Stock enhancement of barramundi in Australia

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INTRODUCTION

Barramundi, Lates calcarifer (Bloch) is a large, catadromous, euryhaline member of the family Centropomidae (Greenwood, 1976). Barramundi, or sea bass as it is known in south-east Asia, is widely distributed throughout the tropical Indo-west Pacific from the Arabian Gulf through Asia to Taiwan Province of China, the Indonesian archipelago, Papua New Guinea and northern Australia. In Australia, its distribution is pantropical from the Ashburton River in Western Australia to southeastern Queensland (see Figure 1; Kailola *et al.*, 1993). It is a popular recreational, commercial and aquaculture species throughout its range (Kailola *et al.*, 1993).

Life history and reproductive biology

The life history and reproductive biology of barramundi is complex and has major ramifications for the management of the fishery. In Papua New Guinea, Moore (1979) first identified barramundi as a protandrous hermaphrodite and this was later confirmed for stocks in northern Australia (Davis, 1982, 1984b; Russell, 1986). Males mature at about four years of age (Moore, 1979) and sex inversion normally occurs when the fish are about seven years old (Moore, 1979; Reynolds and Moore, 1982; Davis, 1982, 1984a). Male barramundi spawn at least once before changing sex (Moore, 1980; Davis, 1984b). Primary females, which are not derived from male fish, are also evident in some barramundi populations (Moore, 1980).

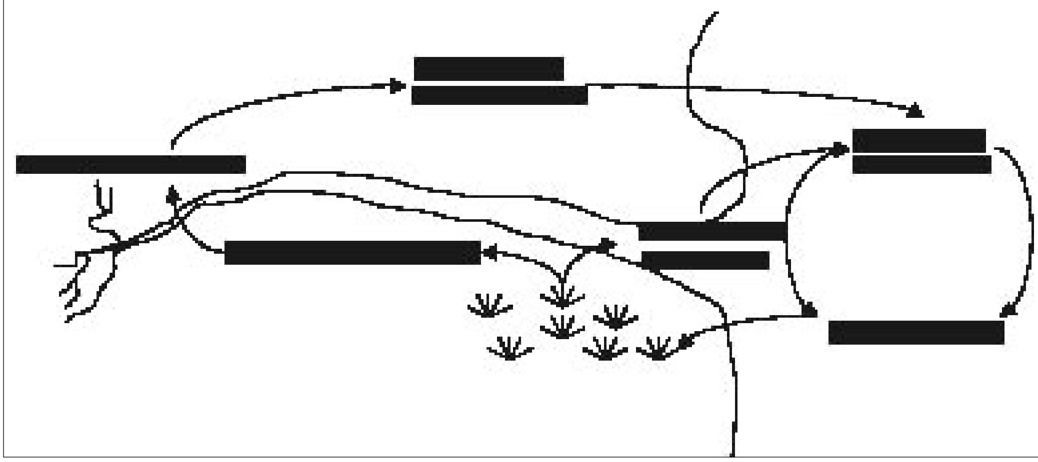
Barramundi in northern Australia spawn between September and March, with latitudinal variation in spawning season, presumably in response to varying water temperatures (Dunstan, 1959; Russell and Garrett, 1983, 1985; Davis, 1985a; Garrett, 1987). In Papua New Guinea, Moore and Reynolds (1982) found that barramundi spawning activity peaked from November to January. In both Papua New Guinea (Moore, 1980, 1982) and parts of northern Australia

FIGURE 1. Distribution of barramundi in Australia

(Davis, 1986; Griffin, 1986, 1987; Russell and Garrett, 1985) barramundi make an extensive seaward, spawning migration from inland freshwaters to coastal waters or estuaries where the salinity is relatively high. Davis (1986) found that some fish from different river systems intermixed but found no evidence that spent fish migrated back into freshwater. Barramundi are highly fecund, with a single female (> 120 cm total length) capable of producing up to 46 million eggs (Dunstan, 1959; Moore, 1982; Davis, 1984b). High salinity appears to be an important factor in determining the location of barramundi spawning grounds (Moore, 1982; Davis, 1985a). These grounds may be located in a variety of habitats including estuaries, coastal mudflats, headlands and other nearshore waters (Moore, 1982; Davis, 1985a; Garrett, 1987).

After hatching, postlarvae enter supralittoral wetlands (Moore, 1982; Davis, 1985a; Russell and Garrett, 1985) and tidal pools and gutters near the spawning grounds where they remain for several months (Russell and Garrett, 1985). Where the opportunity exists, many juveniles subsequently move up into the freshwater reaches of coastal rivers and creeks (Russell and Garrett, 1983, 1985; Davis, 1985a). Pender and Griffin (1996) provided strong evidence that, in the Northern Territory of Australia, some barramundi do not migrate into freshwater and spend their entire life in coastal waters. Juvenile barramundi that move into freshwater habitats remain resident until they are three to four years of age (60–70 cm total length [TL]) when they reach sexual maturity as males, and then move downstream during the breeding season to participate in spawning (Davis, 1982). In Australia, there is little evidence that they return to freshwater after spawning. A generalized life cycle of the barramundi is shown in Figure 2.

FIGURE 2. Diagrammatic representation of the life cycle of barramundi



REVIEW OF FISHERY

Profile of fishery

Commercial and recreational fishing gear

Gillnets are widely used throughout northern Australia in estuaries and coastal areas to catch a range of commercial fish species including barramundi (See Plate 1). The nets are commonly made of monofilament webbing and are subject to a range of operational restrictions depending on local State or Territory regulations. Commercial fishing is restricted to tidal waters. Nets are serviced at regular intervals with fish being removed, processed (filleted or "gilled and gutted") and chilled on ice or frozen. Recreational, indigenous and commercial tour operators cannot use gillnets. They usually fish with live and dead bait and lures in both tidal and freshwaters (see Plate 2). Some indigenous fishers still use traditional fish traps to catch barramundi.

PLATE 1. A barramundi enmeshed in a gillnet

PLATE 2. Recreational fishing for barramundiisapopularsporting activity in Australia

Queensland

The barramundi is a valuable part of a multispecies commercial gillnet fishery, which is composed of almost 50 species (Russell, 1988). The gross value of production (prices paid to the fishers at the wharf) is estimated by Williams (1997) to be $A2.5 million, but when capital investment, indirect benefits and the value of the marketing sector are taken into consideration, the industry is worth considerably more. Costs of production are high, with operating expenses amounting to 60 percent of all the costs for a typical 10-m commercial fishing vessel (QFMA, 1996). In the Gulf of Carpentaria, the level of capital investment to establish a typical barramundi fishing operation is in the order of $A150 000 (QFMA, 1996) although on the east coast fishing units are typically smaller, land-based operations using dinghies (See Plate 3) Fishers may have endorsements to operate in other fisheries including the crab and trawl fisheries. Profitability at present catch rates appears to be quite low, especially for smaller units (QFMA, 1996). Environmental factors could play a role in determining the magnitude of the barramundi catch. In a study of fisheries resources of part of the east Queensland coast, Ludescher (1997) noted a correlation between increased catches and large flow events in major river systems.

There is little available information on the recreational, indigenous and commercial tour fisheries although the Gulf of Carpentaria recreational fishery alone is estimated to have 100 000 participants per year (QFMA, 1996).

PLATE 3. Processing a commercial barramundi catch

Northern Territory
The multispecies commercial inshore gillnet fishery in the Northern Territory is based on barramundi and threadfin salmon *(Polynemus sheridani),* both of which are primarily marketed in fillet form (Fallu, 1996). Fallu (1996) estimated that the commercial value of the barramundi catch was about $A3.3 million. Commercial activity is widely distributed, but the majority of recreational activity is concentrated on the Mary and Daly rivers and streams in the Kakadu region. The recreational fishery is still developing and its value is unknown but thought to be relatively high (Fallu, 1996). There is little information on the indigenous fishery although it is known to be spread along the entire coastline.

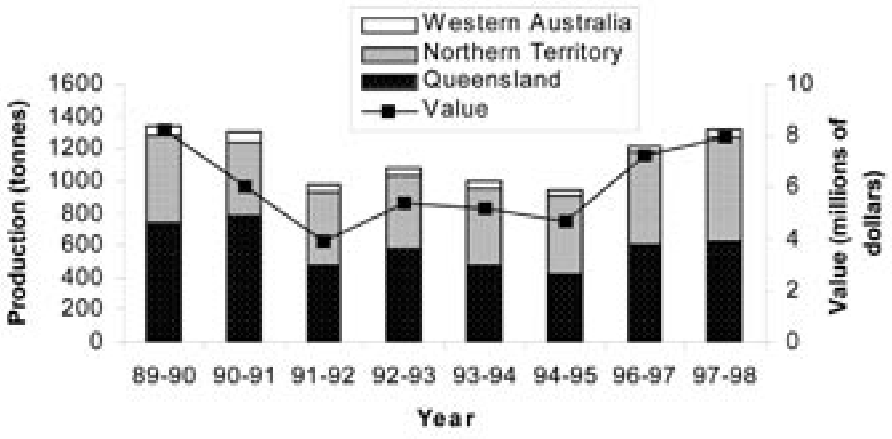
Western Australia
Unlike the coastal areas of the Northern Territory and Queensland, the lack of extensive river systems and mangrove communities make the Kimberley region not well suited to supporting a major barramundi fishery (Anon., 1988). As a result the barramundi fishery in Western Australia has historically been relatively small.

Status of harvest over the last 30 years

Past commercial landings
Figure 3 shows the production and value of the barramundi fishery in Australia from 1989/90 to 1997/98. Queensland and the Northern Territory are the largest producers whereas the fishery in Western Australia is relatively small.

Queensland
In 1981 a compulsory catch-log scheme was introduced into the Gulf of Carpentaria limited-entry gillnet fishery with a similar scheme introduced on the east coast in 1984. Prior to 1981 there was no official monitoring of total commercial barramundi catches in Queensland. Williams (1997) reports that from 1989 to 1995, about 300 commercial boats recorded barramundi catches and that about one-third of

FIGURE 3. Production (by state) and total value of the Australian barramundi fishery between 1989–90 and 1997–98



these boats operated in the Gulf of Carpentaria limited-entry fishery. In an analysis of commercial logbook data, Williams (1997) noted that there had been a decline in the commercial catch from 672 tonnes in 1989 to 501 tonnes in 1995, with a peak catch in 1991 of 738 tonnes. However, whereas total catch on the east Queensland coast has declined, catch per unit effort (CPUE) has remained relatively constant. In the Gulf of Carpentaria Williams reports that both CPUE and total catch have declined for the period. The fishery is also strongly seasonal, with the greatest catches being recorded in the periods immediately prior to (September–October) and during and following (February–April) the wet season.

Northern Territory

Commercial barramundi fishing statistics are available for the Northern Territory from about 1972 when the total catch was 382 tonnes and peaked at 1054 tonnes in 1977 (Department of Primary Industry and Fisheries, 1991). It was during the late 1970s that CPUEs for barramundi showed a consistent downward trend (Fallu, 1996) as a result of an alarming increase in fishing effort (Pender, 1995). This prompted the introduction of legislation regulating effort and CPUE, the latter being considered a significant indicator of the health of the fishery. As a result, the CPUE has improved and remained more or less steady since the late 1980s (Pender, 1995; Fallu, 1996). In 1996 in the Northern Territory there were 28 fully transferable commercial fishing licences, which accounted for a total barramundi catch of 542 tonnes, an increase over catches in 1995 (502 tonnes) and 1994 (447 tonnes) (Fallu, 1996). The recent trend of increased catches may have been the result of greater availability of barramundi or greater efficiency on the part of the commercial fishers. Fallu (1996) estimated that in 1996 at the point of first sale, the commercial component of the barramundi fishery was valued at A$2.8 million. Since the 1970s, the extent of exploitation by recreational fishers has increased significantly along with population growth and development of previously remote areas (Grey, 1986). Grey (1986) also noted an increased community awareness of the economic benefits of recreational fishing, particularly through tourism, which resulted in the active promotion of barramundi fishing as a tourist attraction. In the mid-1980s, in recognition of the growing importance and impact of recreational fishing on the resource, measures were adopted to place further restraints on commercial fishing activity (Grey, 1986).

Western Australia

By comparison with Queensland and the Northern Territory, the commercial barramundi fishery in Western Australia is relatively small with only about five active licences in the northern Kimberley district and an annual production of about 50 tonnes (Anon., 1995). A report by the East Kimberley Recreational Fishing Advisory Committee estimated the value of recreational fishing on the Ord River (1996) to be worth in excess of A$1.1 million (R. Doupé, personal communication).

FISHERY MANAGEMENT

The three Australian states and territory where barramundi fisheries exist have engaged their own individual strategies for management of their fisheries. However, there are a number of common themes including seasonal and area closures, gear restrictions, recreational angler bag limits and size limits on fish. In general, commercial fishers are restricted to operating in specific tidal waters although recreational and indigenous anglers and tour operators can fish in most tidal and non-tidal waters. Specific management regulations pertaining to barramundi in Queensland, Western Australia and the Northern Territory are detailed below.

