Applied economics within pearl farming value chains supporting community livelihoods in Fiji and Tonga

Johnston, William Lee

Johnston, W. L. (2024). Applied economics within pearl farming value chains supporting community livelihoods in Fiji and Tonga [University of the Sunshine Coast, Queensland].
https://doi.org/10.25907/00820
Document Type: Thesis

Applied economics within pearl farming value chains supporting community livelihoods in Fiji and Tonga

Thesis submitted by William Lee Johnston (B.Ag.Econ) for the degree of Doctor of Philosophy (Mariculture Economics) at The University of the Sunshine Coast (School of Science, Technology and Engineering)

Thesis submitted October 2023

Cover photo caption: An image of ear-hung *Pinctada margaritifera* oysters grown for the production of round pearls. The image was captured and supplied by the J Hunter Pearls Fiji company in Savusavu Bay on the island of Vanua Levu in Fiji. Imaged used with permission.

Abstract

Natural marine pearls were a rare and valuable by-product of a fishery targeting pearl oyster shells for their mother-of-pearl (MOP). This fishery developed around the world throughout the 18th century and increased significantly through the 19th century in Australia and the Pacific islands. Overfishing of the MOP resource led to the development of pearl oyster spat collection techniques to assist stock replenishment. While the MOP industry eventually ceased in the 20th century, spat collection provided a basis for pearl culture industries in the Pacific, that utilised pearl nucleated techniques developed in Japan. Today, French Polynesia is the largest producer of cultured round pearls in the south Pacific using the endemic black-lip pearl oyster, *Pinctada margaritifera*. The successful French Polynesian pearl industry was a catalyst for development of pearl culture in other Pacific island countries such as the Cook Islands and Fiji. As well as significant export income, pearl culture offers livelihood opportunities (upstream and downstream) to coastal communities at a number of levels including collection of pearl oyster spat (juveniles) for on-selling to pearl farms as juveniles, and jewellery and MOP shell craft production. Despite being compatible with local lifestyles, round pearl culture has significant barriers to entry including high initial investment, high operational costs, and a requirement for a high level of technical skills. Alternatively, significant opportunities for coastal communities exist from production of mabé pearls (half pearls) because, although not as valuable as high-grade round pearls, they are cheaper to produce, with a shorter culture period, their production requires fewer technical skills and pearls can be produced by local people with minimal training. Diversification of round pearl farms into mabé pearl production, or the establishment of stand-alone mabé pearl farms, is increasingly prevalent in Pacific pearl producing nations, motivated by risk minimisation, a broader market base and a much simpler and less costly entry pathway to the sector. The overall objective of this study was to generate economic knowledge for targeted components of the pearl culture value chains in Fiji and

Tonga, improve understanding of the viability of the pearl sector, documentation of operational costs and inputs to successful pearl culture, assessment of farm viability thresholds, and the impact of adopting new technologies as decision-making tools for pearl farmers. This research was conducted within six research chapters.

The first research chapter (Chapter 2) determined the minimum viable farm scale for round pearl production in Fiji using the black-lip pearl oyster, *P. margaritifera*. Round pearl culture is an important regional industry in Fiji yet significant barriers to entry include high capital outlay and technical requirements, and a high turnover of small to medium size farms has limited industry growth. For this research a viable scale farm model for round pearl culture in Fiji was developed to assist new or potential entrants understand the costs, risks and production levels required for success. Major production costs were labour (51%), oyster stock (18%), and pearl nuclei (10%). The remaining 21% is comprised of marketing costs, other operating expenditure, and capital purchases and replacement. At steady state, median Equivalent Annual Returns (EAR) was determined to be USD 156,362, but inclusion of price and production risk factors reduced EAR to USD 29,463. The model farm achieved an Internal Rate of Return (IRR) of 36% with a Benefit Cost Ratio (BCR) of 1.83 and payback period of five years. Farms holding 100,000 oysters and producing over 8,000 pearls are deemed of viable scale. At this scale, farms can attract overseas pearl seeding technicians, apply economies of scale, and invest profits into future development. Given the average rural household income in Fiji is USD 5,800, round pearl culture offers significant economic opportunity and delivers socio-economic benefits for rural communities in upstream (oyster stock supply) and downstream (handicrafts, jewellery, tourism) activities.

