The responsible approach to marine stock enhancement is a set of principles aimed at maximising the success and benefits of artificially re-stocking depleted fisheries. The benefits of such an approach are evident in the 400% increase in survival of stocked striped mullet in Hawaii through refinement of release techniques, however financially or temporally constrained stocking programs in Australia have not adhered to all principles. A pragmatic approach to address these principles is proposed, using international examples and Australian marine finfish pilot stockings of barramundi, mulloway, sand whiting, dusky flathead and black bream. Biological ranking of candidate species by estuarine residency, a low natural-mortality to growth ratio, a large $L_\infty$ and comparison by recreational value and available rearing technologies, show that mulloway, barramundi and sea mullet are ideal species for stocking in Australia. Australian intermittently closed opening landlocked lagoons and recreational fishing havens, especially near cities, provide experimental opportunities to apply this approach and stock suitable species through small-scale pilot experiments. This would allow evaluation of production and carrying capacity, and density dependent processes with respect to optimal stocking strategies unconfounded by emigration and commercial fishing practices. Twenty per cent of Australians fish each year, and harvest approximately 27 000 t of finfish. Stocking recreationally important species in Australia should give a greater financial benefit, which is spread across a larger cross-section of the community, compared to stocking to enhance commercial fisheries. The pragmatic application of the responsible approach, and stocking of fast growing estuarine residents into recreational fishing havens would enhance the benefit from marine stocking.

Key words: estuary; finfish; recreational fishing; responsible approach; stock enhancement.

INTRODUCTION

Fisheries managers may seek stock enhancement to restore depleted populations of recreationally and commercially significant fish species (Masuda & Tsukamoto, 1998; McEachron et al., 1998; Svåsand, 1998). Stock enhancement
of marine species is a controversial method of fisheries management from economic (Hilborn, 1998), genetic (Utter, 1998) and environmental (Cooney & Brodeur, 1998) perspectives, and gains made from stock enhancement may not be sustainable (Leber, 1999). Nevertheless, there is significant recreational fishing interest in stock enhancement (Hilborn, 1999; Huggan, 2001), and the approach is politically preferable to introducing harsher and less popular conservation measures, such as catch and gear restrictions (Travis et al., 1998). In Australia, the lack of any substantial upwelling (Rochford, 1979) means that nutrient input from estuaries may represent a large proportion of total production. This, coupled with the demonstrated lack of success in stocking oceanic species (Hilborn, 1998; Svåsand et al., 2000), indicates that stock enhancement in Australia should be confined to estuaries and estuarine residents.

Many fish species use estuarine habitats for all or part of their life cycle, and in many cases estuaries are essential for completing a stage of a species life history (Blaber, 1997; Costello et al., 2002). This estuarine dependence is largely a response to the availability of food in estuaries that is absent in offshore waters, and the presence of complex habitats such as mangroves and seagrass to provide shelter from predation and adverse physical conditions for smaller fish (Blaber, 1997). The provision of habitat, and productivity within estuaries has led to ongoing recreational, commercial and subsistence fisheries worldwide, however many estuaries have been adversely affected by pollution, land reclamation and the reduction of fish passage through dam building (Cattrijsse et al., 2002). The flow-on effects from these and other impacts like stocking and habitat restoration are not only relevant for estuarine residents. Those oceanic species that use estuaries throughout their life, such as pilchards Sardinops sagax neopilchardis (Steindachner) and anchovy Engraulis australis (White) (Kailola et al., 1992) will also be affected by activities undertaken in estuaries.

Blankenship & Leber (1995) propose a ten-step responsible approach to marine stock enhancement (Table I), that encourages the application of small-scale experiments. Due to the highly variable nature of the marine environment these experiments are best confined to estuaries. The benefits of such an approach are evident in the successful stock enhancement of sea-mullet Mugil cephalus (Linnaeus) in Hawaii (Leber, 1999) and red-drum Sciaenops ocellatus (Linnaeus) in Texas (McEachron & Daniels, 1995). Whilst some propose further scientific evaluation of stock enhancement technology (Hilborn, 1999) and advocate that it can be used responsibly (Blankenship & Leber, 1995), others classify the approach as techno-arrogant and a halfway technology (Frazer, 1992; Meffe, 1992). Despite these criticisms, estuarine stock enhancement can be a stop-gap measure, and can potentially be used to temporarily supplement recruitment until habitat restoration and stock rebuilding can occur. Habitat restoration may never satisfactorily occur in ports, harbours and other urbanized areas, and in this case stock enhancement may be one pragmatic approach to address declining fish stocks. Successful use of stock enhancement in the future relies on a responsible and cautious approach. Large scale economic and biological failures from stocking programs, such as the salmonid programs in the Pacific Northwest (Hilborn, 1998), show that this should be achieved in a stepwise fashion guided by small-scale research projects to reveal the underlying
mechanisms of stock dynamics and resolve any effect stocking may have. Combining a responsible approach with a sound knowledge of the dynamics and productive capacity of the target ecosystem will help ensure that appropriate species are stocked and sustained by the environment. By drawing on the

TABLE I. Responsible approach to developing, appraising and managing marine stock enhancement proposed by Blankenship & Leber (1995)

Principles

1) Prioritize and select target species for enhancement
   - Initial workshop to define and rank selection criteria
   - Community survey to solicit opinions on selection criteria and identify candidate species
   - Rank candidate species with respect to selection criteria and seek consensus from stakeholders on most appropriate species
2) Develop a species management plan
   - Identify harvest opportunity, stock rebuilding goals and genetic objectives
   - Consider goals and objectives in the context of the management plan for candidate species
   - Evaluate strategies to use in conjunction with stock enhancement
3) Define quantitative measures of success
   - Develop benchmarks against which to measure enhancement success
   - Benchmarks should relate to stock rebuilding goals and genetic objectives
4) Use genetic resource management
   - Identify the genetic risks and consequences of enhancement
   - Define an enhancement strategy
   - Outline research needs and objectives
   - Develop a feedback mechanism
   - Implement genetic controls in the hatchery and a monitoring and evaluation program for wild stocks
5) Use disease and health management
   - Adopt responsible hatchery practice
   - Certify fish are free from viral, parasitic and bacterial infections
6) Form enhancement objectives and tactics
   - Evaluate stock enhancement in an ecological context
   - Evaluate behavioural and physiological deficiencies that may be present in stocked fish
7) Identify released fish and assess stocking effects
   - Develop efficient methods for marking fish
   - Evaluate interactions between hatchery fish and wild stocks and competitors
8) Use an empirical process for defining optimum release strategies
   - Optimise stocking strategies through pilot-scale releases
   - Use empirical data from pilot releases to control enhancement impacts
9) Identify economic and policy guidelines
   - Assess value of enhancement in terms of costs and benefits
10) Use adaptive management
    - Adopt a continuing assessment process that allows improvement over time
    - Allow integration of new ideas and strategies into the management process

This approach was designed to maximize the chance of successful stock enhancement and reduce the probability that failures are repeated. Each step includes a brief summary of the key points proposed by Blankenship & Leber (1995).
experiences of successful and failed marine stock enhancement projects elsewhere, the design of sustainable stocking programs may be possible.

Only nine of the 300 commercially fished species in Australian waters may sustain higher catches with natural recruitment (Kailola et al., 1992). Therefore recent developments in spawning technology and extensive aquaculture techniques for the large-scale rearing of over 20 Australian marine finfish species (Battaglene & Fielder, 1997) may provide for future growth. Australia is taking a cautious approach to stock enhancement before investing in infrastructure or large-scale enhancement projects. Increases of recreational fishing effort in Australia (up to 7.5% per year, Gwynne, 1994), is putting additional pressure on fish stocks, and stocking of marine finfish into estuaries is progressively gaining favour as a management option (Huggan, 2001).

This review examines the status and future prospects of marine finfish stock enhancement in Australia, in the context of the 10-step responsible approach described by Blankenship & Leber (1995). It demonstrates the advantages that intermittently open-closed estuarine lagoons provide as experimental units to assess stocking, the relatively greater benefit for stocking to enhance recreational fisheries over commercial, the selection of suitable species based on growth, and the pragmatic application of these ten guiding principles.