Queensland

"The Queensland Department of Primary Industries" formerly the "Queensland Fisheries Management Authority" (QFMA) is the agency responsible for controlling commercial and recreational fishing activities. Other states and territories have similar organizations or government departments that are responsible for the administration of fisheries legislation. The objective of the Queensland legislation is to ensure that fisheries resources are used in an ecologically sustainable way to achieve optimum community economic and other benefits obtainable through fisheries resources to ensure access to fisheries resources is fair (QFMA, 1996). Management of fisheries in Queensland is essentially through control of effort rather than control of harvest (QFMA, 1996). In Queensland's *Fisheries Act* (1994), there are a number of key management measures pertaining to inshore fisheries. These include:

- a closed season on barramundi from 1 November until 31 January inclusive on the east Queensland coast and October to January in the Gulf of Carpentaria. The exact timing of the closure in the Gulf of Carpentaria is variable and tied to moon phase in order to maximize the number of barramundi spawnings in the closure period (Williams, 1997);
- prohibition on the use of river-set gillnets during the closed season on the east coast and all nets in the Gulf of Carpentaria;
- a recreational bag limit allowing fishers to have only five barramundi in their possession at any one time;
- minimum and maximum mesh sizes and limitations on the total number of nets in the commercial fishery;
- a weekend closure to commercial fishing from 18.00 hours Friday to 18.00 hours Sunday on the east coast;
- minimum (58 cm total length) and maximum (120 cm total length) size restrictions; and
- area closures for commercial fishers in some rivers.

Recently there have been changes to fishing regulations to account for the management of new impoundment recreational barramundi fisheries that have been created as a result of stocking activities. Barramundi impoundment fisheries in Queensland are solely "put and take" fisheries and as such anglers have argued that some of the regulations, which pertain to the natural fisheries, are inappropriate. As a result, in two impoundments barramundi fishing is conditionally permitted all year round and the maximum size restriction of 120 cm has been revoked, although the minimum size and bag limit still apply (QFMA, 1998). There is a prospect that similar operational guidelines may be extended in the future to other freshwater impoundments with developing fisheries. Although there is presently no provision for recreational licences in Queensland, recreational fishers need to purchase a permit to catch barramundi from certain stocked impoundments (QFMA, 1998).

When considering stock enhancement programmes, the QFMA must act in accordance with the principles of ecological sustainable development, maintenance of biodiversity and the precautionary principle (Cadwallader, 1997). Furthermore, Cadwallader (1997) states that the associated benefits and risks of all stocking programmes must be stringently appraised to minimize risk of irreversible damage to existing fisheries resources and the ecological systems on which these resources depend.

Northern Territory

The barramundi fishery is the highest valued fishery in the Northern Territory, with major recreational and commercial sectors but also with traditional Aboriginal people, fishing tourism and aquaculture as important user groups (Pender, 1995). Barramundi wildstocks in the Northern Territory are regarded as a common property resource and, as such, the basic responsibility of fisheries managers is to manage the fishery in the interests of the general community (Lea, Grey and Griffin, 1987). Lea, Grey and Griffin (1987) also assert that management must be consistent with the dual aims of maximizing the net economic benefits from the fishery while maintaining long-term viability of population levels of barramundi throughout its range.

The history of barramundi management in the Northern Territory dates back to 1962 when, in recognition of recreational fishing interests, all freshwaters were closed to gillnetting and traps between April and December (Pender, 1995). Since then there has been a voluntary licence buy-back scheme and numerous regulatory changes were adopted both before and with the establishment of the Barramundi Fishery Advisory Committee in 1990 and the Barramundi Management Plan in 1991 (Department of Primary Industry and Fisheries, 1991; Pender, 1995). In 1996, there were 28 fully transferable licences in the commercial fishery but recreational anglers are presently not required to pay licence fees (Pender, 1995; Fallu, 1996). Management measures (Pender, 1995; Fallu, 1996) include:

- commercial fishers are prohibited from fishing inside the mouths of most rivers and fishing activity is limited to three nautical miles seaward of the low-water mark;
- gear restrictions on commercial fishers include restrictions on mesh size and total length of net;
- area and seasonal closures apply to recreational fishers on the Mary and Daly rivers;
- recreational fisher bag limits of up to five fish per person (fewer in some areas).

Western Australia

In Western Australia, barramundi have a distinct distribution as far south as the Asburton River but the regulated commercial net fishery is primarily in the Kimberley district (north of, 19°S) (R. Doupé, personal communication). Barramundi caught south of this latitude are regarded as a bycatch of other fisheries. For management purposes the fishery is divided into the west and east Kimberley. In the east Kimberly division there is a closed season between December and January inclusive and a net licence allows for the use of 500 m of 112–150 mm mesh. The west Kimberly division has a slightly different closed season (November to January inclusive) and net size of 500 m of 165–177.8 mm stretched mesh.

There were no recreational fishing limits for barramundi until 1995 (R. Doupé, personal communication) when a minimum size limit of 550 mm and bag limit of five fish per person was adopted (R. Doupé, personal communication). Since November 1997, this has been modified for the Ord River region where there is now a size slot limit of 550–800 mm TL and a bag limit of one fish per person (Doupé, 1997). There are no licence requirements.

Outside Queensland, there has been no stock enhancement of barramundi in open river systems carried out to date. There have, however, been attempts to establish an impoundment fishery for barramundi in the Northern Territory. In the mid 1990s about 200 000 barramundi fry were released into Manton Dam on the Adelaide River (R. Griffin, Northern Territory Department of Primary Industry and Fisheries, personal communication). In 1999, a further 3 500 and 1 500 80- mm-long fish were released into Manton Dam and Lake Bennett respectively (G. Schipp, Northern Territory Department of Primary Industry & Fisheries, personal communication). There have been no sanctioned releases of barramundi in Western Australia although Doupé and Bird (1999) suggest that there have been occasional and illicit stockings of barramundi over many years into Lake Kunnunurra in the north of the State. They report that the fate of these releases and the number of resident fish are unknown although occasionally a capture is documented. Doupé and Bird (1999) noted an interest from community groups and government agencies in the development of a recreational barramundi fishery in impounded waters in northern Western Australia.

Aquaculture

The barramundi aquaculture industry in Australia had its beginnings in Queensland in the late 1980s when the Department of Primary Industries established a research programme aimed at adapting Thai culture techniques for Australian conditions (MacKinnon, 1987). Initially eggs for the programme were sourced from wild stocks and the larvae grown out to fingerling size in the hatchery using intensive culture techniques (MacKinnon, 1987). The production technology for barramundi has since developed so that now eggs are sourced from captive broodstock and both extensive and intensive systems are used for larval rearing (see Methodology of sea ranching section).

Barramundi are farmed in cages in freshwater or brackishwater ponds, in sea cages and in land-based recirculating systems (Rimmer, 1995b). Within the natural distribution of barramundi (Queensland, the Northern Territory and Western Australia) they are farmed in ponds or in sea cages. In southern Australia (New South Wales, Victoria and South Australia), where water temperatures are too low for successful outdoor farming of barramundi, they are farmed in indoor recirculating systems or using geothermal water.

The cages commonly used in pond culture are 8 m^3 in size (2 × 2 × 2 m), although larger cages (12–100 m^3) are also used. In ponds, two rows of cages are floated either side of a central walkway, which allows access for feeding and cage maintenance. Each cage is supplied with aeration to maintain a high dissolved oxygen concentration, and injector-type aerators are placed in the ponds to assist with water circulation and to increase dissolved oxygen levels (Rimmer, 1995b). Water exchange rates in ponds vary considerably between different farms, but generally range from 10 to 20 percent of pond volume per day. Sea cages used for barramundi culture are usually sited in estuarine areas where wind and wave action are greatly reduced, and are generally of the "polar cirkel" type originally developed for salmon culture (See Plate 4). Some barramundi are also farmed in earthen or lined ponds without cages, a technique known in Australia as "free-ranging". This technique is reported to result in faster growth and better appearance and colour (silver rather than black) of the fish, and reduces operational costs because cage maintenance is unnecessary. Because of bird predation problems with smaller fish in ponds, the use of "free-ranging" is largely restricted to larger fish (> 1 kg). The major disadvantage of this technique is the difficulty in harvesting the fish without draining the pond. Fish are captured using angling techniques, trapping or seine netting (Rimmer, 1995b).

PLATE 4. A "polar cirkel" type cage used for barramundi farming in an estuary in Australia

In Australia, a number of barramundi farms have been established using recirculating freshwater or brackishwater systems with a combination of physical and biological filtration. One farm in South Australia uses geothermal heated water for barramundi farming. The major advantage of these indoor culture systems is that they can be sited near to markets, thus reducing transport costs for the finished product.

Stocking densities used for cage culture of barramundi generally range from 15 to 40 kg/m^3, although densities may be as high as 60 kg/m^3 (Rimmer, 1995b). Barramundi are fed on commercially available pellets. Several Australian manufacturers now supply pellets developed specifically for barramundi, and a floating/slow-sinking pellet is now available. The use of floating pellets reduces feed wastage because they are available to the fish for longer, and the fish farmer can more easily observe the decreased rate of feeding that signals satiation.

Most farmed barramundi are marketed at "plate size", i.e. 300–500 g weight. Recently, some farms have begun to produce larger fish (about 3 kg) for fillet product (Barlow, Williams and Rimmer, 1996). Growth is highly variable, and depends on various factors including feeding rate, feed quality and stocking density. Generally, barramundi grow from fingerling to 300–500 g in 6–12 months, and to 3 kg in 2 years. No significant differences in growth rate have been found in barramundi cultured in either fresh or salt water (MacKinnon, 1990). Similarly, there appear to be no substantial differences in the growth rates of barramundi from different genetic stocks.

Queensland is the largest producer of farmed barramundi amongst Australian states. In 1997/98, Queensland barramundi farms produced 434 tonnes valued at $A4.34 million (Lobegeiger, 1999). Total barramundi production for Australia is of the order of 600 tonnes valued at around $A6 million.

PRINCIPAL PROBLEMS WITH FISHERY

There is considerable concern about declining barramundi stocks not only in parts of northern Australia (Russell, 1988; QFMA, 1996; Williams, 1997) but also in other parts of the region including Papua New Guinea (Milton *et al.*, 1998). The reasons why barramundi are threatened are complex and related to numerous factors including overexploitation, habitat destruction, pollution and poor land management practices. Recently in Queensland, Williams (1997) has documented a general decline in commercial barramundi catches, although this has varied, particularly as a result of varying levels of effort. For example, on the east coast the total barramundi catch has declined whereas CPUE has remained relatively stable. However, in the Gulf of Carpentaria, both the total catch and the CPUE have declined There has been an upward trend in both catch and CPUE in the Queensland barramundi fishery during the late 1990s. Williams (1997) warns of a number of concerning biological indicators including changing population sex ratios, a diminishing mean size of female fish at sexual maturity that suggest that stocks in the Gulf of Carpentaria are under pressure. Additionally, he points to logbook data and research surveys that show

PLATE 5. Fishway on a tidal barrage on the Burnett River in central Queensland. This type of step and pool fishway is unsuitable for many native Australian fish including barramundi

that between 60 and 70 percent of the barramundi harvested are sexually immature at capture and that fishing operations are largely based on barramundi that have grown just large enough to enter the fishery. This is of major concern, considering that Milton *et al.* (1998) regard barramundi populations as highly susceptible to recruitment overfishing and view the dramatic decline in catch levels of barramundi in the Western Province of Papua New Guinea as evidence of recruitment overfishing. In the Northern Territory, Fallu (1996) noted that barramundi populations have largely recovered from previous overexploitation, which dated back as far as the late 1970s.

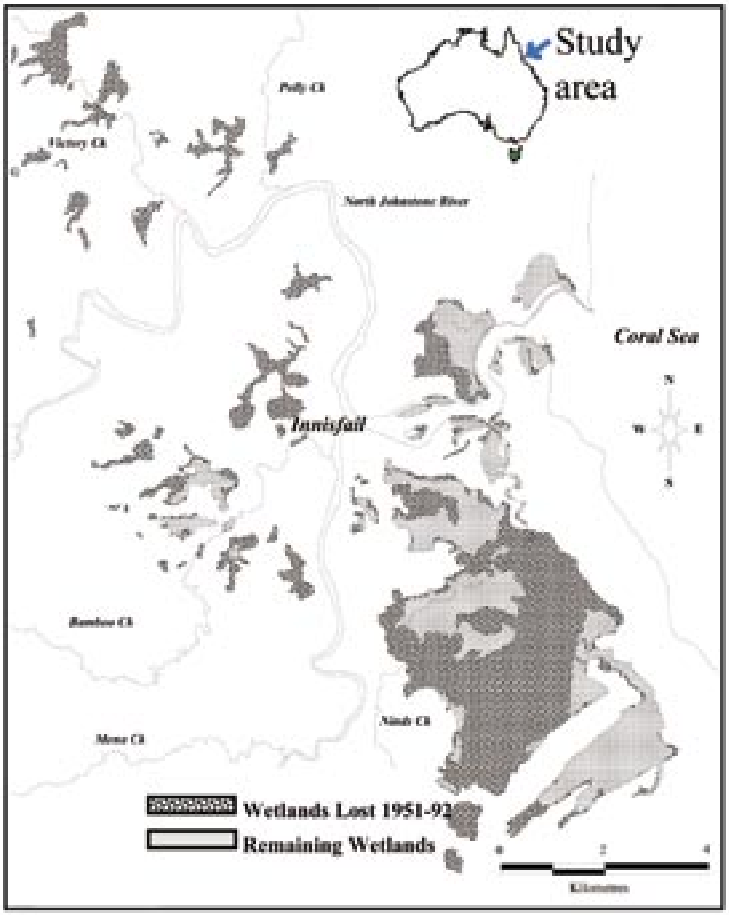
One of the major problems associated with development of effective management plans is a paucity of information for management of the fishery. For example, whereas there are reasonable data on the levels of exploitation in the commercial fishery (Lea, Grey and Griffin, 1987; Quinn, 1987; Fallu, 1996; Williams, 1997) there is little information on either recreational or indigenous catches. Fallu (1996) notes that barramundi is used as a food source for Aboriginal people in coastal areas of the Northern Territory but that the level of utilization is unknown. In an earlier study, Lea, Grey and Griffin, (1987) describe indigenous users as having only a small impact on the fishery in the Northern Territory. The situation is similar in Queensland where the indigenous catches are unknown, although Williams (1997) believes that catches of fisheries resources may be substantial in some areas. The recreational catch of barramundi in Queensland remains unknown (Williams, 1997) whereas in the Northern Territory there have been a series of area-specific angler surveys (Griffin, 1993; Fallu, 1996). In one area of these surveys, the total catch rate was shown to have increased from 0.11 fish/hour in 1986 to 0.23 fish/hour in both 1994 and 1995. Little information is available on the barramundi fisheries in Western Australia.

Lea, Grey and Griffin (1987) assert that to achieve management objectives it is first necessary to obtain estimates of what yield can be sustained by the fishery. Apart from a lack of reliable population parameters for the fishery, they maintain that one large problem faced by managers when aiming to assess the maximum sustainable yield is the lack of data from recreational fisheries. In Queensland, a discussion paper on the Gulf of Carpentaria inshore fishery (QFMA, 1996) concedes that there is insufficient knowledge to demonstrate whether present harvest levels of target species, including barramundi, are sustainable. Furthermore, it admits that sustainable harvest levels are unlikely to be identified for many years. In the absence of definitive data on sustainable harvest levels, the discussion paper maintains that the principles of ecologically sustainable development require that responsible fisheries agencies take a precautionary approach to maintain biological diversity, provide for sustainable use of fisheries resources and ensure the equitable use and allocation of natural resources within and between generations (QFMA, 1996).

With a number of competing industry sectors, it is not surprising that resource sharing is an issue, particularly between the commercial and recreational fishers (Grey, 1986). Although catch statistics for the recreational fishery are either inadequate or non-existent, there is little doubt that increasing populations in regional centres, improved accessibility to fishing grounds and more leisure time are shifting the balance in favour of the recreational fishery. For example, in the Northern Territory, the recreational fishery expansion occurred rapidly and by the early 1980s the annual value of the fishery was about the same magnitude as the commercial catch (Grey, 1987). As a consequence of this shift, the management regulations were subsequently adjusted to take account of the recreational component. Grey (1986) noted that there was also an increasing awareness of the economic benefits of recreational fishing, particularly through tourism, and this had resulted in the active promotion of barramundi as a tourist attraction. Significantly, he suggested that when aquaculture production reaches the point of commercial production, much of the commercial demand for the species to be taken from wild stocks will be alleviated.

Development including urbanization, agricultural expansion and an extension of infrastructure to cater for a developing tourist industry are combining to put further pressure on the resource. As described in the **Life history and reproductive biology** section, barramundi are catadromous and euryhaline, utilizing a range of estuarine coastal and freshwater habitats. Moore (1982), Davis (1985a, 1985b) and Russell and Garrett (1983, 1985) found barramundi postlarvae utilize specific nursery habitats adjacent to estuaries and coastal spawning grounds. Russell and Garrett (1985) suggested that human interference with nursery grounds could lead to a decline in local barramundi stocks and their attendant fisheries. They conjecture that, if a direct relationship exists between nursery areas and barramundi stocks, then it is fortuitous that, with the exception of the east Queensland coast, much of northern Australia is still isolated, sparsely populated and industrially undeveloped. In eastern Queensland in particular, urban, agricultural, tourist and industrial development have impacted on fisheries habitat. In some catchments more than 60 percent of freshwater wetlands (Russell and Hales, 1993; Russell, Hales and Helmke, 1996a, 1996b) (see Figure 4) have been lost primarily to agricultural

FIGURE 4. Loss of coastal wetlands from the Johnstone catchment in northeastern Queensland between 1951 and 1992. Russell and Hales (1992) estimated that in this period about 60 percent of the wetlands were lost to mostly agricultural development



development. There has been further habitat loss through the construction of barrages and dams on coastal rivers, many of which do not make adequate provision to facilitate fish passage (See Plate 5) and alter hydrological and nutrient processes (QFMA, 1996). Agricultural practices in estuary catchments have destroyed riparian zones, and pesticides, fertilizers and sediments have had adverse impacts on fisheries production (QFMA, 1996).

These changes have been occurring progressively over many years and although processes such as Integrated Catchment Management in Queensland are now helping to address some of the environmental issues, many are regrettably irreversible. In such situations where habitat restoration is improbable or impossible and where traditional restrictions on fishing effort are ineffective, stock enhancement is a potentially productive management tool.

UNIQUE FEATURES OF FISHERY

The commercial barramundi fishery in Australia is the major component of a broader multispecies coastal and estuarine gillnet fishery (Russell, 1988). The total production (over 1300 tonnes in 1997/98) by world standards is relatively small, but the product commands high prices and is in high demand. The fishery comprises a number of smaller, individual licensed operators rather than larger, company-owned fleets that characterize many other fisheries. Attempts have been made to take into account the complex biology of barramundi in the development of the management strategies. For example, in Queensland the closed season is designed to protect fish during the period when spawning activity is greatest. In the Gulf of Carpentaria fishery, this has been fine-tuned to the point where moon phase determines the opening and closing of the season (QFMA, 1996). Management regulations for the fishery also take into consideration that Barramundi are protandrous hermaphrodites that mature as males and later change sex to females (Davis, 1985a). In Queensland there is not only a minimum size limit (58 cm) designed to allow fish to mature as males but there is also a maximum size (120 cm) to protect larger, breeding females (QFMA, 1996).

RATIONALE BEHIND SEA RANCHING/ENHANCEMENT

Why was sea ranching chosen?

In Australia, impoundment stockings preceded sea ranching of barramundi. Barramundi were first stocked in impoundments in Queensland with the purpose of creating new recreational fisheries in waters that would otherwise have had only limited fishing potential (MacKinnon and Cooper, 1987). Originally it was proposed to create a recreational fishery in artificial impoundments through the introduction of Nile perch (Midgely, 1968). The rationale for this action was that most Australian freshwater fishes have adapted to riverine conditions, and hence their biology is geared to lotic environments (Barlow, 1984). However, the risks associated with this proposed introduction were considered to outweigh the potential benefits and consequently the responsible agency abandoned the concept of introducing Nile perch to Australia (Barlow and Lisle, 1987). Coincidentally at this time the technology for mass production of barramundi fingerlings was being developed in a number of Queensland hatcheries (MacKinnon and Cooper, 1987) thus providing the prospect of large number of fingerlings being available for stocking into the wild. Instead of the creation of fisheries based on Nile perch, a successful programme was developed to create "put and take" barramundi fisheries in north Queensland impoundments

(Pearson, 1987). This stocking programme was later extended to include open river systems to address perceived declines in natural stocks that arguably are the result of multiple factors including habitat degradation and overexploitation (Rimmer and Russell, 1998b). The first open river system was stocked with hatchery-reared barramundi in 1990 and since then fish have been released into many east coast streams and in the Gulf of Carpentaria drainage system (Rimmer and Russell, 1998b). The fishing community, particularly recreational fishers, is strongly supportive of the concept of barramundi stock enhancement and they have taken the initiative and formed numerous community-based stocking groups (Rimmer and Russell, 1998b). These groups both aggressively promote and are actively involved in the release of barramundi and other species into impoundments and coastal streams. Community stocking groups in Queensland source their fingerlings from both government and commercial hatcheries.

In Australia, Queensland is currently the only state where sea ranching of barramundi is being promoted. A research project is underway in Queensland that is investigating the efficacy and cost-effectiveness of sea ranching (Rimmer and Russell, 1998b). In the Northern Territory, there has been some limited stocking of a freshwater impoundment but no stocking programmes have been instigated in coastal rivers (Doupé and Bird, 1999, R. Griffin, Northern Territory Department of Primary Industry and Fisheries, personal communication). Similarly, in Western Australia there have been no sanctioned releases of barramundi in either impoundments or in coastal rivers, although Doupé and Bird (1999) suggest that there have been occasional illicit stockings of barramundi over many years. Harvest and environmental pressures on barramundi stocks in the Northern Territory and north Western Australia are likely to be considerably lower than those in Queensland because of the lower human population densities and limited development, so the need for stock enhancement in these areas is limited (Rimmer and Russell, 1998b).

Evaluation of other fishery management options

In Queensland, fishery management plans are viewed as fluid documents, and the agency responsible for the management of the barramundi fishery (the QFMA) conducts regular reviews of the fishery management plan (e.g. QFMA, 1996). However, if an issue arises mid-cycle that requires immediate attention, then there is provision for it to be addressed outside the regular review process (e.g. QFMA, 1996).

In most states there are now mechanisms in place that seek to protect remaining fish habitat. For example, in Queensland, legislation provides for the proper management, use, development and protection of fish habitats (Couchman, Mayer and Beumer, 1996). This is being done through the protection of all marine plants, the gazette of Fish Habitat Areas to protect critical habitats and, where appropriate, the restoration of damaged or destroyed habitats of importance to fisheries stocks (Couchman, Mayer and Beumer, 1996).

Cadwallader (1995) suggests that if barramundi breeding grounds have been degraded or destroyed, then stocking may be an appropriate strategy for increasing stock numbers. However, he qualifies this by suggesting that habitat rehabilitation of breeding and nursery areas may be a much better long-term option than an ongoing stocking programme. The extent of the loss of wetland habitat, particularly in eastern Queensland, is documented above and this has undoubtedly impacted on barramundi nursery areas. There is a case for remedial works to address some of these losses and Tait (1995) cites cases where activities such as creation of artificial wetlands are contributing to the rehabilitation of coastal fish stocks. However, in comparison with the scale of the original losses, most of which are permanent, such activities are likely to provide only minimal short-term benefits. Furthermore, ignoring the substantial costs of such a programme, it would appear highly unlikely that any significant tracts of now productive agricultural land would be available for habitat rehabilitation.

METHODOLOGY OF SEA RANCHING

Broodstock selection and management

Barramundi brood fish are collected from the wild using gillnets or electrofishing techniques. The latter is preferred because it causes less physical damage to the fish than gillnets. Because of the increasing numbers of hatchery-reared fish being stocked into eastern Queensland drainages, it is becoming progressively more difficult to guarantee that brood fish caught from the wild are not hatchery-reared fish. In some river systems (e.g. the Johnstone River, near Innisfail) all stocked fish are tagged with coded wire tags (Rimmer and Russell, 1998b), but in most Queensland rivers this is not the case.

Barramundi brood fish are held in fibreglass or concrete tanks (see Plate 6) that range in size from 20 to 200 m^3 and which may operate on either flow-through or recirculating water supply systems. Stocking density in tanks is around 0.5 fish/ m^3, and sex ratios are maintained at about 1 : 1 to 2 : 1 (male to female). Commercial farms may hold "spare" broodstock (i.e. those not currently used for spawning) in cages (Plate 4). Barramundi brood fish are fed once daily at a rate of 1–2 percent of body weight (BW), or three times weekly at 3 percent BW, using commercially available baitfish. Because baitfish may not be well handled or stored between capture and sale, their nutritional quality is often poor. Vitamin supplements are usually added to the baitfish to improve the nutritional composition of the brood fish diet, and prevent diseases associated with vitamin deficiencies. Squid and prawns may also be added to the diet.

PLATE 6. Barramundi broodstock held in a saltwater tank at the Northern Fisheries Centre, Cairns, Queensland

Because of the relatively large size of adult barramundi (females are generally 10– 20 kg in weight), facility size limits the number of fish that can be kept for broodstock purposes. As a result of this, no Australian hatchery (including government hatcheries) currently has the facilities to hold the large numbers of broodstock typically recommended for marine stock enhancement programmes (Allendorf and Ryman, 1987). In general, many captive barramundi do not mature sufficiently to be used as brood fish, and there is some evidence that this proportion varies between different genetic strains. As a "rule of thumb" in Queensland, only about 25 percent of Cairns strain barramundi mature to the point at which they can be induced to breed, whereas this proportion is much lower (<10 percent) for southern Gulf of Carpentaria strain fish kept under identical conditions. Similar low proportions of maturing broodstock have been reported for other marine finfish species, such as red drum *Sciaenops ocellatus* (Tringali and Bert, 1998).

Spawning Induction

Barramundi brood fish may be kept in either fresh or salt water but must be placed in salt water (28–35 ppt) prior to the breeding season to enable final gonadal maturation to take place. Barramundi show no obvious external signs of gonadal development and must be examined by cannulation to determine their gender and reproductive status. The cannula is a 40–50 cm length of clear flexible plastic tubing (3 mm outer diameter, 1.2 mm inner diameter) that is inserted into the urinogenital orifice of males or the oviduct of females after they have been anaesthetized. The cannula is guided into the fish for a distance of 2–3 cm (males) or 6–7 cm (females), and suction is applied to the other end of the cannula as it is withdrawn. After withdrawal, the sample within the cannula is expelled onto a Petri dish or, in the case of eggs, into a vial containing 1–5 percent neutral buffered formalin for later measurement of egg diameter (Garrett and Connell, 1991).

Although environmental manipulation has been used with success to induce spawning in Asian populations of barramundi (Rimmer and Russell, 1998a), Australian populations can only be reliably induced to spawn using exogenous hormone preparations. Barramundi females with eggs 400 µm in diameter or larger are suitable for hormonal induction of spawning; males that are suitable for spawning induction will indicate milt (dense sperm) when cannulated or may produce a small "bead" of milt when moderate external pressure is applied to the belly of the fish (Garrett and Connell, 1991). Barramundi brood fish are usually suitable for spawning induction when water temperatures reach or exceed about 28 °C.

Barramundi have been successfully spawned using a range of hormones at various doses, which are administered by various techniques including injection, slow-release cholesterol pellets and osmotic pumps; but spawning induction is now generally carried out using the leuteinizing hormone-releasing hormone analogues (LHRHa) (Des-Gly^{10})D-Ala^{6},Pro^{9}-LH-RH ethylamide and (Des-Gly^{10})D-Trp6,Pro^{9}-LH-RH ethylamide (Garrett and Connell, 1991). Hormones are injected intramuscularly at the base of the pectoral fin. LHRHa dosages of 3–5 µg/kg body weight usually produce a single spawning, whereas dosages of 10–25 µg/kg usually produce 2–4 spawnings on consecutive nights (Garrett and Connell, 1991). Females only are injected; males do not usually need to be induced.

Fish are injected with hormones in the morning to allow for natural spawning in the evening of the following day. Prespawning behaviour involves the male fish pairing with a female and rubbing its dorsal surface against the area of the female's genital papilla, erecting its fins and "shivering". In the absence of such displays, egg release may occur but the eggs are not fertilized. Spawning occurs 34–38 hours after injection, usually around dusk (Garrett and Connell, 1991).

Barramundi will often spawn for up to five consecutive nights (Garrett and Connell, 1991). In the case of spawnings on consecutive nights, egg production, fertilization rate and hatching rate are normally higher on nights 1 and 2 than on subsequent nights; eggs from spawnings on nights 3 and 4 are frequently discarded because of low fertilization and hatching rates. Fecundity is high and females may produce in excess of 0.4 x-10^{6} eggs/kg; it is not uncommon to obtain 3–4-x-10^{6} eggs from a single night's spawning by a single female barramundi.

FIGURE 5. Newly hatched barramundi larvae. Yolk sac and oil globule are clearly visible. (Drawing by Kirsten Otlee)

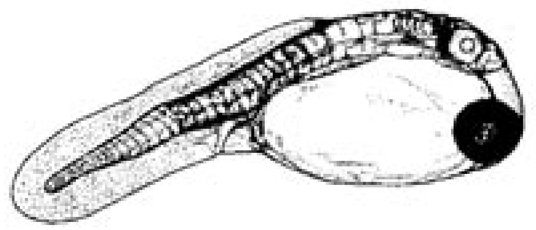
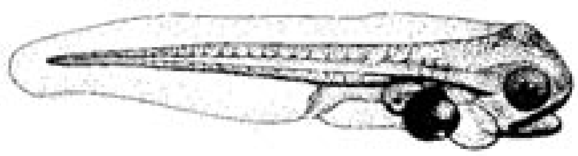


FIGURE 6. Barramundi larvae approximately 3 mm long. Yolk sac has almost completely reabsorbed. (Drawing by Kirsten Otlee)



The breeding season of barramundi can be extended indefinitely by the provision of summer water temperatures (≥-28-°C) and day length (≥-13-h light). Fish subjected to this regime can be induced to spawn at monthly intervals throughout the year, and do not change sex (Garrett and O'Brien, 1993).

Harvesting eggs

At spawning, the sperm and eggs are released into the water column and fertilization occurs externally. Barramundi eggs are 0.74–0.80 mm in diameter with a single oil droplet 0.23–0.26 mm in diameter (NICA, 1986). The fertilized eggs may be positively or neutrally buoyant; unfertilized eggs are generally negatively buoyant (NICA, 1986).

Barramundi eggs are concentrated in the spawning tanks using egg collectors, either inside or outside the tanks. Internal egg collectors consist of bags of 300 µm mesh material, approximately 0.5 m^3 in volume, which are suspended from a hollow PVC frame. Eggs are concentrated in the net using airlifts fitted to the PVC frame. External egg collectors are suitable only for flow-through tank systems and are placed in externally mounted tanks through which the tank effluent passes.

Eggs are placed in larval rearing tanks at densities of up to 1 200 eggs/litre for incubation and hatching. Dead and unfertilized eggs are removed by briefly turning off the aeration in the hatching tank and siphoning out the dead eggs, which sink rapidly to the bottom of the tank.

Egg and larval development

Fertilized eggs undergo rapid development and hatching occurs 12–17 h after fertilization at 27–30 °C (FAO, 1984; NICA, 1986; Ruangpanit, 1987; Parazo *et al.*, 1990). Newly-hatched larvae (Figure 5) have a large yolk, which is absorbed rapidly over the first 24 h after hatching, and is largely exhausted by 50 h after hatching (Kohno, Hara and Taki, 1986). The oil globule is absorbed more slowly and persists for about five days after hatching. The mouth and gut develop the day after hatching (day 2 [D2]) and larvae commence feeding from 45 to 50-h after hatching (Kohno, Hara and Taki, 1986; Parazo *et al.*, 1990) (Figure 6).

Larval rearing

Barramundi are reared to fingerling stage generally ≥20 mm (TL) using either intensive rearing techniques (Rimmer and Russell, 1998a).

Intensive larval rearing

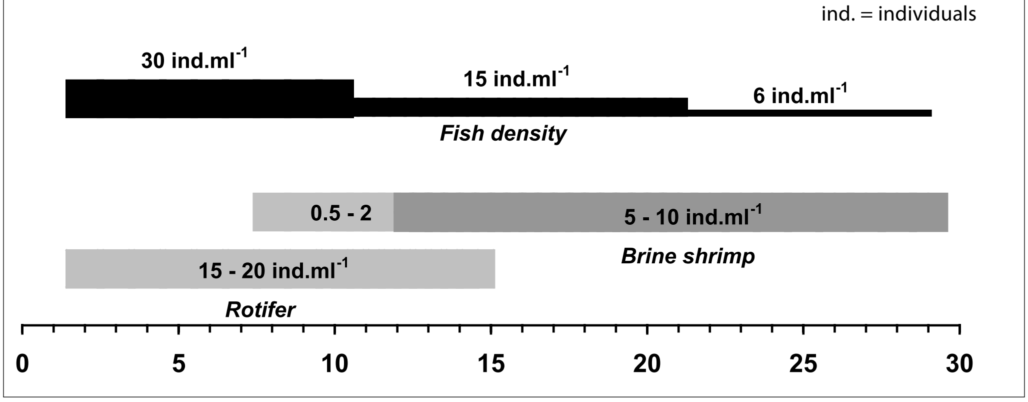
Barramundi larvae are reared intensively in circular or rectangular fibreglass or concrete tanks of up to 5 m^3 capacity. Circular tanks with a conical base are preferred because of better water circulation and drainage compared with rectangular tanks (Russell, 1987). Rearing tanks are constructed with a central bottom outlet fitted with a removable screen to retain larvae (Russell, 1987). Recommended stocking rates for barramundi larvae (up to about 10 mm TL) are 10–40 fish/litre. Overall survival for intensively reared barramundi larvae from hatching to about 10 mm TL is usually around 50 percent.

Both "clear water" and "green water" intensive rearing techniques have been successfully used to rear barramundi (Palmer *et al.*, 1992; Rimmer and Russell, 1998a). Using "clear water" techniques, optimal water quality is maintained by having high rates of water exchange to remove wastes, particularly ammonia. The water supply may be from flow-through or recirculating systems. In "green water" culture, a microalgal culture (usually *Nannochloropsis oculata* or *Tetraselmis* sp.) is added to the rearing tanks at densities ranging from 8–10-× 10^3 to 1–3-× 10^5 cells/ml and the microalgae aid in maintaining optimal water quality by utilizing nitrogenous wastes and carbon dioxide, and producing oxygen. To maintain the desired density of microalgal cells, water changes are limited to 10–50 percent daily for the first 25 days of the rearing period, and 50–75 percent daily thereafter. Rearing tanks are siphoned clean daily, and microalgal cultures are added to maintain the required density of algal cells.

Intensively reared barramundi are fed on rotifers (*Brachionus plicatilis*) from D2 (where D1 is the day of hatching) until D10 (or as late as D15), and on brine shrimp (*Artemia* sp.) from D8 onwards (Rimmer *et al.*, 1994) (see Figure 7). Rotifers are fed 2–4 times daily, at 10–20 individuals/ml. Brine shrimp are fed 2–3 times daily at 0.5–2 individuals/ml initially, gradually increasing to 5–10 individuals/ml.

An important requirement for intensively reared barramundi larvae is adequate nutrition. Barramundi larvae fed diets deficient in highly unsaturated fatty acids (HUFA), particularly 20:5n-3 (eicosapentaenoic acid or EPA), become pale and, when stressed, swim erratically and "faint', after which they either recover (presumably temporarily) or die (Dhert *et al.*, 1990; Rimmer *et al.*, 1994). Feeding procedures developed to overcome this deficiency provide prey organisms of suitable nutritional quality. Rotifers are cultured using microalgae high in HUFAs such as *Nannochloropsis oculata*, which is high in EPA. Both rotifers and brine shrimp may be supplemented with a commercially available HUFA enrichment preparation in liquid or microcapsule form (Dhert *et al.*, 1990; Rimmer *et al.*, 1994).

FIGURE 7. Density of fish and prey for intensive rearing of barramundi larvae



Extensive larval rearing

In Australia, ponds used for the extensive larval rearing of barramundi generally range from 0.05 to 1 ha in area and may be earthen or plastic-lined (see Plate 7) (Rimmer and Russell, 1998a). They are relatively shallow (< 2 m deep) to promote maximum production of phytoplankton and to prevent stratification. The productivity of a pond is controlled by the addition of organic and inorganic fertilizers, which generate the blooms of phytoplankton, bacteria and protozoans that are food sources for zooplankton (Geiger, 1983a, 1983b). Although various inorganic and organic fertilizers can be used, the most commonly used fertilizers are diammonium phosphate (DAP) and lucerne pellets.

Barramundi larvae are stocked into the pond at the time they are ready to commence feeding (usually D2), to coincide with peak densities of the smaller zooplankton, i.e. rotifers and copepod nauplii, which are the initial prey of the larvae (Rutledge and Rimmer, 1991). The larvae are stocked at densities of 400 000–900 000 fish/ha (Rutledge and Rimmer, 1991).

Zooplankton density and water quality parameters, particularly dissolved oxygen, temperature, salinity and pH, are monitored routinely (Rimmer and Rutledge, 1991). Larval and juvenile barramundi are sampled regularly to determine the success of stocking, and to monitor growth and fish health (Rimmer and Rutledge, 1991). Barramundi larvae can be readily sampled from aerated ponds using a zooplankton net (35 cm diameter, 80 cm length, 300 µm mesh size). Juvenile barramundi are sampled using square lift nets 0.25–1.0 m^2 fitted with 1–2 mm mesh size insect screen or similar material. The lift nets are left on the bottom of the pond and are lifted rapidly to trap any juvenile barramundi that are on or directly above the net (Rimmer and Rutledge, 1991).

Barramundi in larval rearing ponds commence feeding on the smaller zooplankton, such as rotifers and copepod nauplii. As the larvae grow, they feed on larger organisms such as copepodites, adult copepods and (if present in the pond) cladocerans. As zooplankton densities decrease as a result of predation, the barramundi switch to benthic food sources, principally midge larvae "blood worms" (Rutledge and Rimmer, 1991).

Extensively reared barramundi larvae grow faster than larvae reared intensively, possibly owing to better nutrition resulting from a more varied diet and to greater prey availability throughout the day. Generally, extensively reared barramundi reach 20–30 mm TL after about three weeks in the pond, at which time they are harvested. By comparison, intensively reared barramundi reach about 10 mm TL after three weeks (Rutledge and Rimmer, 1991). Growth rates of up to 3.8 mm/day and specific growth rates (in length) of up to 28 percent/day have been recorded for extensively reared barramundi larvae. However, growth rates in ponds vary widely and are particularly dependent on water temperature, salinity and food availability. Barramundi are harvested from the ponds when they reach 20 mm TL or greater, and are then transferred to nursery tanks.

PLATE 7. A saltwater pond used for the extensive culture of barramundi. The pond is in the process of being drained prior to harvesting

Survival of extensively reared barramundi averages about 20 percent, but is highly variable, ranging from 0 to 90 percent These figures correspond to production rates of up to 640 000 fish/ha (Rimmer and Russell, 1998a). The lower costs of extensively reared fingerlings, estimated at 40–64 percent that of intensively reared fingerlings (Lobegeiger, 1993), and the lower infrastructure requirements for this technique have resulted in the widespread adoption of extensive larval rearing techniques for barramundi in northern Australia.

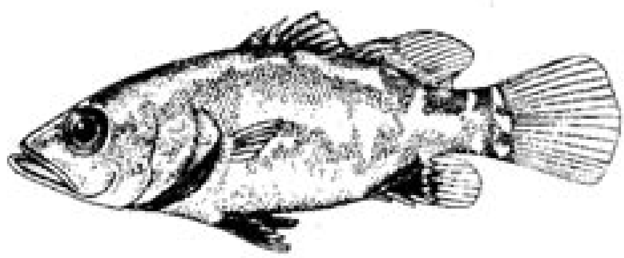
Nursery phase

Juvenile barramundi (Figure 8) are transferred to nursery facilities after they have been harvested from the rearing ponds, or from intensive culture tanks. Most nursery facilities use small cages (about 1 m^3) made from insect screen mesh in concrete tanks or above-ground pools. Many Australian barramundi farms use freshwater ponds for grow-out and thus operate freshwater nursery facilities (Rimmer and Russell, 1998a). Juvenile barramundi (> 10 mm TL) can be transferred from saltwater to freshwater in as little as 6 h with no significant mortality (Rasmussen, 1991).

Once they are in the nursery facility, the fingerlings are weaned to pellets. Barramundi can be weaned to pellet diets from as small as 10 mm TL, although better survival and faster acceptance of pellets are obtained if weaning is delayed until the fish are at least 15–20 mm TL (Barlow Williams and Rimmer, 1996). Barramundi may commence feeding on inert diets within a few hours of harvesting, and most fish commence feeding within a few days.

Barramundi fingerlings are usually supplied to stocking groups, or stocked out directly by the hatchery operator, from the nursery. Stocking of fingerlings directly from the rearing ponds does sometimes occur, but is not often undertaken because it is difficult to obtain an accurate count of the number of fish obtained.

FIGURE 8. Juvenile barramundi. (Drawing by Kirsten Otlee)



Release strategy

In Queensland, stocking groups purchase fish directly from commercial hatcheries, or are supplied by the state government hatcheries. Typically, barramundi of 20– 40 mm TL are stocked, depending on the availability of fingerlings of various sizes. Barramundi fingerlings supplied by commercial hatcheries are sold on the basis of average size, generally for $A0.01 per mm TL. Because of this pricing structure, most stocking groups prefer to purchase larger numbers of cheaper (smaller) fingerlings. One stocking group in northern Queensland usually releases smaller numbers (thousands) of larger barramundi (about 150 mm TL), but there has been no objective comparison of this strategy with that of release of larger numbers of smaller fish.

Release sites are limited by the availability of access for the stocking trucks or transport vehicles (See Plate 8). In some cases, stocking groups may supply boats that are used to distribute the stocked fish more widely than the immediate access area. Preferred release sites for barramundi are those with abundant sublittoral vegetation and other structures to provide shelter for the stocked fish.

Unpublished results from our study in the Johnstone River in far northern Queensland indicate that there are substantial differences in survival of barramundi

PLATE 8. Barramundi being stocked into a north Queensland river

stocked at different sites. The site with the apparent best survival was a freshwater site that has extensive weed (*Vallisneria*) beds that provide excellent habitat for newly released juvenile barramundi. Survival from estuarine sites, despite the availability of extensive mangrove habitat, was much poorer.

Some sites have been found to be unsuitable for release of juvenile barramundi. One site in particular, a freshwater swamp, was stocked for three years with barramundi fingerlings but none has ever been recaptured. This is most likely because of periodic severe declines in water quality in the swamp, resulting in lethally low dissolved oxygen levels (Rimmer and Russell, 1998b).

Limited assessment of size-at-release has demonstrated no significant difference between recaptures of "small" (30–40 mm TL at release) and "large" (50–60 mm TL at release) barramundi (Rimmer and Russell, 1998b). Recently, this research has been expanded to include larger size classes of fish up to 300 mm TL at release. The results of this expanded experimental design have not yet been fully analysed, but it appears that there are proportionally larger numbers of the larger fish (300 mm TL at release) amongst sampled fish.

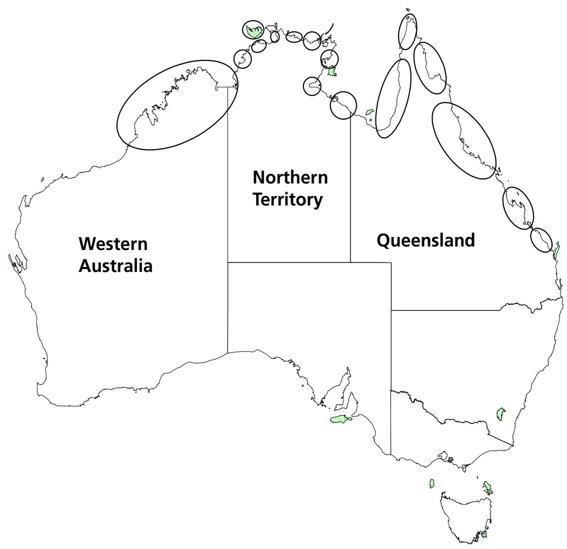
GENETIC RESOURCE MANAGEMENT

Stock structure

The genetic stock structure of barramundi wild stocks in Australia has been studied in detail by Shaklee and Salini (1985), Salini and Shaklee (1988) and Shaklee, Salini and Garrett (1993) and more recently by Keenan (1994). Using allozyme electrophoresis, Shaklee and Salini (1985) reported heterogeneity of barramundi populations in three widely spaced localities in northern Australia. In a later publication, Salini and Shaklee (1988) found genetically distinct barramundi stocks in seven of eight northern Australian locations from which samples were taken. Further sampling found that there were 14 distinguishable populations of barramundi in northern Australia (Shaklee, Salini and Garrett, 1993). A later study by Keenan (1994) differentiated a further two subpopulations of barramundi in the Northern Territory (Figure 9). Keenan (1994) showed that the largest differences in the population structure of barramundi in Australia were between those found on the east coast and stocks to the west. In addition, he suggested that certain populations from the east and west exhibited higher genetic variation than adjacent stocks because they were source populations prior to dispersal during periods of higher sea levels.

Salini and Shaklee (1988) noted that the existence of genetically discrete stocks of barramundi implied that either the geographical separation of such localities or the behaviour of barramundi in these areas, or both, was sufficient to restrict gene flow to a level incapable of overriding the effects of random genetic drift.

FIGURE 9. Genetic stock structure of barramundi in Australia. Sixteen distinct stocks have been identified. (Map adapted from drawings courtesy of C. Keenan, Queensland Department of Primary Industries)



Translocation of non-indigenous genetic stocks

In Queensland, the potential problems associated with translocation of hatchery-reared barramundi derived from one genetic stock into another discrete genetic stock have been recognized by the QFMA. The QFMA has adopted elements of the "responsible approach" to fish stocking (Blankenship and Leber, 1995; Rimmer, 1995a) and any proposed stock enhancement programme requires the associated benefits and risks to be stringently appraised (Cadwallader, 1997). The aim is to enhance fisheries with minimal risk of irreversible damage to existing fisheries resources and the ecological systems on which these resources depend (Cadwallader, 1997). In its draft management plan and regulatory impact statement for Queensland freshwater fisheries (QFMA, 1998) the QFMA has adopted a set of translocation principles for assessing proposals for fish stock enhancement. The guiding principle (Cadwallader, 1997) is in stocking of public and private waters with translocated or non-indigenous genetic stocks of a species to be considered only where a clear economic, social or conservation benefit can be demonstrated, and where no alternative native species in the drainage basin has similar potential. Full details of the translocation principles are given in Appendix 1.

Cadwallader (1997) describes the decision-making process for assessing stock enhancement or translocation proposals as a series of reviews, where failure to satisfy a particular criterion results in the rejection of that proposal. If the proposal satisfies the criterion then it is assessed against the next one, and so on. Genetic and disease risks form part of the assessment criteria.

Salini and Shaklee (1988) also warn of the danger of unmonitored mixing of barramundi from different stocks during hatchery releases for restocking programmes. They suggest that the consequence of mixing natural stocks and hatchery fingerlings derived from a small number of parents is a reduction of naturally occurring genetic diversity and fitness.

Broodstock management

Various aspects of the biology of barramundi in hatcheries affect genetic resource management of the species. Because of the high fecundity of barramundi (Davis, 1985a), only a relatively small number of adult fish need be maintained to supply hatchery demand. Brood fish held under ambient conditions will change sex from male to female, and the hatchery operator must regularly replace male fish to maintain a stock of spawning males (Garrett and O'Brien, 1993). Only a small proportion of these fish (both males and females) will mature sufficiently to produce viable gametes. However, with the development of year-round spawning techniques, only a small number of "good performers" need be held and these can be used for spawning for many years. In fact, most hatcheries rely heavily on a small number of "good performers" that are held under environmental control conditions and are often the major contributors to the genetic pool of the progeny. Based on these factors, inbreeding effects are likely to be high in many hatcheries.

Selective breeding

Commercial hatcheries in Queensland are keen to undertake selective breeding of barramundi to produce faster growing strains. Hatchery-reared broodstock (G1 and G2 generations) are reported to show some differences in their reproductive behaviour in captivity compared with wild caught (G0) fish. In particular, G1 and G2 fish do not exhibit the same response to environmental control conditions as G0 fish, but may change sex even under constant summer photothermal conditions. The Cooperative Research Centre for Aquaculture has supported research into the reproductive biology of captive barramundi broodstock to enable better control of these fish in hatchery environments as a necessary first step towards developing selective breeding programmes (Anderson *et al.*, 1998).

Some commercial farms have commenced mass selection programmes and report dramatically improved growth rates in their G1 and G2 fish. Unfortunately, these selection programmes have been designed without input from professional geneticists and are almost definitely based on small founder populations with little or no outbreeding. Because these same commercial hatcheries also sell fingerlings to local stocking groups, there is considerable concern among government researchers that severe bottlenecking of hatchery populations is taking place, and that these fish may adversely impact on wild barramundi populations if they are stocked in areas where the fish may contribute to breeding populations.

Fish health management

Barramundi larvae reared in Australian hatcheries have periodically suffered severe mortalities (up to 90 percent in some batches) at around D12–D14. Affected larvae became pale and swam erratically in a corkscrewing motion before dying (MacKinnon, 1987). Histological examination of the affected larvae showed extensive vacuolation of the brain and spinal chord and accumulation of excessive fat deposits in the liver (Rodgers and Barlow, 1987). The cause of these mortalities has been variously ascribed to nutritional deficiencies in the live food organisms fed to the barramundi larvae (Rodgers and Barlow, 1987) and to the action of a picorna-like virus in the larvae (Glazebrook, Heasman and de Beer, 1990; Glazebrook and Heasman, 1992; Munday *et al.*, 1992). Similar symptoms have been described for a mortality syndrome seen in sea bass larvae reared in Tahiti (AQUACOP, Fuchs and Nédélec, 1990; Renault *et al.*, 1991).