The second investigation (Chapter 3) assessed the economics of two culture methods that influence round pearl production from the black-lip pearl oyster *P. margaritifera*, utilising cost-benefit analysis methodology. This oyster is used for round pearl production in Polynesia. It is generally cultured using the "ear-hanging" where multiple oysters are attached to a single rope to form 'chaplets', which are suspended from longlines or rafts. In other countries, pearl oysters are cultured using panel (pocket) nets which is more costly than chaplet-based culture but afford more protection to cultured oysters. Prior research has shown that *P. margaritifera* cultured using panel nets produce pearls of higher quality with greater value, and potentially provide higher net profits for pearl farmers. This was tested as an economic hypothesis using cost-benefit analysis to compare pearl production using chaplet-based and panel net-based culture methods. Whole farm data, including gross revenue from pearl sales and annual production costs, both fixed and variable, were analysed. Average annual production cost per pearl culture using panel nets was USD 22.47 and for chaplet-based culture was USD 21.55. However, use of panel nets saved around 3,430 hours of labour over one year, valued at USD 6,860, and offsetting the greater capital investment in panel nets. A chaplet-based pearl farm was estimated to generate USD 65,738 in EAR compared to USD 88,774 for a panel net-based farm. Positive cash flow was achieved one year earlier (in year seven) for the panel net-based farm. This research is the first economic analysis of different pearl culture methods for *P. margaritifera*. Evidence of profitability and cash flow can assist decision making by pearl farmers, regional agencies and research organisations, supporting further development of the black-lip pearl industry in the region.

The third investigation in this study (Chapter 4) undertook an economic assessment of community-based pearl oyster spat collection and mabé pearl production in the western Pacific. Cultured pearl production, and associated activities, are of crucial social and economic importance to remote coastal communities in Polynesia and the western Pacific. This chapter determined the potential profitability of (1) community-based pearl oyster spat collection operations targeting *P. margaritifera*, and the subsequent sale of pearl oysters to round pearl farms; and (2) the use of winged pearl oysters, *Pteria penguin*, collected incidentally from *P.*

margaritifera spat collection operations, for mabé pearl production. The spat collection farm modelled in this chapter comprised four 100-m longlines supporting 1,240 commercial spat collectors (black perforated ribbon sewn concertina-style onto rope), with an estimated capital cost of USD 1,245. The spat collection operation produced 2,332 saleable *P. margaritifera* pearl oysters (sold to round pearl culture operations) with an estimated NPV of USD 10,439. The Modified Internal Rate of Return (MIRR) generated was 12.24%, with a BCR of 1.52, and a payback period of four years. The downstream mabé pearl farm modelled in this chapter comprised two 100-m longlines supporting 2,000 implanted *Pt. penguin* oysters with an estimated capital cost of USD 7,319. Annual production of 5,400 mabé pearls generated an NPV of USD 491,864. The MIRR and BCR of the modelled mabé pearl farm were 22.64% and 7.24, respectively, with a payback period of three years. Incorporating production and price risk into the model reduced the expected NPV of the mabé pearl farm to USD 297,507. The models developed in this study provide valuable new information for prospective pearl oyster spat and mabé pearl farming community groups, donors, funding bodies and other stakeholders, and provide a valuable extension tool supporting further development of the pearl sector in Fiji and the broader Indo-Pacific region.

The fourth investigation (Chapter 5) assessed the economic feasibility of small-scale mabé pearl production in Tonga using hatchery cultured *Pt. penguin*. Mabé pearl culture is an increasingly important rural livelihood in south Pacific countries as it offers a low-cost, low-tech alternative to round pearl culture. Mabé pearl production can be achieved by local people with appropriate training, and the products offer further livelihood opportunities through value-adding and local production of jewellery and handicraft items. The Kingdom of Tonga is unique among south Pacific pearl producing countries in focusing primarily on mabé pearl, not round pearl, culture using *Pt. penguin*. The Tongan mabé pearl sector has developed rapidly over recent years and is sustained by routine hatchery production of spat and recently improved pearl culture methods. This chapter determined the establishment and operational costs of a subsistence-level mabé pearl farm in Tonga and developed an economic model to assess potential profitability of such operations. The representative mabé pearl farm modelled in this study targeted annual mabé pearl production from 100 oysters. Estimated capital cost of establishment was USD 2,027 and major production costs were labour (29%), marketing (24%), and capital purchase and replacement (annualised) (16%). The remaining production costs included nuclei, fuel and energy, repairs and maintenance, and additional operating expenses not otherwise described. Annual production of 231 saleable mabé pearls generated an NPV of USD 107,101. The MIRR and BCR of the modelled mabé pearl farm were 20.46% and 4.86, respectively, with a payback period of four years. Given the average annual income in Tonga is USD 4,020, the modelled mabé pearl farm offers significant economic opportunity (USD 9,338 annual profit after all costs, including owner/operator wages) and supports additional socio-economic benefits for rural communities involved in downstream activities relating to handicraft and jewellery production, and tourism. The findings in this chapter assist stakeholder understanding of costs, risks and production levels required for profitable mabé pearl production.