PRAGMATIC APPLICATION OF THE RESPONSIBLE APPROACH

The Blankenship & Leber (1995) responsible approach to marine stock enhancement (Table I) is designed to reduce the chance of a past failure being repeated. One economic failure is the stocking of pink salmon Oncorhynchus gorbuscha (Walbaum) in Prince William Sound, due to declines in survival and poor market prices (Hilborn, 1998). The stocking of cod Gadus morhua (Linnaeus) in Masfjorden was a biological failure, where competition for food resources led to low survival of hatchery-reared fish (Svåsand et al., 2000). The responsible approach embodies a framework with which aquaculture technology can be used to expand and enhance natural resources, however there are few examples where all principles have been covered (Leber & Arce, 1996; Ziemann, 2004). Many programs may be temporally or financially constrained, and these programs need to identify and address the most pressing points within the 10 principles.

PRIORITISE AND SELECT TARGET SPECIES FOR ENHANCEMENT

Selection of species for stock enhancement could be based on the availability of aquaculture technology or the immediate needs of a lobby group or stakeholder in the community. To remove this bias a framework involving input from the community, and the ranking of candidate species according to some explicitly defined criteria should be employed (Blankenship & Leber, 1995). Some suggested criteria are shown in Fig. 1, however ranking of these primarily depends on the goals, duration and level of funding available for the stocking program. The first step is to determine which species are present or occurred historically in the area to be stocked. There should be evidence of a decrease in
catch due to recruitment limitation from either removal of spawners or physical barriers to recruitment, or evidence of additional carrying capacity (from habitat restoration). Munro & Bell (1997) identify some important biological characteristics of species to be stocked, including fast growth and narrow habitat preferences. Fast growth is important to ensure benefit from stocking is obtained in 2–4 years. Habitat preferences will indicate how many fish to release, and where to release and harvest the fish. Species that are highly migratory, oceanic or non-estuarine residents cannot be effectively stocked, as high rates of dispersal, or dilution confound effective harvest. Ideal candidates for stocking are estuarine residents, at least until they enter the fishery and can be harvested. From a financial perspective, the existence of aquaculture technology for the species, and the demonstrated success of stocking particular species elsewhere can minimize the costs of stocking, whilst enhancing recreational fisheries generally has a better cost-benefit ratio and greater funding potential.

Estuarine resident species for which culture technology is available or is under investigation in Australia are listed in Table II, with some of the above criteria applied for these species. These species are ranked according to number caught in the recreational fishery in 2001 (Henry & Lyle, 2003), and market value is included as an indication of the value of the species to the commercial fishery (but not to the recreational fishery). The growth coefficient ($K$), asymptotic size ($L_\infty$), and natural mortality ($M$) to $K$ ratios are provided where possible. $M/K$ ratios usually lie between 1.12 and 2.5 for all fish species (Ofori-Danson et al., 2001), and lower ratios indicate lower natural mortality and higher growth rate.

<table>
<thead>
<tr>
<th>Scientific name</th>
<th>Family</th>
<th>Common name</th>
<th>Population structure</th>
<th>Legal size (cm)</th>
<th>$K$ ($M/K$ ratio)</th>
<th>$L_\infty$</th>
<th>Ranked recreational catch</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Salmo salar</em></td>
<td>Salmonidae</td>
<td>Atlantic salmon</td>
<td>Known</td>
<td>–</td>
<td>3</td>
<td>0·1 (11)</td>
<td>39</td>
<td>8 Non-native</td>
</tr>
<tr>
<td><em>Onchorhynchus mykiss</em></td>
<td>Salmonidae</td>
<td>Ocean/rainbow trout</td>
<td>Inconclusive</td>
<td>38*</td>
<td>2</td>
<td>0·5 (2·8)</td>
<td>58</td>
<td>8 Non-native</td>
</tr>
<tr>
<td><em>Rhombosolea tapirina</em></td>
<td>Pleuronectidae</td>
<td>Greenback flounder</td>
<td>Unknown</td>
<td>23**</td>
<td>1</td>
<td>–</td>
<td>45#</td>
<td>14 Mainly commercially fished</td>
</tr>
<tr>
<td><em>Ammotretis rostratus</em></td>
<td>Pleuronectidae</td>
<td>Long-snout flounder</td>
<td>Unknown</td>
<td>23**</td>
<td>1</td>
<td>–</td>
<td>25#</td>
<td>14 Mainly commercially fished</td>
</tr>
<tr>
<td><em>Latis lineata</em></td>
<td>Latridae</td>
<td>Striped trumpeter</td>
<td>Unknown</td>
<td>25*</td>
<td>3</td>
<td>–</td>
<td>120#</td>
<td>10 Highly desired but difficult to produce</td>
</tr>
<tr>
<td><em>Cheilodactylus spectabilis</em></td>
<td>Cheilodactyliidae</td>
<td>Banded morwong</td>
<td>Unknown</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>100#</td>
<td>13 Grows to large size, but little information known about the species</td>
</tr>
<tr>
<td><em>Acanthopagrus butcheri</em></td>
<td>Sparidae</td>
<td>Black bream</td>
<td>Under investigation</td>
<td>25</td>
<td>2</td>
<td>0·19</td>
<td>41</td>
<td>3 Very popular angling species, more common to the west coast</td>
</tr>
<tr>
<td><em>Acanthopagrus australis</em></td>
<td>Sparidae</td>
<td>Yellowfin bream</td>
<td>Inconclusive</td>
<td>25</td>
<td>2</td>
<td>0·51</td>
<td>30</td>
<td>3 Very popular angling fish, usually has strong recruitment on east coast</td>
</tr>
<tr>
<td><em>Macquaria novemaculeata</em></td>
<td>Percichthyidae</td>
<td>Australian bass</td>
<td>Known</td>
<td>35</td>
<td>2</td>
<td>0·22 (1·14)</td>
<td>37</td>
<td>12 Commonly stocked in freshwater systems</td>
</tr>
<tr>
<td><em>Pagrus auratus</em></td>
<td>Sparidae</td>
<td>Snapper</td>
<td>Known</td>
<td>30</td>
<td>3</td>
<td>0·29</td>
<td>108</td>
<td>6 Swims out of estuaries</td>
</tr>
<tr>
<td><em>Argyrosomas japonicus</em></td>
<td>Sciaenidae</td>
<td>Mulloway</td>
<td>Under investigation</td>
<td>45</td>
<td>3</td>
<td>–</td>
<td>172</td>
<td>11 Fast growing estuarine resident, successful trials</td>
</tr>
<tr>
<td><em>Sillago ciliata</em></td>
<td>Sillaginidae</td>
<td>Sand whiting</td>
<td>Inconclusive</td>
<td>27</td>
<td>2</td>
<td>0·39</td>
<td>39</td>
<td>1 Very popular angling fish, usually has strong recruitment, successful trials</td>
</tr>
<tr>
<td><em>Sillago maculata</em></td>
<td>Sillaginidae</td>
<td>Trumpeter whiting</td>
<td>Inconclusive</td>
<td>27</td>
<td>1</td>
<td>–</td>
<td>30</td>
<td>1 Very strong natural recruitment</td>
</tr>
</tbody>
</table>

