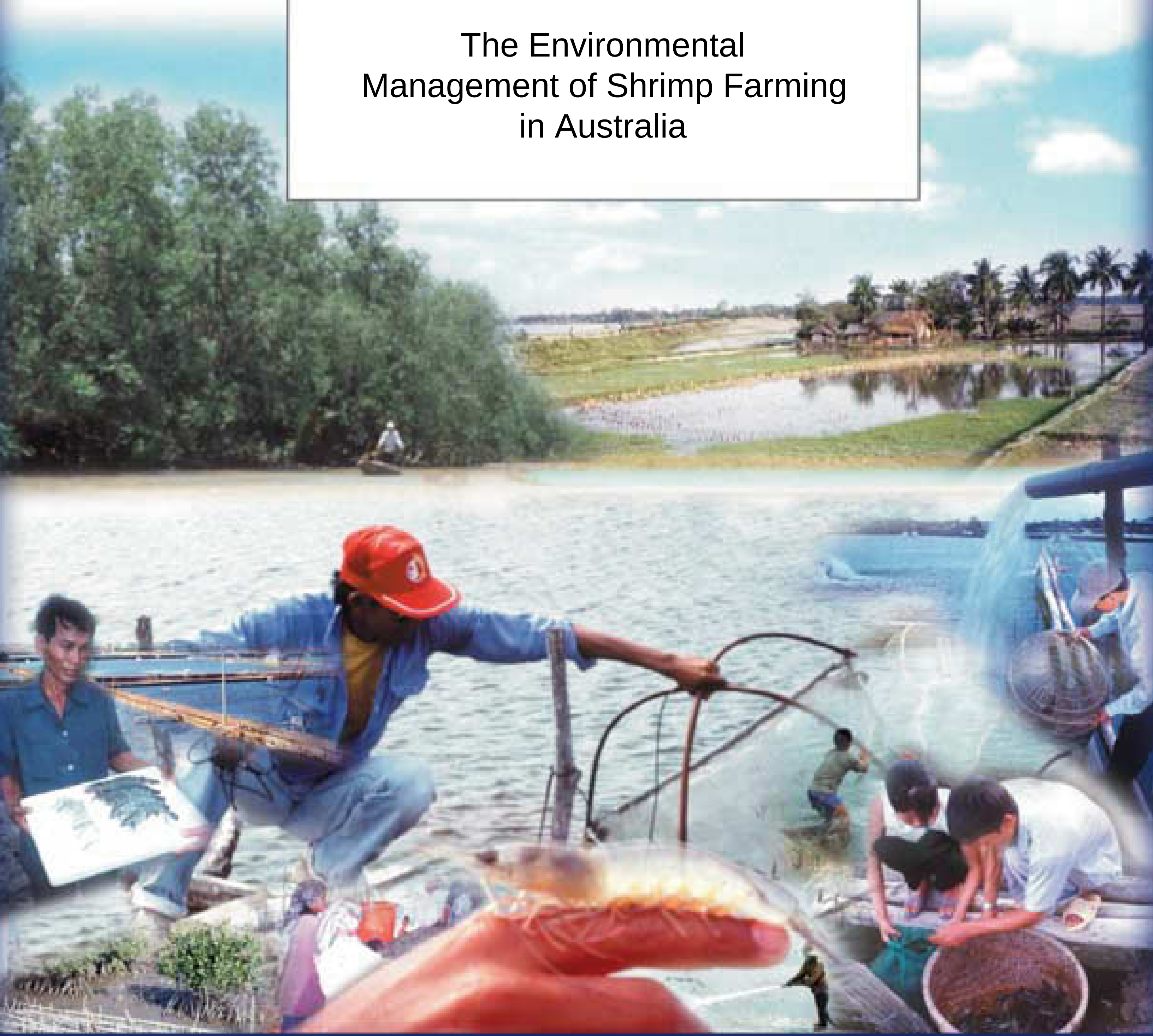
Shrimp Farming and the Environment

The Environmental Management of Shrimp Farming in Australia



A Consortium Program of:

THE ENVIRONMENTAL MANAGEMENT OF SHRIMP FARMING IN AUSTRALIA

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Preparation of this document

The research reported in this paper was prepared under the World Bank/NACA/WWF/FAO Consortium Program on Shrimp Farming and the Environment. Due to the strong interest globally in shrimp farming and issues that have arisen from its development, the consortium program was initiated to analyze and share experiences on the better management of shrimp aquaculture in coastal areas. It is based on the recommendations of the FAO Bangkok Technical Consultation on Policies for Sustainable Shrimp Culture[1], a World Bank review on Shrimp Farming and the Environment[2], and an April 1999 meeting on shrimp management practices hosted by NACA and WWF in Bangkok, Thailand. The objectives to the consortium program are: (a) Generate a better understanding of key issues involved in sustainable shrimp aquaculture; (b) Encourage a debate and discussion around these issues that leads to consensus among stakeholders regarding key issues; (c) Identify better management strategies for sustainable shrimp aquaculture; (d) Evaluate the cost for adoption of such strategies as well as other potential barriers to their adoption; (e) Create a framework to review and evaluate successes and failures in sustainable shrimp aquaculture which can inform policy debate on management strategies for sustainable shrimp aquaculture; and (f) Identify future development activities and assistance required for the implementation of better management strategies that would support the development of a more sustainable shrimp culture industry. This paper represents one of the case studies from the Consortium Program.

The program was initiated in August 1999 and comprises complementary case studies on different aspects of shrimp aquaculture. The case studies provide wide geographical coverage of major shrimp producing countries in Asia and Latin America, as well as Africa, and studies and reviews of a global nature. The subject matter is broad, from farm level management practice, poverty issues, integration of shrimp aquaculture into coastal area management, shrimp health management and policy and legal issues. The case studies together provide an unique and important insight into the global status of shrimp aquaculture and management practices. The reports from the Consortium Program are available as web versions (http://www.enaca.org/shrimp) or in a limited number of hard copies.

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[1] FAO. 1998. Report of the Bangkok FAO Technical Consultation on Policies for Sustainable Shrimp Culture. Bangkok, Thailand, 8-11 December 1997. FAO Fisheries Report No. 572. Rome. 31p.
[2] World Bank. 1998. Report on Shrimp Farming and the Environment – Can Shrimp Farming be Undertaken Sustainability? A Discussion Paper designed to assist in the development of Sustainable Shrimp Aquaculture. World Bank. Draft

Abstract

In Australia, strict Commonwealth and state environmental regulations have constrained uncontrolled development of shrimp farming. A high level of resources, relative to the size and value of the industry, has been devoted to collaborative research on the environmental management of shrimp farming in Australia. This research has quantified nutrient processes in shrimp ponds, determined whole farm nutrient budgets, analyzed effluent composition, determined the effects of different effluent treatment strategies, and traced the fate of effluent in receiving waters. The research findings are being used to provide a scientific basis for discharge license requirements for shrimp farming. These data are also being incorporated into an advanced geographic information and decision support system in order to improve site selection and aquaculture planning. Despite these improvements, however, public concerns persist about the environmental management of shrimp farms.

One potential avenue for providing a more logical and systematic basis for this debate is through the establishment of environmentally sustainable development (ESD) performance criteria for the industry. The current study begins this process with an initial focus on the Queensland shrimp farming industry. A central finding of this study is that environmental management of shrimp farms needs to be incorporated into environmental management of the water body and catchments adjacent to shrimp farms. By this means, aquaculture can be compared to other forms of agriculture, particularly in relation to permitted discharge loads. This concept is not unique to Queensland or Australia but has rarely been addressed for any location. We anticipate that this study will provide an opportunity to determine more effective ways of broadening the environmental planning and licensing of shrimp farming to include environmental standards for the whole catchment.

Contents

Abbreviations

CRCA	Cooperative Research Centre for Aquaculture
DSS	Decision Support Systems
ESD	Environmental Sustainable Development
FAO	Food and Agriculture Organization of the United Nations
FRDC	Fisheries Research and Development Coorporation
GIS	Geografical Information System
NACA	Network of Aquaculture Centres in Asia-Pacific
NEMP	National Environment Protection Measure
NGO	Non Governmental Organization
NWQMS	National Water Management Strategy
SCFA	Standing Committee on Fisheries and Aquaculture
WWF	World Wildlife Fund

Acronyms

AUS$	Australian Dollars
Ha	Hectare
MT	Metric Tons
TSS	Total Suspended Solids

Introduction

Shrimp farming constitutes an expanding, high-value primary industry in coastal areas of Australia. Currently, there are approximately 500 ha of ponds distributed throughout Queensland, New South Wales, and the Northern Territory. An increase in the number of hectares under production is anticipated in these states, and the industry is expected to expand into Western Australia. The species currently farmed are *Penaeus monodon* (2,000 MT), *P. merguiensis* (500 MT) and *P. japonicus* (200 MT), with total annual production of 2,700 MT, valued at AUS $50 million. By global standards, the Australian industry is small, accounting for only 0.3% of world production of farmed shrimp.

The relatively small Australian shrimp farming industry has developed in the wake of substantial and very rapid expansion in shrimp farming in Southeast Asia, and South and Central America where poor environmental management practices have caused widespread concerns (Naylor et al. 1998). Some of the issues that have attracted criticism of shrimp farming practices around the world are less relevant in Australia. For example, considerable attention has been focused on the destruction of mangroves due to shrimp farming activities in Asia, Central America, and South America (Primavera 1993; Phillips et al. 1993; Dierberg and Kiattisimkul 1996; Naylor et al. 1998). In Australia, the clearing of mangroves is strictly controlled; all marine plants including mangroves are protected and may be cleared only under permit. It is now well recognized that mangroves are suboptimal sites for shrimp farming because they tend to have acid sulphate soils and high pond construction costs and often harm important natural fisheries habitats (Csavas 1993). Studies of the habitat requirements of commercially caught shrimp species in Australia have further emphasized the importance of sustaining mangrove forests (Staples et al. 1985).

In comparison to shrimp farming in these other parts of the world, the high level of community awareness and strict environmental regulations in Australia have ensured that the industry has developed under close scrutiny of environmental regulators (Preston et al. 1997; Preston and Rothlisberg 2000). Although this has prevented uncontrolled development, the prospect of industry expansion continues to fuel public concerns and debate about the environmental management of shrimp farms.

One of the key environmental concerns in Australia, and elsewhere, is that untreated pond effluent could contribute to the turbidity and eutrophication of coastal regions. In Australia, the regions raising the greatest concern are those adjacent to unique and environmentally sensitive areas such as the Great Barrier Reef and other marine parks. From an aquaculture industry perspective, many existing farmers, and those seeking to enter the industry, feel that environmental regulators are targeting aquaculture producers unfairly, compared to agriculture producers. Permitted discharge loads of suspended solids and nutrients are very stringent, and the associated financial costs of both upstream and downstream monitoring programs are high.

In response to concerns about potential adverse environmental impacts, the Australian shrimp industry, scientific research community, and regulatory agencies have committed substantial resources to collaborative research aimed at understanding and improving the environmental management of the industry. Outputs from the research include accurate quantification of effluent composition and the effects of different effluent treatment strategies (Preston and Rothlisberg 2000; Preston et al. 2000); the fate of effluent discharged into mangrove creeks (Wolanski et al. 2000; Trott and Alongi 2000); and improved methods of site selection in aquaculture planning (Preston et al. 1997). These outputs have been incorporated into updated license conditions and have resulted in an improved ability to base future site selection planning on scientifically rigorous information. Therefore, recent lessons learned from research on environmental management, industry practices, regulatory processes, and communication strategies in Australia may contribute to the progress of sustainable shrimp aquaculture practices internationally.

Recent workshops to communicate research results, industry practices, and regulatory policies to a broad range of stakeholders have identified gaps in knowledge, ongoing community concerns, and potential avenues for further improvements in the environmental management of shrimp farms in Australia. Against this background, the purpose of this paper is to review both current status and future needs in the environmental management of shrimp farming in Australia.

Governance, Legislation, and Policy

Commonwealth Government

The Commonwealth Government has passed laws and has been pursuing a number of initiatives relevant to the environmental management of shrimp farming. These are summarized here.

1. The Environment Protection and Biodiversity Conservation Act of 1999.
    - Matters of national environmental significance trigger the involvement of the Commonwealth Government in the assessment of aquaculture projects; these include: World Heritage properties, Ramsar wetlands, migratory species, threatened species, and ecological communities.
2. Revisions to Schedule 4 of the Wildlife Protection (Regulation of Exports and Imports) Act of 1982.
    - Revised in 1999 to improve the sustainability of wild capture fisheries.
    - Species protected under this law include any aquaculture species for which there is a commercial wild capture fishery.
3. The Commonwealth, State and Territory governments are currently developing the National Water Quality Management Strategy (NWQMS).
    - The NWQMS's policy objective is to achieve the sustainable use of the nation's water resources by protecting and enhancing their quality while maintaining economic and social development.
    - A key document is the Australian and New Zealand Guidelines for Fresh and Marine Water Quality, which are being revised to include aquaculture and human consumers of aquatic food.
4. The Commonwealth's proposed National Environment Protection Measure (NEPM) for marine and estuarine water quality.
    - A NEPM may achieve a nationally consistent approach and will have statutory backing in all jurisdictions.
5. The development of national ecologically sustainable development (ESD) indicators.
    - The Standing Committee on Fisheries and Aquaculture (a committee of the Commonwealth Government Ministerial Council on Forestry, Fisheries and Aquaculture) has recently developed measures to report progress toward the ESD objective of fisheries legislation.
    - Indicators will cover ecologically sustainable development in environmental, social, and economic contexts.
    - Shrimp farming has been included as a case study to support developing these indicators (currently in progress).

State Governments

Aquaculture management plans have been developed and implemented by most states in Australia. These plans are generally constrained by laws and policies that have not historically been designed to accommodate issues relating to aquaculture. A recent comparison of current environmental management regulations in the Australian states showed local differences but some commonalities, such as:

- The broad objectives and policy intent of planning and environmental licensing laws are similar– that is, to achieve appropriately sited and operated aquaculture facilities.
- Common themes in laws and policies include: principles of ESD; public consultation for larger developments or those that may have significant impact; and a trend toward integrating other approvals, licenses, and permits into the development approval process.

Given that these laws and policies are written for a wide range of activities, and not for shrimp farms specifically, it will be a big task to reconcile the existing variations amongst jurisdictions. Furthermore, it is inevitable that individual jurisdictions will continue to modify their own laws and policies in response to issues other than shrimp farming and national consistency.

Research on Environmental Management

The recent focus of research on the environmental effects of shrimp farming in Australia has been largely directed by priorities identified by key stakeholders. The priorities for a nationally coordinated research program on the environmental management of shrimp farming were clearly identified in a series of regional workshops held in 1996. Workshop participants included representatives from shrimp farming and other relevant industries, research, and government primary industry agencies and environmental protection agencies. The outcome of these workshops was the development of an integrated study of the environmental management of shrimp farming in Australia (Montague 1999). Support for the research was provided by the Cooperative Research Centre for Aquaculture (CRCA), the Fisheries Research and Development Corporation (FRDC), and an environmental research levy of all Australian shrimp farmers.

The principal objective of the research was to provide scientifically rigorous information on shrimp pond and effluent management in Australia. It was anticipated that this research would assist in addressing both national and international concerns about pond management practices that can result in poor water quality; poor health of farm stocks; low production rates; and adverse environmental impacts on adjacent coastal environments. Effective environmental management of shrimp farms requires a detailed understanding of the pond ecosystem, pond and shrimp feeding management practices, the nature of pond effluent, the effectiveness of effluent treatment systems, and the fate of effluent if it is discharged into adjacent receiving environments. The research program addressed these issues by conducting multidisciplinary studies at representative farms and targeted experiments in controlled laboratory conditions.

Efforts to improve pond water quality and sustain farm productivity have been hampered by a lack of knowledge about the major nutrient pathways in ponds and the response of the pond ecosystem to management practices. Recent research has led to the development of precise sampling methods for key components of the pond ecosystem, based on a quantitative understanding of temporal and spatial variability in water quality (Preston et al. 1995; Burford 1997; Burford et al. 1998; Burford and Glibert 1999). The application of these sampling techniques has significantly improved our understanding of the causes of fluctuations in water quality, including the role of bacteria (Burford et al. 1998), protozoa (Patterson and Burford, in press), phytoplankton (Burford 1997), zooplankton (Coman et al. 1999), as well as the shrimp (Jackson and Wang 1998).

This research has demonstrated that most of the nitrogen, the nutrient of primary environmental concern in coastal ecosystems, is added in the form of formulated feed (Preston et al. 2000). Furthermore, most of the nitrogen is not retained by the shrimp but enters the pond system, where it is rapidly cycled (Burford and Glibert 1999). Pond sediments play a key role in this process (Burford 2000). In addition, the type, positioning, and number of pond aerators deployed in ponds affects both sediment and pond water quality (Peterson 1999a, 1999b; Peterson et al. 2000). This research has important implications for attempts to reduce waste production within ponds and highlights the importance of an integrated approach to waste reduction involving the disciplines of nutrition, health, genetics, and ecology (Burford et al. 2001)

Progress in shrimp farm environmental research has been enhanced by the development of novel software, Pondman 2[3], for storing a broad spectrum of data on pond conditions and management practices. What originally was intended as software for collecting and managing research data has been further developed

[3] Available at: www.bne.marine.csiro.au/~pondman

into a comprehensive program that is being used by farmers to assist with most aspects of farm management. In addition, the commercially available data provides valuable input to analysis by researchers of the key factors that affect variations in shrimp production efficiency.

Shrimp pond effluent was characterized and quantified over the entire production season at three shrimp farms. The study demonstrated that untreated shrimp pond discharges contain elevated levels of total suspended solids (TSS), nitrogen, and phosphorus, compared to intake water (Preston et al. 2000). However, farms using settlement ponds reduced TSS loads by 60%, total phosphorus by 30%, and total nitrogen by 20%. One of the major achievements of the CRC/FRDC research project has been in developing and promoting the use of settlement ponds to treat pond effluent prior to either recirculation or discharge to adjacent waterways. All new farms, or expansions of existing farms, now require the use of effluent treatment systems to meet discharge standards. Many existing farms are also exploring the use of treatment ponds for reducing discharge loads and recapturing otherwise wasted nutrients. Field studies and tank trials have already demonstrated that effluent nutrients can be successfully recaptured using secondary cash crops such as seaweeds, bivalves, and fish (Lin 1995; Jones and Preston 1999; Jones et al. 2001).

A major component of the CRC/FRDC research was to improve our understanding of the path of effluent once discharged into receiving environments. The regions of greatest concern are those adjacent to unique and environmentally sensitive areas such as the Great Barrier Reef and other marine parks. By refining and extending existing hydrodynamic models, computer graphics have now been generated to improve our understanding of the fate of farm effluent in tidal creeks (Wolanski et al. 2000). The zone of influence of pond effluent on the water quality and phytoplankton biomass in a tropical mangrove creek has also been examined (Trott and Alongi 1999, 2000). Ecosystem health indicators (phytoplankton and macroalgal bioassays) have also been used to provide integrated measures of the zone of influence of discharges from shrimp farms, which complement existing physical and chemical indices (Costanzo et al. 2001).

In summary, the CRC/FRDC research has generated scientific data on shrimp pond nutrient processes, effluent composition, treatment options, and the fate of effluent in receiving environments. In this process, research has served to provide scientific information to industry, regulators, the general public, and policy makers in order to inform debate on an acceptable level of control and regulation of the industry.

Geographic Information and Decision Support Systems

Many of the problems associated with low production and adverse environmental impacts from aquaculture (or upon it) could be avoided by better site selection (Phillips et al. 1993; Preston et al. 1995). Aquaculture site selection in the coastal zone is increasingly recognized as a complex task. Coastal aquaculture activities interact with a broad range of activities, including agriculture, urbanization, tourism, coastal zoning and environmental restrictions, boating, shipping, and capture fisheries. For land-based aquaculture, site selection also requires decisions about soil types, vegetation, topography, distance from waterways, protected habitats, and potential sources of upstream pollution and permitted effluent discharge in receiving waters.

Given the complexity of site selection, we are examining the potential role of Geographic Information Systems (GIS) in aquaculture planning. In commencing this process, we examined the continent of Australia on a coarse scale, and the Logan River basin in southeast Queensland on a fine scale (Preston et al. 1997). The study used a two-stage approach. The first stage eliminated the grossly unsuitable portion of the study area, identifying it using low-resolution, cheap, and easily available data. The second stage then focused on the remaining area with high-resolution, more expensive data. The results demonstrated that this approach maximizes the efficiency of analyzing complex spatial data sets. The major constraint (or limiting factor) was the initial selection of the study area, a 10-km-wide coastal strip of mainland Australia north of 32°S latitude. This constraint eliminated ~98.2% of the Australian continent from further analysis. With this constraint declared as an assumption, the analysis was able to focus on the remaining ~1.8% of the continent. We are currently exploring the potential of using a computer-based decision support system to improve the fine-scale (site-by-site) environmental planning of shrimp farming within individual catchments.

Consultation, Communication, and Consensus

The environmental performance of the Australian shrimp farming industry is recognized internationally for being strictly controlled and regulated. However, in some sectors of the Australian community there remains a strong perception that shrimp farming inevitably results in adverse environmental impacts. The challenge for the industry, regulators, and research community is, therefore, to ensure that the environmental management standards of the industry are credible and defensible. To move toward this objective, a national workshop entitled "Environmental Management of Shrimp Farming in Australia" was held in Brisbane in May 2000. Participants in the workshop included representatives from Commonwealth and state environmental and primary industry agencies, the shrimp farming industry, research providers, environmental lobby groups (World Wildlife Fund and Australia Marine Conservation Society), and other interested stakeholders.

The workshop participants concluded that the environmental management of shrimp farms needs to be incorporated into the broader environmental management of catchments. This issue is not unique to Queensland or Australia but has rarely been addressed anywhere. This will place shrimp farming in the context of all catchment users, including urban communities, agriculture, and other industry. Shrimp farming has the potential to have a significantly lower impact on the aquatic environment than do many of the other users of the catchment. This is because nutrient loads from shrimp farming can be controlled via prevention and treatment methods within farms, whilst discharges from other forms of agriculture are diffuse and, as such, difficult to treat or minimize.

The Standing Committee on Fisheries and Aquaculture (SCFA) in Australia has already developed measures to report progress toward the environmentally sustainable development (ESD) objective of fisheries legislation. With the support of FRDC, case studies to test the application of the agreed ESD reporting framework are now being conducted. The shrimp farming industry in Queensland has been selected as the first aquaculture case study in Australia.

Initial results from this case history have demonstrated the benefits of a structured approach to assessing the particular environmental issues of shrimp farming within broader environmental, economic, and social perspectives. The case study examined the potential for resolving environmental management issues through the establishment of ESD performance criteria for the industry. The potential benefits of developing and implementing ESD performance criteria include:

- International and domestic recognition that the industry is operating within management standards that protect the environment;
- An industry clearly focused on continuous improvement of its environmental performance;
- Reduction in community and NGO resistance to existing and future Australian shrimp farming operations; and
- Significant market benefits from compliance with environmental standards.

Future Needs

In Australia, decisions are currently being made about the most sustainable forms of primary industry in coastal areas, in order to ensure the effective management of the environment. The results of our research on shrimp pond effluent composition and treatment are helping to provide a solid scientific basis for ensuring that the shrimp farming industry is well placed in the future to meet these challenges. However, there is considerable work to be done to ensure the sustainable development of the industry. In particular, further investment in the development and implementation of integrated waste management has significant potential to improve the economic and environmental performance of the industry (Burford et al. 2001).

Within ponds, waste nutrients can be significantly reduced through a combination of improved feeds and feed management, lining or partial lining of ponds, sediment/sludge removal, and stimulating the processes of nitrification and denitrification (Burford et al. 2001). There is also considerable potential to use selective breeding of domesticated shrimp in order to improve nitrogen retention. Currently, most Austrlian shrimp farmers are using unselected offspring from wild stocks. However, selective breeding of other aquaculture species has demonstrated that nutrient retention can be significantly improved. For example, selective breeding of salmon in one study improved protein retention by 35–44% over five generations, coupled with a 77% improvement in growth rate (Gjedrem 1998).

The cost-effective use of settlement ponds and other effluent treatment systems for shrimp farming is at an early stage of development in Australia and elsewhere. Although the benefits of using settlement ponds are substantial, the primary improvement in water quality is reduced TSS levels in farm discharge. Reduction of nutrients (phosphorus and nitrogen) using settlement ponds is less effective; yet the environmental impact of nutrients from farms (eutrophication) is potentially just as damaging as that produced by suspended solids. Therefore, there is a continuing need for further research to develop more efficient means of reducing nutrient discharge from shrimp farms. Recently, rapid progress has been made in developing shrimp farming systems with minimal or no release of water (see Boyd and Clay's case study of Belize Aquaculture, Ltd.). Currently, one farm in the Northern Territory is successfully using a minimal water exchange system, and trials have also commenced in Queensland. Further development and more widespread use of these systems have great potential to improve the environmental management of shrimp farming.

Continuing efforts need to be directed towards developing national and international environmental standards and methods of enforcement or encouragement (for example, using eco-labeling to obtain a market advantage). In order to achieve this objective, it will also be necessary to ensure that monitoring or auditing techniques can accommodate the rapid temporal variation in pond and effluent nutrient concentrations.

Finally, we advocate a more structured approach to aquaculture planning, including the use of Geographic Information and Decision Support Systems (GIS/DSS) to assess the economic, environmental, and social impacts of different land-use scenarios. This approach will require combining GIS/DSS technology–including geographic, biological, hydrodynamic, economic, and social parameters–with modeling of carrying capacity under different land-use scenarios, including shrimp farming. This approach has considerable potential to reduce conflicts arising from unplanned aquaculture development.

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References

Burford, M.A. 1997. Phytoplankton dynamics in shrimp ponds. *Aquaculture Research* 28: 351-360.

Burford, M.A. 2000. Fate and transformation of dietary nitrogen in penaeid prawn aquaculture ponds (PhD dissertation). The University of Queensland, Brisbane, Australia.

Burford, M.A., E.L. Peterson, J.F.C. Baiano and N.P. Preston. 1998. Bacteria in shrimp pond sediments: their role in mineralizing nutrients and some suggested sampling strategies. *Aquaculture Research* 29: 843-849.

Burford, M.A. and P.M. Glibert. 1999. Short-term nitrogen uptake and regeneration in early and late growth-phase shrimp ponds. *Aquaculture Research* 30: 215-227.

Burford, M.A., C.J. Jackson and N.P. Preston. 2001. Reducing nitrogen waste from shrimp farming, an integrated approach. In: C. Browdy and D. Jory (eds.), The New Wave, Proceedings of the Special Session on Sustainable Culture, Aquaculture 2001. The World Aquaculture Society, Baton Rouge, Louisiana, United States. pp. 35-43.

Coman, F.E., N.P. Preston and R. Connolly. 1999. Zooplankton population dynamics in prawn ponds. In: Abstracts of the World Aquaculture Society Conference, Sydney. p. 169.

Costanzo, S.D., M.J. O'Donohue, W.C. Dennison, N.R. Loneragan and M. Thomas. 2001. A New Approach for Detecting and Mapping Sewage Impacts. *Marine Pollution Bulletin* 42 (2): 149-156.

Csavas, I. 1993. Aquaculture development and environmental issues in the developing countries of Asia. In: R.S.V. Pullin, H. Rosenthal and J.L. Maclean (eds.), *Environment and Aquaculture in Developing Countries*. ICLARM, Manila. pp. 74-101.

Dierberg, F.E. and W. Kiattisimkul. 1996. Issues, impacts and implications of shrimp aquaculture in Thailand. *Environmental Management* 20: 649-666.

Gjedrem, T. 1998. Selective Breeding in Aquaculture. *Infofish International* 3: 44-48.

Jackson, C.J. and Y. Wang. 1998. Modelling growth rate of *Penaeus monodon* Fabricius in intensively managed ponds: effects of temperature, pond age and stocking density. *Aquaculture Research* 29: 27-36.

Jones, A.B. and N.P. Preston. 1999. Sydney rock oyster, *Saccostrea commercialis* (Iredale and Roughley), and filtration of shrimp farm effluent: effects on water quality. *Aquaculture Research* 30: 1-7.

Jones, A.B., W.C. Dennison and N.P. Preston. 2001. Integrated treatment of shrimp effluent by sedimentation, oyster filtration and macroalgal absorption: a laboratory scale study. *Aquaculture* 193: 155-178.