Infection of larvae with the barramundi picorna-like virus (since reclassified as a *nodavirus*) was readily controlled with improved hatchery methods and this virus then had little effect on barramundi production (Anderson *et al.*, 1993). However, there has been considerable concern about the possible transfer of this pathogen to native fish species inhabiting southern Australian waterways, via barramundi farmed in recirculation production facilities in southern states (New South Wales, Victoria and South Australia) where the barramundi does not naturally occur. In response, fisheries authorities in the southern Australian states have imposed health assessment measures to reduce the chance of barramundi nodavirus being introduced to local waters. These measures include:

- limiting barramundi hatcheries and farms to indoor recirculation systems, with strict controls on effluent;
- histological assessment of the health status of any batches of barramundi fingerlings imported from interstate; and
- requirement to notify fish health authorities in the event of a disease outbreak.

Further research is currently under way to examine the susceptibility of a range of native fishes to barramundi nodavirus, with a view to reviewing these management controls.

Columnaris disease (caused by bacteria of the *Flexibacter/Cytophaga* group) is a particularly important disease of barramundi in nursery facilities (Anderson and Norton, 1991). Columnaris disease typically occurs soon after fish are harvested from the larval rearing ponds and are introduced to the nursery tanks (usually within 24 h from harvesting). Health surveys of juvenile barramundi reared in ponds have shown that they are largely free of ectoparasites.

MONITORING AND EVALUATION PROGRAMMES

Enhancement goals

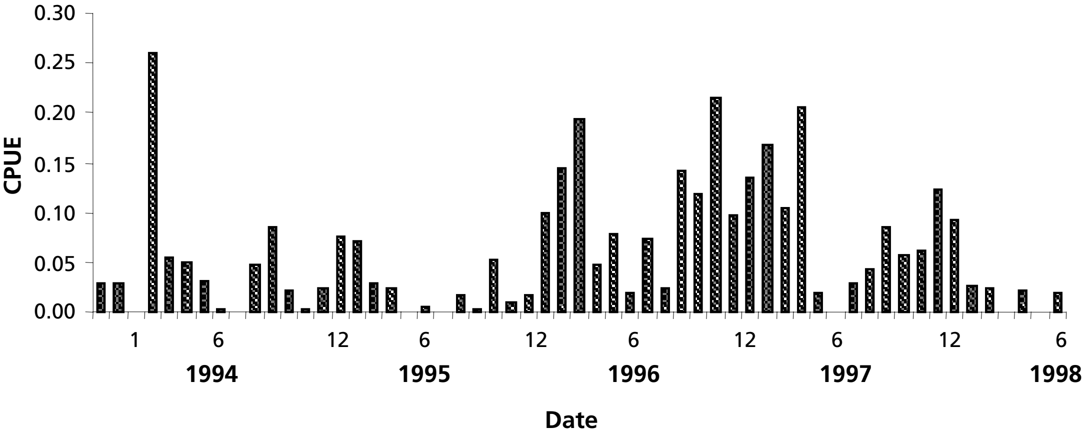
Prior to the commencement of stocking programmes, fishers in Queensland had expressed concern over perceived declines in barramundi populations (Rimmer and Russell, 1998b). Available evidence (see Principal problems with fishery section) seems to support this view, and although the reasons for the decline are contentious, habitat degradation and overexploitation appear to be major factors (Rimmer and Russell, 1998b). The primary goal of fish stocking groups in Queensland is to restore depleted barramundi stocks and therefore improve production. In addition, the Queensland Department of Primary Industries has initiated a series of trial stockings of barramundi into the Johnstone River, north Queensland, to assess the efficacy of stock enhancement as a management tool and to evaluate its cost-effectiveness.

Measure of success

Demonstrating improved catches is probably the major performance indicator of most stocking programmes although Cowx (1994) points out that such a stocking exercise still might not be successful if it does not lead to a successful spawning stock or sustained recruitment. Leber, Brennan and Arce (1995) assert that the central issue that needs resolution in marine stock enhancement is the hypothesis that hatchery releases can actually increase population size of the stocked species. They maintain that two important and largely untested predictions underlie this hypothesis. The first is that significant numbers of hatchery fish can survive in the wild and the second is that released hatchery fish actually increase abundances rather than displace wild stocks. We have attempted to test both of these predictions in the trial stocking of barramundi into the Johnstone River in north Queensland.

To test the first prediction that hatchery fish can survive, it was first necessary to be able to discriminate between hatchery fish and wild stocks. Richards and Edwards (1986) believed that the only effective method of assessing the success of a stocking was to mark the fish before release and to monitor the catches. A number of techniques to mark juvenile barramundi were trialled and coded wire tags were found to be the most suitable (Russell and Hales, 1992). Russell and Hales (1992) found that, when

FIGURE 10. CPUE for the recreational barramundi fishery in the Johnstone River between October 1993 and June 1998



implanted into the cheek muscle, coded wire tags had no significant effect on either survival or growth and tag retention was generally > 96 percent and tagging mortality < 1 percent. All fish released in the Johnstone River barramundi stock enhancement experiment were marked with coded wire tags and a monitoring programme implemented that drew samples from commercial, recreational and research catches (Russell and Rimmer, 1997; Rimmer and Russell, 1998b). Stocked fish have entered the fishery and comprise around 20 percent of barramundi from relevant size classes in the research catches (Rimmer and Russell, 1998b), 13 percent in commercial catches and 19 percent in recreational catches. There appears to little likelihood that large-scale dispersal of stocked fish into other river systems will impact on the success of the stocking. Most (62 percent) stocked barramundi were recaptured within 3 km of their release location catches (Rimmer and Russell, 1998b) and only about 1 percent have made coastal or inter-riverine movements.

The second prediction of Leber, Brennan and Arce (1995) confirming that released hatchery fish actually increase abundances rather than displace wild stocks is more problematic. In the Johnstone River study we proposed to test this by determining changes in the CPUE of the recreational fishery using voluntary angler record cards (Russell and Rimmer, 1997; Rimmer and Russell, 1998b). From December 1993 to August 1998 about 2 300 cards were received detailing over 4 700 angler hours of fishing activity. Data were supplied on more than 7 000 fish from over 40 different freshwater, estuarine and marine species.

The data reflected the seasonal nature of the fishery by showing large variation within years with monthly CPUE generally less during the cooler winter months and then peaking before the start of the closed season in November and immediately after the opening of the fishery in February (Figure 10) (Rimmer and Russell, 1998b). There is also considerable variation between years and it is difficult to decipher any increasing trend in CPUE that could be attributable to fish stocking. The variability of the data aside, using angler record cards to collect data on the recreational fishery has a number of inherent difficulties not the least of which is to persuade anglers to fully participate over a long period of time. Our attempts to have recreational anglers participate in the angler record card survey were only partially successful, and we were forced to rely on a liaison officer both to distribute record cards and to assist anglers in completing them.

Assessing the impact of stock enhancement on the commercial fishery was also difficult because of the low numbers of commercial fishers working in the Johnstone River catchment. Although there are five or six commercial barramundi fishers in the Johnstone River catchment, only two or three frequently fished this system, and all regularly fished adjacent rivers. Consequently, commercial catch data were highly variable. Whereas stocked fish are now a significant component of the Johnstone River recreational and commercial fisheries, the question of whether stocking equates to an increase in production is yet to be answered and needs to be further addressed.

Economic analysis (cost/benefit)

Rimmer and Russell (1998b) have undertaken preliminary analyses of the costs and benefits of stocking hatchery-reared barramundi into coastal waterways. The costs of purchasing a similar number of same-sized fingerlings from commercial hatcheries were used to calculate the total value of the stocking. Using the results of a previous study (Russell, 1988) they assumed that barramundi would be caught in the recreational and commercial fisheries in a ratio of around 1 : 3. They also acknowledged that the value of barramundi to the commercial and recreational sectors would be different. Rutledge *et al*. (1990) estimated that the direct costs incurred by a recreational fisher in northeast Queensland to catch a barramundi was approximately $A50. To a commercial fisher, the average barramundi (5 kg whole weight, with a fillet return of about 50 percent valued at $A10/kg) is worth around $A25. Using these data, Rimmer and Russell (1998b) calculated that less than 1 percent of the total number of fish released would need to be subsequently caught to cover the purchase price of the fingerlings. They emphasize that these analyses are conservative and do not include provisions for indirect economic benefits (Rutledge *et al*., 1990) or indirect costs. On this basis they concluded that stocking of barramundi is likely to be a cost-effective management technique. Further, more detailed, analyses are needed to quantify additionally the economic benefits of barramundi stock enhancement.

Interactions with natural populations

There is little evidence of any significant interactions between stocked and natural populations of barramundi. They simultaneously occupy the same habitats, they form mixed schools and there is no evidence of any differences in catchability. There is no information on extraordinary interactions with other species. Growth of stocked fish is similar to growth rates documented for natural populations of barramundi in rivers in Papua New Guinea and in the Northern Territory and other parts of Queensland (Davis and Kirkwood, 1984; Rimmer and Russell, 1998b).

ASSOCIATED MANAGEMENT STRATEGIES

In Queensland, a fish stocking permit needs to be issued by the responsible fisheries management agency (QFMA, 1998). In general, authorities to stock public waters are only issued to fish stocking groups comprising members of the local community and to groups that have developed a recognized fish stocking plan (QFMA, 1998). These authorities are issued for periods up to five years for approved stocking plans. Proposals to stock conservation areas such as National Parks, World Heritage Areas and Marine Parks are only considered in consultation with the appropriate managers of those areas. Stocking activities must also be consistent with the translocation policy for non-indigenous genetic stocks, which is outlined in the Genetic resource management section.

In north Queensland, special management provisions were developed to facilitate barramundi fish stocking in the Russell/Mulgrave rivers. All commercial gillnetting for barramundi in those rivers was stopped and a three-year moratorium was placed on the use of cast and seine nets by recreational fishers ostensibly to protect stocked barramundi fingerlings. No information is available on the impact of these measures.

MEASURES TAKEN TO PROTECT AQUATIC BIOLOGICAL DIVERSITY AND OTHER FISHERIES

To date there is no indication that aquatic biological diversity has been affected by stocking barramundi in open systems. However, stocking barramundi in rivers and estuaries is a relatively recent innovation and the numbers stocked are low by world standards (typically thousands or tens of thousands per year per catchment). In Queensland, releases are controlled by a permit system administered by the Queensland Fisheries Management Authority (Cadwallader, 1997). Although barramundi stocking in other Australian states is less widespread than in Queensland, stockings in the Northern Territory and in Western Australia are also controlled by the respective state Fisheries Departments.

There has been considerable debate about the impacts of barramundi stocking, and debate continues, particularly regarding the genetic impacts. Queensland, the Northern Territory and Western Australia have translocation policies that limit or prohibit the interstate importation of barramundi and limit within-state translocation to prevent mixing different genetic strains.

SCOPE FOR ADAPTIVE MANAGEMENT

The results achieved to date from our stock enhancement research readily lend themselves to adaptive management. For example, we have demonstrated that survival of fish stocked at different locations varies substantially, with no survival of fish stocked in one particular location (Rimmer and Russell, 1998b). Optimal stocking sites appear to be those with extensive sublittoral vegetation that provides shelter for juvenile barramundi. One strength of the Queensland stocking system, which relies heavily on the activities of local stocking groups, is that local people have a good knowledge of potential stocking sites, so that better sites can be accessed. This is particularly the case with fishers, who make up most of the membership of these stocking groups, and are familiar with large areas of local waterways and the available habitat.

Our ongoing and future research will include experiments focused on size-at-release, release season and "soft" release strategies. This research is aimed at providing information to be used to develop improved stocking practices, and to improve the cost-efficacy of stocking programmes.

GENERAL CONCLUSIONS

General lessons

Our research has demonstrated that stocked barramundi survive to enter both the recreational and the commercial fisheries. Unfortunately, the generally low but highly variable catch rates that we have found in both the commercial and the recreational sectors have precluded demonstrating that stocked barramundi actually enhance the fishery. This demonstrates the difficulty in showing enhancement in an area with a small population base, and thus a small sample of both recreational and commercial fishers.

We have demonstrated that stocking even small numbers of barramundi (tens of thousands per year) can have a significant impact on local stocks. This has important implications in terms of genetic management of stocking for barramundi. Based on our results, it is relatively easy to produce large numbers of fish from a restricted genetic base and to impact a local population with these fish. It is essential that genetic management strategies for barramundi are developed and implemented rapidly to prevent adverse genetic impacts among stocked populations.

Our cost–benefit analysis has shown that even a modest contribution to the fishery (equivalent to < 1% survival) is cost effective. Although we have been unable to demonstrate that stocked fish enhance catches, such a modest contribution can be regarded as readily achievable.

Strengths and weakness of the programme

An important feature of Queensland's barramundi stocking programme is the active involvement of community stocking groups, which is both a strength and a weakness of the programme. Community involvement in stocking provides greater community ownership of the programme and its outcomes. However, most of the members of these stocking groups have little or no technical knowledge of many of the issues involved in marine stock enhancement.