*TABLE II. Summary of estuarine finfish species for which aquaculture technology exists, or is under investigation in Australia*
<table>
<thead>
<tr>
<th>Species</th>
<th>Family</th>
<th>Common Name</th>
<th>Status</th>
<th>Length</th>
<th>Weight</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acanthopagrus berda</td>
<td>Sparidae</td>
<td>Pikey bream</td>
<td>Unknown</td>
<td>23*</td>
<td>2</td>
<td>0.38 (0.81)</td>
<td>Large inshore species, limited to northern Aust.</td>
</tr>
<tr>
<td>Lates calcarifer</td>
<td>Centropomidae</td>
<td>Barramundi</td>
<td>Known</td>
<td>58*</td>
<td>2</td>
<td>1.82</td>
<td>Iconic status with recreational fishers. Very popular angling fish,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>successful stockings, limited to northern Aust.</td>
</tr>
<tr>
<td>Lutjanus johnii</td>
<td>Lutjanidae</td>
<td>Golden snapper</td>
<td>Unknown</td>
<td>35*</td>
<td>2</td>
<td>0.38</td>
<td>Limited time in estuary</td>
</tr>
<tr>
<td>Lutjanus argentimaculatus</td>
<td>Lutjanidae</td>
<td>Mangrove jack</td>
<td>Unknown</td>
<td>35*</td>
<td>2</td>
<td>0.19 (1.31)</td>
<td>Popular angling fish, but slow growing and difficult to produce</td>
</tr>
<tr>
<td>Mugil cephalus</td>
<td>Mugilidae</td>
<td>Mullet</td>
<td>Unknown</td>
<td>30</td>
<td>1</td>
<td>0.40 (0.83)</td>
<td>Predominately commercially targeted</td>
</tr>
<tr>
<td>Anguilla australis</td>
<td>Anguillidae</td>
<td>Shortfinned eel</td>
<td>Known</td>
<td>30</td>
<td>1</td>
<td>–</td>
<td>Mainly freshwater</td>
</tr>
<tr>
<td>Sillaginodes punctata</td>
<td>Sillaginidae</td>
<td>King George whiting</td>
<td>Known</td>
<td>27</td>
<td>2</td>
<td>1.17</td>
<td>Highly popular both commercially and recreationally</td>
</tr>
<tr>
<td>Platycephalus fuscus</td>
<td>Platycephalidae</td>
<td>Dusky flathead</td>
<td>Unknown</td>
<td>36</td>
<td>1</td>
<td>0.22</td>
<td>Very popular angling fish, estuarine resident, successful trials</td>
</tr>
<tr>
<td>Caranx spp.</td>
<td>Carangidae</td>
<td>Trevally</td>
<td>Unknown</td>
<td>–</td>
<td>1</td>
<td>0.30</td>
<td>Highly migratory, drifts in and out of estuaries</td>
</tr>
<tr>
<td>Lethrinus spp.</td>
<td>Lethrinidae</td>
<td>Emperors</td>
<td>Under investigation</td>
<td>38</td>
<td>2</td>
<td>0.50 (0.58)</td>
<td>Occasionally in estuaries, more targeted to rocky reefs</td>
</tr>
</tbody>
</table>

This list has been updated from an earlier list of species in Battaglene & Fielder (1997). The status of the population structure is given for each species. Although technology is available to culture these fish, many of these species listed are lacking in crucial information on population structure. Legal sizes are for New South Wales, Queensland (*) or Victoria (**). Value represents ranges from $AU 1–5 kg^{-1} (1), $AU 6–10 kg^{-1} (2) or $AU 11–15 kg^{-1} (3) from Sydney or Melbourne Fish Markets in 2003. All natural mortality (M) and growth (K) coefficients, and maximum length (L_{\infty}) values are taken from Froese & Pauly (2003), except for (#) which are maximum recorded lengths from Kuitter (2002). M/K values are provided for species for which M was available through Froese & Pauly (2003). M/K values are a ratio of natural mortality (M) to growth (K) coefficients (after Munro & Bell, 1997). A low M/K value and a large L_{\infty} are good biological attributes for a candidate stock enhancement species. Ranked recreational catch represents a rank of the listed species by total numbers caught during the 12 months to 2001 (Henry & Lyle, 2003), this information is not available for all species. Those species receiving equal rank have had their data grouped in Henry & Lyle (2003). Note that although relevant, geographical range or stock status are not considered here.
Low $M/K$ ratios and high asymptotic size are additional attributes that may be used to define ideal candidate species (Munro & Bell, 1997).

Successful enhancement has been achieved elsewhere for several identical or related species to those in Table II. For example, striped mullet *M. cephalus* have been successfully stocked in Hawaii (Leber, 1994). Small-scale releases of cultured fish (20 000–81 000 individuals) into nursery habitats in Kaneohe Bay in 1991 led to an increase in abundance by up to 33% at some release sites (Leber et al., 1995). By optimizing release strategies, survival of released *M. cephalus* increased over 400% (Blankenship & Leber, 1995) and provided a 20% contribution to catch in recreational fisheries in Hawaii (based on estimates from coded-wire-tagged individuals, Blankenship & Leber, 1995; Leber et al., 1995).

Australian *M. cephalus* (sea mullet) has an important commercial fishery for both local and export markets, with a national catch of 5100 t for 2003 worth over $AU12 million (ABARE, 2004), and there is evidence for a decline in the stock in NSW waters at present (Smith & Deguara, 2002). The relatively low economic value of *M. cephalus* (Table II) does not take into account the export of roe and the value of this species to many rural communities in Australia. In addition, *M. cephalus* can be cultured at low cost using wastewater from prawn aquaculture (Palmer et al., 2002).

The Texas Parks and Wildlife Department (TPWD) implemented a program that aimed to significantly ($P = 0.10$) increase landings of red drum *S. ocellatus* by sport-boat anglers over historic catch rates (Matlock, 1990), through a combination of stocking and bag/size limits (McEachron & Daniels, 1995; McEachron et al., 1995). Currently, the TPWD releases between 20 and 30 million red drum fingerlings (25 mm TL) annually into Texas bays (Silva & Bumgardner, 1998), and post-1990 this has contributed to an increase of up to 30% in recreational catch rates (McEachron & Daniels, 1995; McEachron et al., 1998). Red drum have similar growth rates and life history to the jewfish or mulloway *Argyrosomus japonicus* (Temminck & Schlegel), which are endemic to the waters of southern Australia (Kailola et al., 1992). Both species exhibit growth up to 1 mm d$^{-1}$ (Silva & Bumgardner, 1998; Fielder et al., 1999), and remain in estuaries until they can be harvested (Kailola et al., 1992; McEachron et al., 1995). Catches of this species in Australia have been steadily declining over the past 20 years from 250 t in 1980/81 to 64 t in 1999/00 (ABARE, 2001).

Several other Australian species may prove viable candidates for stock enhancement (Fig. 1 and Table II). *Sillago ciliata* (Cuvier), *Platycephalus fuscus* (Cuvier), and *Acanthopagrus butcheri* (Munro) and *A. australis* (Günther) are ideal enhancement candidates because they are common residents of estuaries, and are heavily targeted recreational species, thus are more likely to produce a higher return on investment in stocking than for commercial species or species less targeted. Unfortunately these species take >5 years to reach legal size, and are not demonstrably recruitment limited. *Lethrinus* sp. (Bloch & Schneider) has a relatively low M/K ratio, but they migrate in and out of estuaries and are not as common in the recreational catch. Species such as *Lates calcarifer* (Bloch) and *A. japonicus* are valuable and highly sought after sportfish, and *M. cephalus* is important to both recreational and commercial fisheries (Table II). These three latter species are fast growing estuarine residents for the majority of their lives,
and *L. calcarifer* and *A. japonicus* have been successfully stocked previously in Australia (Table III), and *M. cephalus* in Hawaii (Leber & Arce, 1996).

**DEVELOP A SPECIES MANAGEMENT PLAN**

The development of individual species management plans will evaluate the uncertainties, assumptions and expectations about the performance of the enhancement program (Blankenship & Leber, 1995). Australian fisheries resources are generally managed by fishery, rather than at the species level, but reviewing the biology of the target species in the context of the overall fishery management plan will enable enhancement efforts to be targeted toward areas where success will be maximized. For example, a closure in the NSW Estuary Prawn Trawl fishery for part of the year may provide the opportunity to stock species that use the trawling grounds as a nursery area. Although this approach deviates from the responsible approach (which advocates individual species management plans), management by fishery allows the consideration of the impacts of stock enhancement on all aspects of the fishery (ecosystem based management). Stock enhancement can also help address the objectives of the fishery management strategy, such as performance targets. Management plans using stock enhancement should be designed so that stocked fry or fingerlings are protected by closed seasons surrounding release times, or stocking into nursery areas that are closed to fishing, and/or protection from destructive fishing methods.

In March 2001 a saltwater recreational fishing license was introduced in NSW, generating funds for a recreational fishing trust to improve recreational fishing in NSW. A large proportion of the initial funds generated by this license have been used to buy back commercial fishing licenses, and create 30 estuarine recreational fishing havens (RFHs), which are estuaries closed to commercial fishing (NSWF, 2002). The advent of recreational fishing havens in Australia provides an opportunity to stock into areas that are not susceptible to commercial fishing with destructive gear types like beam or otter trawling (Gibbs et al., 1980), cast-netting and beach-hauling (Otway & Macbeth, 1999). In addition, stocking projects may be completed alongside restoration of habitat that has been damaged by commercial fishing or urbanization.

Management plans involving stock enhancement may also include habitat restoration to assist stocking efforts (Blankenship & Leber, 1995). Habitat restoration is often advocated in place of stocking, however in urbanized areas it may never occur to a level where the fishery is actually enhanced (Elliott & Hemingway, 2002). In Australia, there are several discouraging examples of habitat restoration in urbanized areas. One such example is the transplantation of *Zostera capricornia* seagrass beds to compensate for the environmental effects of construction of the third Sydney airport runway in Botany Bay. Natural recolonization or the large-scale transplanting of seagrass failed to produce any sustained increase in seagrass biomass or shoot density due to high wave energy and water movement as a result of the runway (Gibbs, 2001). American shad *Alosa sapidissima* (Wilson) restoration in the Susquehanna River is a promising example of habitat restoration being used in conjunction with stocking of fingerlings to rebuild fish stocks. American shad populations declined
### Table III. Pilot marine finfish stocking projects undertaken in Australia to date, and adherence to the ten principles of marine stock enhancement

<table>
<thead>
<tr>
<th>Species</th>
<th>State</th>
<th>Duration</th>
<th>Fish released size (mm)</th>
<th>Number</th>
<th>Marking method</th>
<th>Number of principles addressed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Sillago ciliata</em></td>
<td>Sth. Qld.</td>
<td>3 years</td>
<td>22–101</td>
<td>346 250</td>
<td>SPA</td>
<td>1, 5, 7 &amp; 9</td>
<td>Butcher <em>et al.</em> (2003)</td>
</tr>
<tr>
<td><em>Platycephalus fuscus</em></td>
<td>Sth. Qld.</td>
<td>3 years</td>
<td>29–58</td>
<td>86 000</td>
<td>SPA</td>
<td>1, 5, 7 &amp; 9</td>
<td>Butcher <em>et al.</em> (2003)</td>
</tr>
<tr>
<td><em>Argyrosomus japonicus</em></td>
<td>Nth. NSW</td>
<td>3 years</td>
<td>40–106</td>
<td>75 000</td>
<td>OTC</td>
<td>5, 7 &amp; 8</td>
<td>Fielder <em>et al.</em> (1999)</td>
</tr>
<tr>
<td></td>
<td>Sth. &amp; Nth. NSW</td>
<td>Ongoing</td>
<td>50–100</td>
<td>127 000</td>
<td>OTC</td>
<td>5, 7, 8 &amp; 9</td>
<td>Taylor <em>et al.</em> (unpubl. data)</td>
</tr>
<tr>
<td><em>Acanthopagrus butcheri</em></td>
<td>WA</td>
<td>3 years</td>
<td>&lt;203</td>
<td>Several thousand</td>
<td>T-bar</td>
<td>7</td>
<td>Lenanton <em>et al.</em> (1999)</td>
</tr>
<tr>
<td><em>Lates calcarifer</em></td>
<td>Nth. Qld.</td>
<td>9 years</td>
<td>30–300</td>
<td>108 000</td>
<td>CWT</td>
<td>5, 7, 8 &amp; 9</td>
<td>Rimmer &amp; Russell (1998)</td>
</tr>
<tr>
<td></td>
<td>Sth. Qld.</td>
<td>2 years</td>
<td>10</td>
<td>600 000</td>
<td>Not marked</td>
<td>Nil</td>
<td>Palmer (1995)</td>
</tr>
</tbody>
</table>

A maximum of four of the ten-principles of Blankenship & Leber (1995) were addressed or partially addressed by an Australian study (numbers correspond to principles in Table I). *Sillago ciliata* and *Platycephalus fuscus* stocking were part of the same project. No monitoring was carried out for the South Queensland *Lates calcarifer* stockings.

SPA, scale pattern analysis; OTC, oxytetracycline hydrochloride; CWT, coded wire tags; ALC, alizarin complexone.

Sth. Qld., South Queensland; Nth. Qld., North Queensland; Sth. NSW, South New South Wales; Nth. NSW, North New South Wales; WA, Western Australia.
dramatically after the construction of four hydroelectric dams along the course of the river (Hendricks, 2003; St. Pierre, 2003). Between 1985 and 2000, fish ladders and fish lifts have been constructed at each of the dams to re-open approximately 750 km of spawning habitat, over 166 million American shad larvae and fingerlings have been released into the river, and over 266 000 individuals have been transported upstream past the power stations (St. Pierre, 2003). Over this time period American shad counts in the Conowingo Dam (16 km upriver from Chesapeake Bay) increased from 300 year\(^{-1}\) to over 250 000 year\(^{-1}\) (St. Pierre, 2003).

Stock enhancement may also be used to address the objectives of aquaculture management plans. For example, the culture of fingerlings for release (e.g. \textit{M. cephalus}) using waste nutrients in Australian prawn farm settlement ponds would have a two-fold benefit of minimising the waste released into the environment and producing fingerlings at a relatively low cost (Palmer\textit{ et al.}, 2002).

**DEFINE QUANTITATIVE MEASURES OF SUCCESS**

Carrying capacity is a measure of the biomass of a given population that can be supported, in terms of available food and habitat (including available refugia) in the ecosystem (Cooney & Brodeur, 1998). It varies among species depending on the behaviour and bioenergetic efficiency of the fish. Carrying capacity may be under-exploited if the stock is recruitment limited (Svåsand\textit{ et al.}, 2000), but exceeding the carrying capacity of an ecosystem can lead to the displacement of other individuals that share the resources, or a shift in the ecosystem (Molony\textit{ et al.}, 2003). Habitat restoration or creation may be used to increase carrying capacity to historic levels, and enhance the capacity of the ecosystem to support additional recruits or mitigate anthropogenic effects. Defining enhancement measures of success and objectives concern the degree to which a system can support additional recruits in terms of habitat and food, which is largely on the carrying capacity of a system. This notional concept can be pragmatically assessed by the growth and survival of released fish, a result of density dependent processes of predation, growth, cannibalism and competition (Myers & Cadigan, 1993; Kellison\textit{ et al.}, 2002), or through linking an estimation of available resources with growth in the target species. Results can often be confounded by migration in and out of the system, and changes to the system caused by stocked fish (Rutledge, 1989). In addition, wild or competitor species may be displaced if density is too high. Munro & Bell (1997) propose that knowledge of the carrying capacity of the target habitat is required to make effective use of juveniles and prevent overstocking, as shown by the failed experience with cod in Western Norway (Moksness, 2004) and salmon in the Pacific Northwest (Cooney & Brodeur, 1998). Enhancement objectives and measures of success should therefore be defined by the modelled carrying capacity in terms of available food and habitat resources, or by growth and survival targets for released fish, rather than historical catch rates.

Several ecological risks associated with marine stocking are reviewed by Molony\textit{ et al.} (2003), and grouped into three broad areas. Species-specific risks

include genetic and disease risks, increased intra-species competition, shifts in prey consumption and the resulting potential displacement of wild conspecifics (Molony et al., 2003). Interspecific risks include increased interspecific competition and potential displacement of competing species (Molony et al., 2003). On a larger scale, ecosystem-wide risks include shifts in prey abundance, shifts in the distribution or biomasses of other species and resulting extinctions, and physical environmental damage from the actual stocking (Molony et al., 2003). With the exception of genetic and disease risks (described in later sections) and physical environmental damage, most of the risks described above can be alleviated by a suitable assessment of the carrying capacity for the target species in the target system and small-scale pilot experiments to evaluate in situ the effects of stocking on conspecifics, competitors and prey.

Carrying capacity for higher trophic levels is often estimated from primary production in a system. In marine systems production can be regulated by nutrient upwelling (Aksnes et al., 1989), and from terrestrial sources (Luo et al., 2001). Australian oceanic waters are characteristically nutrient depleted, as there are no northward moving currents to transport nutrient rich sub-Antarctic waters to the continental shelf. In addition, there is limited terrestrial runoff to estuaries in southern Australia, and the majority of coastal soils around Australia are deficient in phosphates (Rochford, 1979). The primary nutrient deficiency may constrain the capacity of some estuaries to support additional recruits (Kearney & Andrew, 1995). Australia also has a large number of eutrophic estuaries resulting from nutrient runoff from agricultural/urban land usage, and poor tidal flushing due to constricted openings. In these situations, constricted openings can also limit recruitment to the estuary from ocean spawners. Production in estuarine systems can be estimated by water quality models, such as the Simple Estuarine Response Model (SERM, Baird et al., 2003). Primary and secondary production estimates from these models can be linked through the trophic cascade to determine both ideal stocking density, and potential production of the stocked species through bioenergetic models for the target species (e.g. Pauly, 1986; Giske et al., 1991; Salvanes et al., 1992; Luo et al., 2001). This approach can provide a baseline for setting quantitative measures of success based on the productive capacity of the ecosystem. Pilot-scale releases can be used to refine this baseline to account for actual density-dependent processes in the field. Pilot-scale release-recapture experiments can also be used to test assumptions about the carrying capacity of a target ecosystem and enhancement tactics (Leber et al., 1995), linking stocking density and survival with estimated carrying capacity. These programs can be expensive, and success may be hindered when stocking open systems as fish have the opportunity to emigrate from the stocking site. The selection of a suitable site to test stocking tactics should be primarily based on the inability for fish to move large distances away from the release site, and the selection of a site within the natural habitat range for the species. This pilot-scale release requirement is minimized through a modelling approach to theoretically assess ideal stocking density. If stocking occurs close to the level the system can sustain, high growth and survival should follow and the need for a large series of pilot-scale releases may be reduced.
USE GENETIC RESOURCE MANAGEMENT

Stock enhancement has a range of potential effects on the genetics of wild populations of marine finfish. The Blankenship & Leber (1995) approach involves five key points to minimize deleterious genetic effects (Table I).

All stock enhancement programs pose some risk to the effective population size (Tringali & Bert, 1998). The higher fecundity of marine species may lead to a potentially higher susceptibility to genetic problems than for less fecund salmonids and freshwater species as there is a greater opportunity for fortuitous survival of offspring from very few matings (Utter, 1998). Marine/estuarine species are typically more genetically homogenous than freshwater/catadromous species and often show relatively little stock separation (Blankenship & Leber, 1995). For example, the common estuarine species in southern Australia *A. japonicus* (Black & Dixon, 1992) and *A. butcheri* (Farrington *et al*., 2000) exhibit panmictic populations, while northern Australian catadromous species *L. calcarifer* (Shaklee & Salini, 1985; Salini & Shaklee, 1988) and *Polydactylus sheridani* (Günther) (Garrett, 1997) exhibit geographic genetic differentiation. Stock-specific management practices should be applied when species display geographic differentiation (Shaklee *et al*., 1993) to prevent deterioration of localized genetic characteristics, and stocking programs involving such species need to closely monitor the effective size of the hatchery broodstock. To minimize potential erosion of localized genetic characteristics as a result of stocking, *L. calcarifer* fingerlings stocked in northern Queensland were produced using only broodstock that were taken from the population targeted for enhancement (M. Rimmer, pers. comm.).

The first four points for responsible genetic resource management (Table I) may be applied in the planning stage of the enhancement project, however genetically monitoring and controlling hatchery and wild populations is both costly and difficult to implement. Aquaculture facilities in Australia are limited in size and number, and maintenance of sufficient numbers of effective breeders as broodstock to preserve genetic diversity may prove too expensive for many operators. It is accepted that between 100 and 200 breeders with an equal sex ratio is sufficient to maintain most genetic variation in hatchery populations (Bartley *et al*., 1995; Carvalho & Cross, 1998), and the successful application of this is observed in the culture of white seabass *Atractoscion nobilis* (Ayres) in California (Bartley *et al*., 1995) and of red drum *S. ocellatus* in Texas (King *et al*., 1995). Where the maintenance of large numbers is not feasible, the strip spawning of wild individuals from the population to be stocked may provide a viable alternative, depending on the ease of capture and response of the species to handling. This method has been used successfully for red drum (Colura *et al*., 1990) and the Black Sea bass *Centropristis striata* (Linnaeus) (Chappell *et al*., 2001), and with several Australian species including snapper *Pagrus auratus auratus* (Tabata & Taniguchi) (Cleary *et al*., 2002), black bream *A. butcheri* (Haddy & Pankhurst, 2000) and striped trumpeter *Latris lineata* (Forster) (Ruwald *et al*., 1991).

USE DISEASE AND HEALTH MANAGEMENT

Stocking of diseased fish into the wild could contaminate wild stocks or result in low survival of released fish (Johnson & Jensen, 1986; Bakke *et al*., 1990).
High nutrient and organic loads, and low flushing of wastes in culture situations have the potential to lead to bacterial, viral and/or protozoan proliferation. Handling stress, exposure to unnatural conditions and high rearing densities increase the vulnerability of fish to pathogens. In addition, the use of antibiotics such as oxytetracycline in hatcheries may increase antibiotic resistance in bacteria. Several diseases are prevalent in the aquaculture of Australian marine finfish including pilchard herpesvirus in *Sardinops sagax neopilchardis*, flounder herpesvirus in *Rhombelsolea tapirina* (Günther) and barramundi nodavirus in *L. calcarifer* (Munday & Owens, 1998).

The disease and health guidelines implemented in Florida in association with red drum stockings require that all groups of fish pass certified bacterial, viral and parasite inspections before release (Blankenship & Leber, 1995), where infection levels in healthy wild populations are used to determine maximum acceptable levels in fish for release. The health assessment index (HAI) used by Palmer *et al.* (2000a) to provide a health profile for fish destined for release in the Maroochy Estuary stocking program in Queensland, accounted for many of these concerns, and could provide measures of fingerling quality for covariate analysis of survival from different batches released. Sub-samples of each batch of fingerlings were examined macroscopically and rated with a HAI score, scoring a degree of normality (0–3) of fins, eyes, gills, liver, spleen, kidney, gall and the presence of mesenteric fat, whitespot and trematodes (Palmer *et al.*, 2000a). Numerical values for all parameters are summed for each fish in a sample and averaged for the population, the best score being 0 and the worst score being 30. The use of HAI should be supplemented where necessary with veterinary inspections to detect such things as vacuoles in the central nervous system of larval fish, which are evidence of a nodavirus infection (Munday *et al.*, 1992). In addition, all activities involving the use of vertebrate animals should have relevant animal care and ethics approval, to ensure ethical and humane handling and euthanasia of infected or diseased animals.

**IDENTIFY RELEASED HATCHERY FISH AND ASSESS STOCKING EFFECTS**

Recognizing stocked fish is essential to assess the effectiveness of enhancement, as natural fluctuations in fish stocks can mask successes or failures (Blankenship & Leber, 1995). For the performance of stocked and wild fish to be comparable, tags must not affect behaviour, biological functions or survival (Buckley & Blankenship, 1990). Three cheap, simple and effective methods of tagging used for marine species in Australia are coded-wire tags, scale pattern analysis and chemical marking of otoliths.

Coded-wire tags (CWT) implanted in snout cartilage (Jefferts *et al.*, 1963), the gut-cavity or various muscles (Ingram, 1989; Russell *et al.*, 1991) using automatic injectors, are detected by portable or stationary X-ray or electronic metal detectors. To read the tag’s binary code it must be removed from the fish (Ebel, 1974; Wooley *et al.*, 1990). Coded-wire tags were successfully used in the evaluation of coastal enhancement efforts of barramundi, *L. calcarifer*, in North Queensland (Russell *et al.*, 1991; Russell & Hales, 1992; Rimmer & Russell, 1998), however set-up costs were relatively high. This project allowed insertion of
up to 270 tags per hour, 93% retention after two months, with no decrease in tag retention after 394 days at liberty (Russell & Hales, 1992).