The fifth investigation (Chapter 6) assessed the production cost of farm-ready *Pt. penguin* used for mabé pearl production in Tonga. The Tongan mabé pearl sector is developing rapidly, stimulated by routine supply of spat to mabé pearl farmers, from the government hatchery at no cost. It is likely that some level of cost recovery for spat supply will be considered as the sector strengthens, but information on hatchery production costs is limited. This chapter determined the costs of operating the government pearl oyster hatchery in Tonga and developed an economic model to assess the production cost of juvenile oysters. Modelling was based on a single annual hatchery generating 6,600 oysters from the ocean-based nursery for delivery to commercial pearl farms. Estimated capital cost was USD 19,079 (excluding government buildings and chattels) and the major production costs were hatchery labour (37%), capital purchase and replacement (20%), and nursery labour (10%). The remaining 33% of production costs comprises electricity, repairs and maintenance, hatchery consumables, and other operating expenditure. Total annual costs for the pearl oyster hatchery were USD 13,263, equating to a cost of USD 2.01 per oyster supplied to farmers in Tonga. Given significant annual profits (EAR) of around USD 9,338 that can be generated from 100 harvested oysters (Chapter 5), there is justification for cost recovery. Results will be valuable to key stakeholders and have regional relevance for hatchery production of high-value aquaculture opportunities.

The sixth and final investigation (Chapter 7) examined the influence of production method on the profitability of mabé pearl farming using traditional and research-informed nucleus implanting practices with *Pt. penguin*. Mabé pearls are produced by attaching hemispherical nuclei to the inner shell surface of pearl oysters where subsequent coverage with nacre (mother of pearl, MOP) produces commercial pearls after a culture period of around 12 months. Traditionally, local mabé pearl farmers attempt to maximise pearl output by implanting four high-profile nuclei into each oyster. Recent research has indicated that fewer nuclei, and those with lower profile, may improve the overall quality of resulting mabé pearls and this has been adopted as best-practice by Tongan mabé pearl farmers. This chapter reports an economic comparison of these two nucleus implanting arrangements. Results showed that annual returns were not dissimilar with the traditional implanting method (four high-profile nuclei) generating USD 6,977 per annum, while the recommended best-practice method (two low-profile, one high-profile nuclei) generated USD 6,795 per annum. While the traditional method may generate potentially higher annual returns, there are two key considerations that favour the best-practice method: (1) reduced labour commitment that provides greater opportunity to engage in other livelihood activities; and (2) the production of a higher grade of pearls is more supportive of developing high value export markets for Tongan mabé pearls.

Collectively, the findings of this thesis present the most comprehensive economic evaluation of pearl culture and associated upstream and downstream value chain activities in the western Pacific. This research clearly demonstrates, beyond doubt, the critical need for applied economics in ex-ante and ex-post research and development activities of both potential, and existing pearl farming value chain activities, to ensure informed decisions are made for the benefit of the pearl sector. More broadly, such an approach is recommended for all regional mariculture interventions in the future. The lack of applied economics in determining research priorities, underpinning informed decision making, is fundamental in providing a level of confidence that investments are allocated wisely. This research has established an economic platform for pearl culture value chain activities in Fiji and Tonga to support development and enhance the livelihoods of communities that engage in activities in the pearl culture value chain in the western Pacific.

"Lessons have not been learned. In particular some research and development organisations and government fisheries departments have repeatedly promoted development trials without undertaking the most basic analysis of production and marketing costs. Risks have not been assessed, and there has been a failure to compare objectively mariculture with existing and other potential income generating activities. As a result, many small communities have served as guinea pigs for the testing of ambitious, technically driven and in many cases naïve projects."

Hambrey Consulting (2011) for the Secretariat of the Pacific Community (SPC)

Declaration by author

This thesis *is composed of my original work*, and contains no material previously published or written by another person except where due reference has been made in the text.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of the Sunshine Coast, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of Graduate Research.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

Declaration of originality

I declare that this thesis is my own work and has not been submitted in any other form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

____

William L. Johnston

9th October 2023

Publications included in this thesis

Seven publications resulted from this thesis:

Johnston, W.L, Hine, D. and Southgate, P.C. 2019. Overview of the development and modern landscape of marine pearl culture in the south Pacific. *Journal of Shellfish Research*. 38(3): 499-518.

Johnston, W.L, Hine, D. and Southgate, P.C. 2018. Economic modeling of round pearl culture in Fiji and assessment of viable farm size. *Journal of Shellfish Research*. 37(1): 79-91.

Johnston, B., Hine, D., Kishore, P. and Southgate, P.C. 2019. Cost–benefit analysis of two culture methods that influence pearl production from the black-lip pearl oyster, *Pinctada margaritifera*. *Journal of the World Aquaculture Society*. 50(3): 510-521

Johnston, B., Kishore, P., