaria ambigua) and silver perch (Bidyanus bidyanus)*. NSW Fisheries, Sydney. 33 pp.

Usui, A. (1991). *Eel Culture*, Oxford: Fishing News Books . 148 pp.

Zeller, B.M. and Beumer, J.P. (1996). Eel harvesting and culture in Queensland A discussion paper. Department of Primary Industries, Queensland.

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