Patterns on scales or otoliths have many applications in species and stock discrimination (Anas & Murai, 1969; Major et al., 1972; Ross & Pickard, 1990; Barlow & Gregg, 1991; Willett, 1993, 1996; Silva & Bumguardner, 1998). Several studies have shown that intercirculi distances on scales are dependent on growth rates, which in turn can be manipulated in hatcheries through environmental factors that influence metabolic processes (feeding rates, water temperature, stress, Pepperell, 1989; Volk et al., 1990). Sudden drops in water temperature have been shown to produce optically dense zones, and unique patterns have been induced with regularly repeated thermal cycles and feeding regimes (Volk et al., 1990), however natural variations in growth can create interpretation difficulties so the induced marks must be distinctive. Scale pattern analysis was applied to the sand whiting S. cilliata and dusky flathead P. fuscus during the pilot stocking program in Queensland in 1995. This technique allowed 75–89% correct classification of fish as stocked or wild (Palmer et al., 2000b; Butcher et al., 2003).

Captive fish populations can be marked en-masse by immersion in chemicals that produce fluorescent marks on otoliths, including tetracycline, calcein, alizarin compounds, and strontium (Brothers, 1990). Immersion in fluorescent chemicals can also produce marks in fin-spines (Fig. 2), which are ideal for sampling fisheries as marks can be detected without mutilation of the fish (Taylor et al., 2005). Oxytetracycline (OTC) is an antibiotic regularly used in

![Fig. 2. Transverse anal fin spine section from a mulloway (Argyrosomus japonicus) 120 days after release (100 mm TL) showing an alizarin complexone mark when the fingerling was 100 mm (OE = outer edge of fin spine, A = ALC mark). Chemical marks such as alizarin complexone that are incorporated and maintained in the fin spine allow non-invasive detection of stocked fish. Scale bar represents 100 μm.](image-url)
hatchery practice, and has been successfully used to mark cod *G. morhua* in enhancement experiments in Norway (Svásand, 1993), and hatchery-produced larval and juvenile striped bass *Morone saxatilis* (Walbaum) (Secor et al., 1991) with minimal mortality. Dilution of seawater is necessary since OTC hydrochloride chelates with Mg$^{2+}$ and Ca$^{2+}$ ions which reduces the amount of chemical available for uptake (Hettler, 1984; Lunestad & Goksøyr, 1990). Tetracycline marks can persist for up to four years (Drawbridge et al., 1993), however mark retention in calcified structures exposed to sunlight (e.g. scales) is minimal since tetracycline degrades in UV light (Blom et al., 1994). Marking of Australian species by immersion in OTC has met with mixed success. Immersion of sand whiting *S. ciliata* and dusky flathead *P. fuscus* in OTC generally resulted in low mark quality and high mortality (Palmer et al., 2000b; Butcher et al., 2003), while OTC immersion of mulloway *A. japonicus* in diluted seawater resulted in high mark quality and negligible mortality and retention of marks in stocked fish 420 days after marking (Taylor et al., 2005).

Alizarin compounds have been used to mark otoliths in concentrations from 3 to 1000 mg L$^{-1}$. (Tsukamoto et al., 1989; Blom et al., 1994). Generally, marking using alizarin complexone has no detectable effect on growth and mortality (Tsukamoto, 1988; Beckman & Schulz, 1996; Sanchez-Lamadrid, 2001), and marks have been retained for over two years (Tsukamoto et al., 1989), but it is comparatively expensive (>AU$12$ g$^{-1}$). Alizarin red S is a cheap alternative to alizarin complexone (~AU$0.50$ g$^{-1}$), but has been shown to cause mortality in eggs and larvae at concentrations 100–400 mg L$^{-1}$ (Blom et al., 1994). Alizarin complexone was also successfully used to batch mark *A. japonicus*, and marks were retained in stocked fish up to 120 days after marking (Fig. 3, Taylor et al., 2005). Double immersions also provide the opportunity to identify individuals from different release cohorts or treatments.

<table>
<thead>
<tr>
<th>Prey species</th>
<th>Stocked species</th>
<th>Competitor species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exceptional recruitment/conditions, potentially stock at a greater density</td>
<td>Stocking successful, evaluate change in prey/predator abundance</td>
<td>Exceptional recruitment/conditions, potentially stock at a greater density</td>
</tr>
<tr>
<td>Stocking level inadequate at present</td>
<td>Stocking level ineffective, consider changing stocking strategy</td>
<td>Stocking level adequate at present</td>
</tr>
<tr>
<td>Stocking level too high</td>
<td>High prey:predator ratio, stocking density may be increased</td>
<td>Displacement due to stocking may be occurring</td>
</tr>
<tr>
<td>Recruitment failure</td>
<td>Stocking may have failed</td>
<td>Recruitment failure</td>
</tr>
<tr>
<td>Adverse conditions</td>
<td></td>
<td>Adverse conditions</td>
</tr>
</tbody>
</table>

Fig. 3. Hypothetical system development matrix for stock enhancement of a finfish species. Performance of the stocking activity is evaluated in terms of the abundances of the three groupings shown (prey species, stocked species and competitor species), and possible strategies for future stocking activities adjusted in response (matrix structure adapted from Thom, 1997).
Some enhancement projects have examined genetic marking as a means to identify stocked fish. Lower levels of genetic divergence in many marine fish species (Baduge & Gunnar, 2001) make cultured populations attractive candidates for intentional genetic marking, however selective breeding for specific genotypes may affect performance traits in the cultured population, thus in the long term affecting the performance of augmented populations (Utter & Seeb, 1990). A relatively small number of founder individuals with the desired genotype can cause a narrow genetic base in fish cultured for release, as was found for *G. morhua* in Western Norway (Utter & Seeb, 1990; Jørstad, 1994). Markers also need to be selectively neutral, and usable markers may be difficult to obtain. The dangers, difficulty, and cost involved in this approach do not support the use of intentional genetic marking.

USE AN EMPIRICAL PROCESS TO DEFINE OPTIMUM RELEASE STRATEGIES

It is logistically difficult to quantify survival of stocked fish in coastal environments (Leber et al., 1996), but this information is central to the successful implementation and evaluation of a stock enhancement program (Blankenship & Leber, 1995). The relative survival of fish can have significant implications for the size at release, the quantities of fish that are stocked, and the season, time and habitat suitabilities. For example, several red drum releases in Texas (McEachron et al., 1998), Florida (Willis et al., 1995) and South Carolina (Smith et al., 1997) have shown variable survival in response to salinity and temperature, the effects of which are amplified with decreasing size-at-release. Survival can be maximized by timing releases so that size modes between hatchery and wild stocks were similar (Leber et al., 1997), and stocking fish at a density that ecosystem production can support.

Release strategies should be refined to maximize survival through pilot-scale releases (Blankenship & Leber, 1995). If monitored effectively, small-scale release experiments can point to operational procedures that optimize survival and cost-benefit, and ultimately minimize any adverse ecological effects. This is evident in the successful stocking of striped mullet *M. cephalus* in Hawaii (Leber & Arce, 1996) and red drum *S. ocellatus* in Texas (McEachron et al., 1998) where pilot-scale experiments were used to refine techniques. All marine releases conducted in Australia to date (Table III) have been pilot studies with broad aims that mainly concern evaluating whether stocked fish can survive and recruit to commercial or recreational catches. The next step in Australian enhancement studies is to resolve optimal habitat, season and size of release in a closed system, un-confounded by emigration. There are few completely closed marine systems, however 92% of estuaries in New South Wales (NSW) have restricted entrances (Griffiths, 2001a), and 54% of south-east Australian estuaries are classified as having intermittently opened entrances (ICOLLs, Roy et al., 2001). An experimental approach was used by Kellison et al. (2003) to refine release strategies and evaluate pilot enhancement for the summer flounder *Paralichthys dentatus* (Linnaeus), however this was in an open river system. As ICOLLs are not always open to the sea, they can serve as temporary experimental units to both assess carrying capacity and define optimum release strategies in the absence of
emigration. The opportunity also exists to genetically evaluate whether natural populations are augmented or replaced by stocking activities in a semi-closed system (Hilborn, 1999).