Lin, C.K. 1995. Progression of intensive marine shrimp culture in Thailand. In: C.L. Bowdy and J.S. Hopkins (eds.), *Swimming Through Troubled Waters* (Proceedings of the special session on shrimp farming), Aquaculture '95. World Aquaculture Society, Baton Rouge, Louisiana, United States. pp. 13-25.

Montague, P. 1999. Annual report for the Cooperative Research Centre for Aquaculture. Sydney, Australia.

Naylor, R.L., R.J. Goldburg, H. Mooney, M. Beveridge, J. Clay, C. Folke, N. Kautsky, J. Lubchenco, J. Primavera and M. Williams. 1998. Nature's subsidies to shrimp and salmon farming. *Science* 282: 883-884.

Patterson, D.J. and M.A. Burford. 2001. A guide to the protozoa of marine aquaculture ponds. CSIRO Publishing, Melbourne. p. 54.

Peterson, E.L. 1999 a. The effect of aerators on the benthic shear stress in a pond (PhD dissertation). James Cook University, Townsville, Australia.

Peterson, E.L. 1999 b. Benthic shear stress and sediment quality. *Aquacultural Engineering* 21: 85-111.

Peterson, E.L., J.A. Harris and L.C. Wadhwa. 2000. CFD modelling pond dynamic processes. *Aquacultural Engineering* 23: 61-93.

Phillips, M.J., C.K. Kwei Lin and M.C.M. Beveridge. 1993. Shrimp culture and the environment: lessons from the world's most rapidly expanding warm water aquaculture sector. In: R.S.V. Pullin, H. Rosenthal, and J.L. Maclean (eds.), *Environment and Aquaculture in Developing Countries*. ICLARM, Manila. pp. 171-196.

Preston, N.P., M.A. Burford. C.J. Jackson and P.C. Crocos. 1995. Sustainable shrimp farming in Australia–prospects constraints. In: *Proceedings of PACON Sustainable Aquaculture 95*, Hawaii. pp. 308-316.

Preston, N.P., I. Macleod, P.C. Rothlisberg and B. Long. 1997. Environmentally sustainable aquaculture production–an Australian perspective. In: D.A. Hancock, D.C. Smith, A. Grant, and J.P. Beumer (eds.), *Developing and Sustaining World Fisheries Resources: The State of Science and Management*. Second World Fisheries Congress, Brisbane 1996. Vol 2: Proceedings. CSIRO, Melbourne. pp. 471-477.

Preston, N.P. and P.C. Rothlisberg. 2000. Aquaculture–Environmental impacts. In: *Outlook 2000*. Proceedings of the National Outlook Conference, Canberra, 29 February-2 March. Vol. I: Natural Resources. ABARE, Canberra. pp. 255-261.

Preston, N.P., C.J. Jackson, P.J. Thompson, M. Austin and M.A. Burford. 2000. Prawn farm effluent: origin, composition and treatment. FRDC 95/162. Final Report, Fisheries Research and Development Corporation, Canberra.

Primavera, J.H. 1993. A critical review of shrimp pond culture in the Philippines. *Reviews in Fisheries Science* 1:151-201.

Staples, D.J., D.J. Vance and D.S. Heales. 1985. Habitat requirements of juvenile penaeid prawns. In: P.C. Rothlisberg, B.J. Hill, and D.J. Staples (eds.), Second National Prawn Seminar. NPS2, Cleveland, Australia. pp. 47-54.

Trott, L.A. and D.M. Alongi. 1999. Variability in surface water chemistry and phytoplankton biomass in two tropical, tidally dominated mangrove creeks. *Marine and Freshwater Research* 50:451-457.

Trott, L.A. and Alongi, D.M. 2001. The impact of shrimp pond effluent on water quality and phytoplankton biomass in a tropical mangrove estuary. *Marine Pollution Bulletin* 40:947-951.

Wolanski, E., S. Spagnol, S. Thomas, K. Moore, D. Alongi, L. Trott and A. Davidson. 2000. Modelling and visualising the fate of shrimp pond effluent in a mangrove-fringed tidal creek. *Estuarine, Coastal and Shelf Science* 50:85-97. Special Issue: *Visualisation in Marine Science*. Available on-line at: www.idealibrary.com, Article No. ecss. 1999.0535.