Management of the genetic resources of stocked barramundi populations remains a major challenge. As noted above, the large size of adult barramundi coupled with the low proportion of fish that breed in captivity means that large hatcheries are necessary to hold the numbers of brood fish necessary to support a marine enhancement programme.

Future prospects and limitations

The barramundi is a highly prized finfish species in northern Australia, and is in demand by both the recreational and the commercial fishery sectors (Rutledge *et al.*, 1990). Stocking barramundi is perceived by the community to be a successful method for enhancing barramundi populations, and there is increasing demand throughout northern Australia for stocking programs to be continued or expanded (Doupé and Bird, 1999).

Limitations to the expansion of stock enhancement of barramundi are largely related to genetic issues and the environmental impacts of stocking large numbers of peak predators in aquatic systems. The policy enacted by most Australian state fisheries authorities that limits stocking of barramundi to the progeny of fish originating from the local genetic strain effectively limits the geographical area where barramundi can be stocked. For example, in Queensland, only three of the six strains found in the wild are represented in hatcheries.

There has also been concern expressed regarding the impact of stocking large numbers of peak predators into aquatic systems, and the impacts that this may have on a range of aquatic species. For example, what density of barramundi represents a "natural" density in the highly impacted catchments where barramundi are usually stocked? This and other questions will need to be addressed before sea ranching for barramundi in Australia is fully accepted as a legitimate and essential component of fisheries management.

References

Allendorf, F.W. & Ryman, N. 1987. Genetic management of hatchery stocks. In N. Ryman & F. Utter, eds. *Population genetics and fishery management*, pp. 141– 159. Seattle, USA, University of Washington Press.

Anderson, I., Barlow, C., Fielder, S., Hallam, D., Heasman, M. & Rimmer, M. 1993. Occurrence of the picorna-like virus infecting barramundi. *Austasia Aquaculture*, 7(2): 42–44.

Anderson, I.G. & Norton, J.H. 1991. Diseases of barramundi in aquaculture. *Austasia Aquaculture*, 5(8): 21–24.

Anderson, T.A., Matthews, S.J., Gamage, K.R., Appleford, P., Garrett, R., Rimmer, M., Hall, M. & Schipp, G. 1998. CRC for aquaculture project – control of reproduction in barramundi. *In* M. J. Wingfield, ed. *Proceedings of the Australian Barramundi Farming Workshop*, pp. 10–17. Cairns, Australia, 30–31 July 1998.

Anon. 1988. Draft management plan released for barramundi. *FINS* 21(3): 28–31.

Anon. 1995. Barramundi *Lates calcarifer. Special series on aquaculture species*, Number 9. Perth, Australia, Fisheries Western Australia.

AQUACOP, Fuchs, J. & Nédélec, G. 1990. Larval rearing and weaning of seabass, *Lates calcarifer* (Block), on experimental compound diets. *In* J. Barret, ed. *Advances in tropical aquaculture*, pp. 677–697. Proceedings of a Workshop, 20 February – 4 March 1989, at Tahiti, French Polynesia. AQUACOP IFREMER Actes de Colloque 9.

Barlow, C.G. 1984. The Nile perch project: progress and plans. *Search*, 15(3–4): 88–91.

Barlow, C.G. & Lisle, A. 1987. Biology of the Nile perch *Lates niloticus* (Pisces: Centropomidae) with reference to its proposed role as a sport fish in Australia. *Biol. Conserv.*, 39: 269–289.

Barlow, C., Williams, K. & Rimmer, M. 1996. Sea bass culture in Australia. *Infofish Int.*, 2(96): 26–33.

Blankenship H.L. & Leber K.M. 1995. A responsible approach to marine stock enhancement. *Am. Fisheries Soc. Symp.*, 15: 167–175.

Cadwallader, P.L. 1995. The need for a responsible approach to fish stocking in Queensland. *In* P. Cadwallader & B. Kirby, eds. *Fish stocking in Queensland – getting it right*, pp. 2–7. Proceedings of Symposium, Townsville, 11 November 1995.

Cadwallader, P. 1997. The decision-making process in relation to the enhancement of catadromous fish stocks in Queensland, Australia. *In First International Symposium on Stock Enhancement and Sea Ranching.* Bergen, Norway, 8–11 September 1997. 88 pp.

Couchman, D., Mayer, D. & Beumer, J. 1996. *Departmental procedures for permit applications assessment and approvals for marine plants.* Queensland Department of Primary Industries. 62 pp.

Cowx, I.G. 1994. Stocking strategies. *Fisheries Manage. Ecol.*, 1: 15–30

Davis, T.L.O. 1982. Maturity and sexuality in barramundi, *Lates calcarifer* (Bloch), in the Northern Territory and south-eastern Gulf of Carpentaria. *Australian J. Marine Freshwater Res.*, 33: 529–545.

Davis, T.L.O. 1984a. A population of sexually precocious barramundi, *Lates calcarifer*, in the Gulf of Carpentaria, Australia. *Copeia* 1: 144–149.

Davis, T.L.O. 1984b. Estimation of fecudity in barramundi, *Lates calcarifer* (Bloch), using an automatic particle counter. Australian J. Marine Freshwater Res., 35: 111–118.

Davis, T.L.O. 1985a. Seasonal changes in gonad maturity, and abundance of larvae and early juveniles of barramundi, *Lates calcarifer* (Bloch) in Van Dieman Gulf and the Gulf of Carpentaria. *Australian J. Marine Freshwater Res.*, 36: 177–190.

Davis, T.L.O. 1985b. The food of barramundi, *Lates calcarifer* (Bloch), in coastal and inland waters of Van Diemen Gulf and the Gulf of Carpentaria, *Australia. J. Fish Biol.*, 26: 669–682.

Davis, T.L.O. 1986. Migration patterns in barramundi, *Lates calcarifer* (Bloch), in van Diemen Gulf, Australia with estimates of fishing mortality in specific areas. *Fisheries Res.*, 4: 243–258.

Davis, T.L.O. & Kirkwood G.P. 1984. Age and growth studies on barramundi, Lates calcarifer (Bloch) in northern Australia. *Australian J. Marine Freshwater Res.*, 35: 673–690.

Department of Primary Industry and Fisheries. 1991. *Northern Territory Barramundi Fishery Management Plan.* Fisheries Division. 85 pp.

Dunstan, D.J. 1959. *The barramundi Lates calcarifer (Bloch) in Queensland waters.* CSIRO Division of Fisheries and Oceanography, Technical Paper Number 5. 22 pp.

Dhert, P., Lavens, P., Duray, M. & Sorgeloos, P. 1990. Improved larval survival at metamorphosis of Asian seabass (*Lates calcarifer*) using 3-HUFA-enriched live food. *Aquaculture* 90: 63–74.

Doupé, R. 1997. Getting a grip on Kimberley barra. *Western Fisheries,* 21–25.

Doupé, R.G. & Bird, C. 1999. Opportunities for enhancing the recreational fishery of Lake Kununurra using barramundi *Lates calcarifer*: a review. *Proc. Royal Soc. Queensland*, 108: 41–48.

Fallu, R. 1996. *Barramundi – status report 1996.* Northern Territory Department of Primary Industry and Fisheries.

FAO. 1984. *Manual for spawning of seabass, Lates calcarifer, in captivity*, by T. Tattanon & B. Tiensongrusmee. Rome, FAO. 22 pp.

Garrett, R.N. 1987. Reproduction in Queensland barramundi (*Lates calcarifer*). *In* J. W. Copland & D. L. Grey, eds.*Management of wild and cultured sea bass / barramundi (Lates calcarifer)*, pp. 38–43. Proceedings of an International Workshop held at Darwin, N.T., Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Garrett, R.N. & Connell, M.R.J. 1991. Induced breeding in barramundi. *Austasia Aquaculture* 5(8): 10–12.

Garrett, R.N. & O'Brien, J.J. 1993. All-year-around spawning of hatchery barramundi in Australia. *Austasia Aquaculture*, 8(2): 40–42.

Geiger, J.G. 1983a. Zooplankton production and manipulation in striped bass rearing ponds. *Aquaculture*, 35: 331–351.

Geiger, J.G. 1983b. A review of pond zooplankton production and fertilization for the culture of larval and fingerling striped bass. *Aquaculture*, 35: 353–369.

Glazebrook, J.S. & Heasman, M.P. 1992. Diagnosis and control of picorna-like virus infections in larval barramundi, *Lates calcarifer* Bloch. *In* M. Shariff, R. P. Subasinghe and J. R. Arthur, eds. *Diseases in Asian aquaculture I*, pp. 267–272. Manila, Fish Health Section, Asian Fisheries Society.

Glazebrook, J.S., Heasman, M.P. & de Beer, S.W. 1990. Picorna-like viral particles associated with mass mortalities in larval barramundi, *Lates calcarifer* (Bloch). *J. Fish Diseases*, 13: 245–249.

Greenwood, P.H. 1976. A review of the family Centropomidae (Pisces: Perciformes). *Bull. Br. Museum (Natural History) Zool.*, 29: 4–81.

Grey, D.L. 1986. The development and management of the Northern Territory barramundi (*Lates calcarifer*) fishery. *In* J. L. McLean, L. B. Dizon & L.V. Hosillos, eds. *Proceedings of the First Asian Fisheries Forum*, pp. 375–380. Manilla, Asian Fisheries Society.

Grey, D.L. 1987. An overview of *Lates calcarifer* in Australia and Asia. *In* J. W. Copland & D. L. Grey eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 15–21. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Griffin, R.K. 1986. The importance of mangrove/coastal wetland to three commercial fisheries in the Northern Territory; particularly for barramundi (*Lates calcarifer*). *In* K. N. Bardsley, J. D. S. Davie & C. D. Woodroffe, eds. *Proceedings of a conference on coastal tidal wetlands of Australian monsoon region*, pp. 277–283. Darwin, Australia, Northern Australian Research Unit, Australian National University.

Griffin, R.K. 1987. Life history, distribution and seasonal migration of barramundi, *Lates calcarifer* (Bloch) in the Daly River, Northern Territory, Australia. *In* M. J. Dadswell, R. J. Klauda, C. M. Moffitt & R. L. Saunders, eds. *Proceedings of an international symposium on common strategies of anadromous and catadromous fishes*, pp 358–363. Boston, USA, American Fisheries Society Symposium No. 1.

Griffin, R.K. 1993. The recreational fishery for barramundi, (*Lates calcarifer*) in the Mary River, Northern Territory, 1986–1992. *Fishery report* Number 30. Department of Primary Industry and Fisheries, Northern Territory. 16 pp.

Kailola, P.J., Williams, M.J., Stewart, P.C., Reichelt, R.E., McNee, A. & Grieve, C. 1993. *Australian Fisheries Resources*. Bureau of Resource Sciences and the Fisheries Research and Development Corporation.

Keenan, C.P. 1994. Recent evolution of population structure in Australian barramundi, *Lates calcarifer* (Bloch): an example of isolation by distance in one dimension. *Australian J. Marine Freshwater Res.*, 45: 1123–1148.

Kohno, H., Hara, S. & Taki, Y. 1986. Early larval development of the seabass *Lates calcarifer* with emphasis on the transition of energy sources. *Bull. Japan. Soc. Sci. Fisheries*, 52: 1719–1725.

Lea, R., Grey, D. & Griffin, R. 1987. Utilisation and wildstock management of barramundi (*Lates calcarifer*) in the Northern Territory. In J. W. Copland & D. L. Grey, eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 82–86. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Leber, K.M., Brennan, N.P. & Arce, S.M. 1995. Marine enhancement with striped mullet: are hatchery releases replenishing or displacing wild stocks? *Am. Fisheries Soc. Symp.*, 15: 376–387.

Lobegeiger, R. 1993. Economic benefits of the extensive rearing system for barramundi larvae. *Queensland Aquaculture News*, Issue 2 (July, 1993): 7 pp.

Lobegeiger, R. 1999. *Report to Farmers: Aquaculture Production Survey Queensland 1997–98*. Queensland Department of Primary Industries Information Series QI99017. 24 pp.

Ludescher, C.M. 1997. *Fisheries resources between Bowen and Tully – an inventory.* Queensland Fisheries Management Authority. 136 pp.

MacKinnon, M.R. 1987. Rearing and growth of larval and juvenile barramundi (*Lates calcarifer*) in Queensland. *In* J. W. Copland & D. L. Grey eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 148– 153. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

MacKinnon, M.R. 1990. Status and potential of Australian *Lates calcalifer* culture. *In* J. Barret, ed. *Advances in tropical aquaculture*, pp. 713–727. Proceedings of a Workshop, 20 February – 4 March 1989, at Tahiti, French Polynesia. AQUACOP IFREMER Actes de Colloques 9.

MacKinnon, M.R. & Cooper, P.R. 1987. Reservoir stocking of barramundi for enhancement of the recreational fishery. *Australian Fisheries*, 46(7): 34–37.

Midgely, S.H. 1968. *A study of Nile perch in Africa (and consideration as to its suitably for Australian tropical inland waters).* Winston Churchill Memorial Trust Fellowship Report No. 3.

Milton, D.A., Die, D., Tenakanai, C. & Swales, S. 1998. Selectivity for barramundi (*Lates calcarifer*) in the Fly River, Papua New Guinea: implications for managing gill-net fisheries on protandrous fishes. *Mar. Freshwater Res.*, 49: 499–506.

Moore, R. 1979. Natural sex inversion in the giant perch (*Lates calcarifer*). *Australian J. Marine Freshwater Res.*, 30: 803–813.

Moore, R. 1980. *Reproduction and migration in Lates calcarifer* (Bloch). University of London. 213 pp. (Ph.D. thesis)

Moore, R. 1982. Spawning and early life history of barramundi *Lates calcarifer* in Papua New Guinea. *Australian J. Marine Freshwater Res.*, 33: 647–661.

Moore, R. & Reynolds, L.F. 1982. Migration patterns of Barramundi, *Lates calcarifer* in Papua New Guinea. *Australian J. Marine Freshwater Res.*, 33: 671–682.

Munday, B.L., Langdon, J.S., Hyatt, A. & Humphrey, J.D. 1992. Mass mortality associated with a viral-induced vacuolating encephalopathy and retinopathy of larval and juvenile barramundi, *Lates calcarifer* Bloch. *Aquaculture*, 103: 197–211.

NICA. 1986. *Technical manual for seed production of seabass.* Songkhla, Thailand, National Institute of Coastal Aquaculture. 49 pp.

Palmer, P.J., Burke, J.B., Willett, D.J. & Simpson, R.R. 1992. *Development of a low-maintenance technique for rearing barramundi (Bloch) larvae.* Queensland Department of Primary Industries Information Series QI92036. 19 pp.

Parazo, M.M., Garcia, L.Ma.B., Ayson, F.G., Fermin, A.C., Almendras, J.M.E., Reyes, D.M. Jr & Avila, E.M. 1990. *Sea bass hatchery operations.* Aquaculture Extension Manual No. 18, Aquaculture Department, Southeast Asian Fisheries Development Center. 38 pp.

Pearson, R.G. 1987. Barramundi breeding research - laying the foundations for industry. *Australian Fisheries*, 46(7): 2–3.

Pender, P. 1995. Northern Territory Barramundi fishery – management decisions taken for reasons of biological and non biological necessity. *In* F. Prokop, ed. *The best available information – its implications for recreational fisheries management.* Western Australian Fisheries Management Paper No. 87: 86–90.

Pender, P.J. & Griffin, R.K. 1996. Habitat history of Barramundi *Lates calcarifer* in a north Australian river system based on barium and strontium levels in scales. *Trans. Am. Fisheries Soc.*, 125: 679–689.

QFMA. 1996. *Queensland Gulf of Carpentaria Inshore Finfish Fishery.* Discussion Paper Number 1, Queensland Fisheries Management Authority. 42 pp.

QFMA. 1998. *Queensland Freshwater Fisheries–Draft Management Plan and Regulatory Impact Statement.* Queensland Fisheries Management Authority. 100 pp.

QFMA. 1999. *Overview of the Fisheries (Freshwater) Management Plan 1999.* Queensland Fisheries Management Authority. 15 pp.

Quinn, R.H. 1987. Analysis of fisheries logbook information from the Gulf of Carpentaria, Australia. *In* J.W. Copland and D. L. Grey, eds. *Management of wild and cultured sea bass/barramundi (Lates calcarifer)*, pp. 92–95. Proceedings of an International Workshop held at Darwin, Australia, 24–30 September 1986. Australian Centre for International Agricultural Research Proceedings No. 20.

Rasmussen, I.R. 1991. Optimum acclimation rates from salt – to freshwater for juvenile sea bass *Lates calcarifer* Bloch. *Asian Fisheries Sci.*, 4: 109–113.

Renault, T., Haffner, P., Baudin Laurencin, F., Breuil, G. & Bonami, J.R. 1991. Mass mortalities in hatchery-reared sea bass (*Lates calcarifer*) larvae associated with the presence in the brain and retina of virus-like particles. *Bull. Eur. Assoc. Fish Pathol.*, 11: 68–73.

Reynolds, L.F. & Moore, R. 1982. Growth rates of barramundi *Lates calcarifer* in Papua New Guinea. *Australian J. Marine Freshwater Res.,* 33: 663–670.

Richards, W.J. & Edwards R.E. 1986 Stocking to restore or enhance marine fisheries. *In* R. H. Stround, ed. *Fish culture in management*, pp.75–80. Bethesda, USA, American Fisheries Society.

Rimmer, M. 1995a. Applying World's best practice to fish stocking programs in Queensland. *In* P. Cadwallader & B. Kerby, eds. *Fish stocking in Queensland – getting it right*, pp. 82–89. Proceedings of the Symposium held in Townsville, Queensland, 11 November 1995. Brisbane, Australia, Queensland Fisheries Management Authority.

Rimmer, M.A. 1995b. B*arramundi farming – an introduction*. Queensland Department of Primary Industries Information Series, QI95020. 26 pp.

Rimmer, M.A., Reed, A.W., Levitt, M.S. & Lisle, A.T. 1994. Effects of nutritional enhancement of live food organisms on growth and survival of barramundi, *Lates calcarifer* (Bloch), larvae. *Aquaculture Fisheries Manage.*, 25: 143–156.

Rimmer, M.A. & Russell, D.J. 1998a. Aspects of the biology and culture of *Lates calcarifer. In* S. De Silva, ed. *Tropical mariculture*, pp. 449–476. London, Academic Press.

Rimmer, M.A. & Russell, D.J. 1998b. Survival of stocked barramundi, *Lates calcarifer*, in a coastal river system in far northern Queensland, Australia. *Bull. Mar. Sci.*, 62(2): 325–336.

Rimmer, M.A. & Rutledge, W. 1991. *Extensive rearing of barramundi larvae.* QI91012. Queensland Department of Primary Industries Information Series.

Rodgers, L.J. & Barlow, C.G. 1987. Better nutrition enhances survival of barramundi larvae. *Australian Fisheries*, 46(7): 30–32.

Ruangpanit, N. 1987. Developing hatchery techniques for sea bass (*Lates calcarifer*): a review. *In* J. W. Copland & D. L. Grey, eds. *Management of wild and cultured seabass/barramundi (Lates calcarifer)*, pp. 132–135. Proceedings of an International Workshop, Darwin, Australia. Australian Centre for International Agricultural Research, Proceedings Number 20.

Russell D.J. 1987. Review of juvenile barramundi (*Lates calcarifer*) wildstocks in Australia. *In* J. W. Copland & D. L. Grey, eds. *Management of wild and cultured seabass/barramundi (Lates calcarifer)*, pp. 44–49. Proceedings of an International Workshop, Darwin, Australia. Australian Centre for International Agricultural Research, Proceedings Number 20.

Russell, D.J. 1988. *An assessment of the east Queensland inshore gillnet fishery.* Report Number QI88024. Brisbane, Australia, Queensland Department of Primary Industries. 57 pp.

Russell, D.J. & Garrett, R.N. 1983. Use by juvenile Barramundi Lates calcarifer and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. *Australian J. Mar. Freshwater Res.*, 34: 805–811.

Russell, D.J. & Garrett, R.N. 1985. Early life history of Barramundi *Lates calcarifer* in north-eastern Queensland. *Australian J. Mar. Freshwater Res.*, 36: 191–201

Russell, D.J. & Hales, P.W. 1992 Evaluation of techniques for marking juvenile barramundi *Lates calcarifer* (Bloch), for stocking. *Aquaculture and Fisheries Manage.*, 23: 691–699.

Russell, D.J. & Hales, P.W. 1993. *Stream habitat and fisheries resources of the Johnstone River Catchment*. Report No. QI93056. QI96008. Brisbane, Australia, Queensland Department of Primary Industries. 59 pp.

Russell, D.J., Hales, P.W. & Helmke, S.A. 1996a. *Stream habitat and fish resources in the Russell and Mulgrave Rivers Catchment*. QI96008 Brisbane, Australia, Queensland Department of Primary Industries. 52 pp.

Russell, D.J., Hales, P.W. & Helmke, S.A. 1996b. *Fish resources and stream habitat of the Moresby River Catchment.* QI96061. Brisbane, Australia, Queensland Department of Primary Industries. 50 pp.

Russell, D.J. & Rimmer, M.A. 1997. Assessment of stock enhancement of barramundi, *Lates calcarifer* (Bloch) in a coastal river system in far north Queensland, Australia. *In* D. A. Hancock, D. C. Smith & J. P. Beumer, eds. *Developing and sustaining world fisheries resources – the state of science and management*, pp. 498–503. Proceedings of 2nd World Fisheries Congress, 28 July – 2 August, 1996, Brisbane, Queensland.

Rutledge, W.P. & Rimmer, M.A. 1991. Culture of larval sea bass, *Lates calcarifer* (Bloch), in saltwater rearing ponds in Queensland, Australia. *Asian Fisheries Sci.*, 4: 345–355.

Rutledge, W.P., Rimmer, M., Russell, D., Garrett, R. & Barlow, C. 1990. Cost benefit of hatchery-reared barramundi, *Lates calcarifer* (Bloch), in Queensland. *Aquaculture and Fisheries Manage.*, 21: 443–448.

Salini, J.P. & Shaklee, J.B. 1988. Genetic structure of barramundi (*Lates calcarifer*) stocks from northern Australia. *Australian J. Mar. Freshwater Res.*, 39: 317–329

Shaklee, J.B. & Salini, J.P. 1985. Genetic variation and population subdivision in Australian barramundi, *Lates calcarifer* (Bloch). *Australian J. Mar. Freshwater Res.*, 36: 203–218.

Shaklee , J.B., Salini, J.P. & Garrett, R.N. 1993. Electrophoretic characterisation of multiple genetic stocks of barramundi perch in Queensland, Australia. *Trans. Am. Fisheries Soc.*, 122:685–701.

Tait, J. 1995. Habitat rehabilitation – looking beyond the easy fix for natural fish stocks. *In* P. Cadwallader & B. Kirby, eds. *Fish stocking in Queensland – getting it right*, pp. 41–50. Proceedings of Symposium, Townsville, 11 November 1995.

Tringali, M.D. & Bert, T.M. 1998. Risk to genetic effective population size should be an important consideration in fish stock-enhancement programs. *Bull. Mar. Sci.* 62: 641–659.

Williams, L.E., ed. 1997. *Queensland's fisheries resources – current condition and recent trends 1988–1995*. Brisbane, Australia, Queensland Department of Primary Industries. 101 pp.

Appendix 1

TRANSLOCATION PRINCIPLES

Principles for translocation of fishes in Queensland as listed in QFMA (1999)

The following translocation policy principles have been adopted by the QFMA to ensure that the stocking of fish into public and private waters for recreation, conservation or, where appropriate, other purposes is in accordance with the principles of ecologically sustainable development, including the maintenance of ecological systems and the protection of biodiversity, and dealing cautiously with risk, uncertainty and irreversibility (the Precautionary Principle).

- Stocking public or private waters with translocated species or non-indigenous genetic stocks of a species will be considered only where a clear economic, social or conservation benefit can be demonstrated, and where no alternative native species in the drainage basin has similar potential.
- Translocation will not be permitted in catchments where the integrity of native fish communities remains substantially intact and/or there are one or more threatened species of fish or other aquatic organisms (conservation priority catchments) and/or there are several native fish species of value (translocation unnecessary catchments)
- Translocation of species accorded threatened status because of habitat loss or other factors will be supported. Here, the emphasis is on the establishment of breeding populations (to be carried out in accordance with the principles of the draft Australian and New Zealand Environment and Conservation Council policy for the translocation of vertebrate animals in Australia).
- With the exception of threatened species, preference will be given for translocating species, which will not form self-sustaining populations in their target environment.
- Where a basin or river system is contiguous with another State, the agreement of that State must be obtained before any translocation can take place. Queensland will seek reciprocal agreements with other States.
- All potential translocations will be subject to disease risk assessments to minimize the risk of disease transfers.
- All proposals to translocate fish species or non-indigenous stocks of the same species are to be considered on a case-by-case basis according to a decision-making protocol and standard procedures.

The QFMA and the Department of Primary Industries, Fisheries Group have recognized that translocations must be strictly controlled if irreversible damage to native fish communities is to be avoided. It is recognized that a number of translocations have occurred in the initial 10 years of the Government's recreational Freshwater Fishing Enhancement Programme and that these have created valuable recreational fisheries. These are allowed to continue, but new translocations will be considered only if there is very good evidence that the risks are minimal. Preference will be given to species that will not reproduce in their new environment, as such translocations are reversible.

This approach has been developed by the QFMA and the DPI in consultation with fish stocking associations. It allows for the responsible development of Queensland's recreational freshwater fisheries without threatening the State's wild fisheries.