ICOLLs are often eutrophic (Roy et al., 2001), with large abundances of forage fish species (e.g. Atherinidae, Clupeidae and Gobiidae) and Crustacea (Robinson et al., 1982; Gray et al., 2000). The restricted or closed entrances produce a physical barrier to recruitment that can result in recruitment limitation of species that spawn at sea or at the mouths of estuaries (Griffiths, 2001b). Recruitment limitation in these ICOLLs from both physical barriers and removal of spawners may justify enhancement of some species. Furthermore, 40% of recreational fishing havens are classified as having restricted entrances or being ICOLLs, and this has several implications for stock enhancement. In the absence of commercial trawling and beach hauling in estuaries, additional prawns and other forage resources may be available, and juvenile fish are less likely to become by-catch of commercial fishing gear. Experimental manipulation of size/cost at release and stocking density could be achieved in ICOLLs, although these systems can unpredictably open to the sea with heavy rainfall.

IDENTIFY ECONOMIC AND POLICY GUIDELINES

The goals of a stocking program should also be evaluated in terms of program cost against perceived or calculated benefit. Economic models not only weigh the costs against the benefits of enhancement programs, but may also aid policy makers, and create additional funding opportunities through reprioritization, legislation, and user fees (Blankenship & Leber, 1995). Cost-benefit analysis (Rutledge, 1989) is a pragmatic way of deriving economic objectives and predicting the value of enhancement (Table IV), however the aesthetic value of catching a fish and associated dollar value of a fish to a recreational fisher may be over-estimated. Possible costs and benefits of stocking, and examples of some cost-benefit evaluations are shown in Table IV. Motivational characteristics change for different angler groups, preventing a general formula for estimating the aesthetic value of fishing (Fedler & Ditton, 1994). Evaluating enhancement of stocks that are predominantly commercially fished may result in much higher cost/benefit ratios (e.g. Hilborn, 1998) as there is little aesthetic value, and the dollar value is usually limited to the market price of the species. More detailed bioeconomic models are available for cost/benefit analysis, such as that developed for prawn stock enhancement in Western Australia (Loneragan et al., 2003). In any case, clear financial goals should be defined alongside quantitative measures of success for enhancement projects, providing an additional benchmark against which the success of a program can be gauged. These benchmarks should be set before commencement of the program.

USE ADAPTIVE MANAGEMENT

Adaptive management is a process for changing both production and management to control the effects of enhancement, thus allowing improvement over time (Blankenship & Leber, 1995). An effective adaptive management process may be difficult with many different stakeholders that are involved in a stock
**Table IV. Financial considerations of stocking in the context of cost/benefit analysis**

<table>
<thead>
<tr>
<th>Steps in developing cost/benefit analyses*</th>
<th>Costs of stocking</th>
<th>Benefits of stocking</th>
<th>Examples of cost/benefit analyses</th>
</tr>
</thead>
</table>
| 1) Separate development cost from production and monitoring costs | Initial capital and ongoing investment  
- Building hatchery facilities  
- Hatchery maintenance (equipment + health standards)  
- Broodstock management | Valuing recreational fishing  
- Aesthetic values†  
- Willingness to pay and contingent valuation analysis‡ | Stocked barramundi in Queensland**  
- 64,500 50 mm fingerlings stocked in an impoundment  
- Each recaptured fish valued at $AU153  
- Break-even at c. 1% survival |
| 2) Decide the proportion of development costs that are usable in other projects or to industry | Planning  
- Running workshops  
- Developing management plans  
- Pre-stocking surveys | Valuing commercial fishing  
- Market value of fish | Stocked red drum in Texas§  
- 15 million fingerlings released per year  
- Each recaptured fish valued at $US445  
- Break-even at c. 0.01% survival |
| 3) Place a monetary value on the harvested product from all sectors involved in the fishery | Stocking  
- Health assessment  
- Effective tagging of fish  
- Fish transport  
- Optimization of releases | Other benefits  
- Employment in rural communities  
- Creation of new industries | Flathead and whiting in Queensland***  
- See Table III for numbers stocked  
- Recaptured fish cost $AU17–24 each  
- Each recaptured flathead valued at c. $AU2.70  
- Each recaptured whiting valued at c. $AU1.70 |
### Table IV. Continued

<table>
<thead>
<tr>
<th>Steps in developing cost/benefit analyses*</th>
<th>Costs of stocking</th>
<th>Benefits of stocking</th>
<th>Examples of cost/benefit analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4) Monitor the net effect</strong>&lt;br&gt;of stocking for a sufficient period</td>
<td>Monitoring&lt;br&gt;● Fishery independent sampling&lt;br&gt;● Fishery dependent sampling&lt;br&gt;● Genetic monitoring&lt;br&gt;● Results analysis&lt;br&gt;● Communication of results&lt;br&gt;● Adaptive management</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>5) Estimate regional/state effects as a result of stocking</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>6) Convert all aesthetic and environmental gains to monetary values in a robust way</strong></td>
<td></td>
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</tr>
</tbody>
</table>

enhancement program. A single body should be appointed by stakeholders to oversee and manage the program, especially if the program operates across state or national boundaries.

A system development matrix (Thom, 1997) is one practical approach to evaluating the performance of a stocking project in an adaptive management context. A simple example of this approach applied to a stocking project (Fig. 3), is for a situation where changes in the catch (or abundance) of prey, predator and stocked species provide the input for making management decisions. If the abundance of prey, stocked or competitor species alters from a reference condition (catch rates immediately prior to stocking), then the matrix provides some output to assist the management decision. A code of practice for stock enhancement in Australia, adapted as a flow chart (Butcher, 2001, Fig. 4), shows an adaptive management approach to marine stock enhancement. Such an approach should ideally involve an initial assessment of the stock, evaluation of the ecosystem to determine if stocking is feasible, the development of the stocking program and consideration of the risks, and the monitoring of the stocking program. The key point of the framework (Fig. 4) is the feedback loop from the monitoring and evaluation stage back into various stages of the process. The use of this code of practice (Fig. 4), combined with a matrix to assess the existing situation in the stocking program and provide feedback for decision making (Fig. 3), will provide a feasible way to integrate adaptive management into the stocking program. An alternative, more complex flow-chart is described in Molony et al. (2003), however this model does not allow pilot investigations of stocking to proceed before legislative changes are implemented. The potentially time-consuming process of legislative change may be useless if pilot studies later reveal stocking to be unsuitable or unsuccessful.

AUSTRALIAN MARINE FINFISH ENHANCEMENT

Enhancement of freshwater fisheries in Australia began in Tasmania in 1861 (Dix, 1987) and developed into stock enhancement programs undertaken by fishing clubs and governments in most states. Despite the relative success of freshwater projects, the enhancement of marine fisheries in Australia is still in its infancy and at present there are no ongoing marine finfish-stocking programs. There have been seven intentional releases of marine finfish into Australian estuaries all of which released <600 000 fingerlings over the course of the trials (Table III). Only four were monitored and can be considered as pilot studies (Fielder et al., 1999; Lenanton et al., 1999; Butcher et al., 2000a; Russell et al., 2004).

BARRAMUNDI IN NORTHERN QUEENSLAND

Barramundi (L. calcarifer) were the first marine finfish to be stocked and monitored in Australia, beginning in 1986 for impoundments, and 1993 in open systems (Rimmer & Russell, 1998). Fish were released into artificial impoundments or inland lakes in an effort to create inland recreational fisheries, where stocked fish did not reproduce naturally. Since the inception of this program
Fig. 4. Stock enhancement code of practice (modified from Butcher, 2001). The process of stock enhancement involves assessing the status of a fishery, planning and developing techniques for stocking. Once this has been done, an adaptive management structure can provide for considerable refinement of techniques and policies to increase both financial and environmental benefits, or avoid future detrimental effects. Dashed lines represent areas where feedback can assist future management decisions.
over 21 million fingerlings have been released and inland recreational barramundi fisheries have been created (A. Hamlyn, pers. comm.). Experimental stockings of barramundi in the Johnstone River aimed to provide information on size- and site-specific survival and cost-benefit. Almost 110 000 coded-wire tagged fish (30–300 mm) have been released between 1993 and 1999 (Table III, Russell et al., 2004). Early experiments indicated that size-at-release did not affect probability of recapture (Rimmer & Russell, 1998), however the 1997–1999 stockings demonstrated that maximum survival was obtained from releases of fish 300 mm long in an upper estuarine habitat, compared to freshwater or estuarine habitats (Russell et al., 2004). Cost-benefit analysis however, showed that to recoup the costs of the program as few as 0.8% of the 30 mm fish that were released would need to be recaptured (Rimmer & Russell, 1998) compared with 9.8% of the 300 mm fish (Russell et al., 2004).

SAND WHITING AND DUSKY FLATHEAD IN QUEENSLAND

The Maroochy Estuary fish-stocking program was the largest marine stocking program undertaken in Australia, with approximately 432 000 sand whiting (S. ciliata) and dusky flathead (P. fuscus) released over three years (Table III, Butcher et al., 2000a). This study was based on some of the principles of Blankenship & Leber (1995), and aimed to develop rearing technologies for the target species, and to stock and undertake a full-scale monitoring program to assess the effectiveness of stocking. Mass production of both S. ciliata and P. fuscus was achieved using controlled green-water larval rearing and extensive pond culture. Post-stocking mortality after one month was as high as 67 ± 15% (mean; 39 ± 11%), however the project examined alternative release strategies (i.e. stocking habitats) to minimize this. Oxytetracycline (OTC) marking trials were unsuccessful, and scale-circuli analyses were developed to assess the origin of recaptured fish. Recruitment to the commercial catch was as high as 28% for P. fuscus and 52% for S. ciliata, however the estimated cost of each fish was around 680% of the retail value (financial value of stocked fish to recreational fishers was not monitored in this study). Although the stated aims were achieved, the project failed to show any increase in population size over the numbers estimated prior to stocking. The results may have been confounded by a large fish kill in the Maroochy estuary experienced during the project (Butcher et al., 2000b).

MULLOWAY IN NEW SOUTH WALES

A project was undertaken in 1997 by New South Wales Fisheries to evaluate the production of mulloway (A. japonicus) juveniles using intensive and extensive techniques, and to stock three intermittently closed-opening landlocked lagoons (ICOLLS) with approximately 75 000 A. japonicus juveniles (Table III, Fielder et al., 1999). This project was successful in rearing large numbers of A. japonicus using extensive techniques involving large (1 ha) earthen outdoor ponds. Hatchery reared fish were successfully labelled with OTC and released into three coastal lagoons on the New South Wales coast (<5 m deep, <10 km²).
area). Heavy post-stocking predation was experienced in one lake, and juvenile fish were observed swimming to sea after heavy rainfall in another, such that no recaptures were obtained from two estuaries. Fish were recaptured from Smiths Lake at six, seven and nine months after stocking, and entered the commercial and recreational fishery 18 months post release. Fish grew at around 1 mm d\(^{-1}\) regardless of season, and recaptured fish were successfully verified as of hatchery origin by OTC marks. The small-scale release had an evident effect on the fishery in Smiths Lake for several years following the stocking, with a 1500% increase in total catch (catch averaged for four years before and four years after fish entered fishery), compared to an overall decrease in total estuarine catch over the years following the stocking (D. Makin, pers. comm.).

**BLACK BREAM IN WESTERN AUSTRALIA**

This pilot study aimed to determine the survival and growth rate of hatchery-reared black bream (*A. butcheri*) in the wild, and whether they entered the recreational fishery (Dibden et al., 2000). The study followed on from the release of 200 000 *A. butcheri* fingerlings into inland saline and freshwater impoundments in Western Australia, to investigate the conditions that provided optimum growth and survival (Table III, Lenanton et al., 1999). Open system stocking consisted of the release of 767, 14 month-old fish (~150 mm) tagged with external T-bar tags into the Upper Swan River. Twelve percent of these tagged fish were recaptured up to three years later by recreational fishers. The recaptured fish showed a growth rate significantly higher than wild fish of the same age, however the extent to which the stocked fish contributed to the recreational fishery could not be determined as the number of wild *A. butcheri* caught was not monitored throughout the experiment.

Whilst these four projects addressed their respective aims, none have addressed all 10 principles of the responsible approach (Table III). All but one project undertook marking and monitoring of stocked fish, two projects did some economic modelling, and three attempted to optimize release strategies for a species (Table III). These pilot projects were aimed at addressing specific areas of the responsible approach, and this information could potentially be synthesized to form a larger study incorporating all of the 10 principles. Future stocking with suitable species in Australia should now aim to expand the preliminary knowledge gained from these projects to address the core factors that are paramount to successful stocking: stocking the appropriate environment with a suitable density of the correct species.

**STOCK ENHANCEMENT: ECOLOGY IN A MANAGEMENT CONTEXT**

It is not an aim of this review to detail how stock enhancement should fit into the overall management objectives for a fishery or ecosystem (Molony et al., 2003). Australia has recently adopted an ecosystem based management (EBM) approach to facilitate the ecologically sustainable use of Australia’s ocean resources (Alder & Ward, 2001). Molony et al. (2003) propose that stock enhancement be included in EBM by considering stock enhancement within a
hierarchy comprising individual fish stocks on the lowest level, and ecosystem or bioregion at the highest, with enhancement being targeted at individual fish stocks only. A four-component approach can be used to achieve this: (1) review all information about the ecosystem, fishery and stock involved; (2) compare and identify fishery management tools available to be applied; (3) if stock enhancement is appropriate, develop objectives and processes along with experimental pilot trials; and (4) if pilot work is successful, then full-scale stock enhancement can proceed (Molony et al., 2003).

Whether stocking can be undertaken in a sustainable fashion remains to be seen, however it is possible that a correctly managed stocking program may eventually overcome a recruitment bottleneck such that a stock can support itself once again. The stocking of marine finfish also provides the unique opportunity to address many core ecological assumptions and hypotheses that underpin fisheries management strategies (Miller & Walters, 2004). Precautionary approaches to stocking marine species (Molony et al., 2003) may often mean that nothing is done in view of the potential risks. Rather than applying the strict precautionary principle (Anon, 2000), a responsible approach to marine stock enhancement should allow stocking to proceed in a fashion that minimizes the risks of stocking on the ecosystem, satisfies the principles of EBM, and achieves social and economic objectives especially in rural areas.

**CONCLUSION: MAXIMISING THE BENEFIT AND SUCCESS FROM STOCKING**

The initial step in designing a stock enhancement program should be to identify those ecosystems where there may be additional carrying capacity, and then addressing which species to stock into that environment based on recruitment limitation and factors described in step one of the responsible approach (Fig. 1).

While Australia’s commercial fishing production is low, representing only 0.2% of the world total (Kearney & Andrew, 1995), the Australian recreational fishing industry is important to the economy. Almost 20% of the population fished at least once during the 12 months prior to 2001, harvesting almost 27 000 t of finfish. The industry was valued at $AU1800 million for that time period (for all recreational fishing, including ~3000 t of invertebrates harvested, Henry & Lyle, 2003), while wild caught commercial fisheries for 2001 were valued at $AU1790 million (for all wild caught fisheries), with over 100 000 t of finfish harvested (ABARE, 2002).

Examining the responsible approach in an Australian context reveals several criteria that have the potential to both maximize the success and benefit of releases, and facilitate the further application of the ten-principles of marine stock enhancement. Whilst stock enhancement projects elsewhere have often concentrated on stocking fish for capture in commercial fisheries, cost/benefit analyses show that stocking of recreationally important species should increase the benefit obtained from money invested (Rutledge, 1989; Rutledge et al., 1990, 1991; Rimmer & Russell, 1998). With lower cost-benefit ratios, and the importance of the recreational fishing industry in Australia, stocking recreational species in urbanized ICOLLs protected from commercial fishing is feasible. By
stocking fast growing, estuarine residents such as mulloway and barramundi, at an acceptable density into recreational fishing havens, and refining techniques using ICOLLS as experimental units, Australia can apply responsible principles to marine fish stock enhancement and achieve the maximum benefit from stocking.

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**Electronic Reference**
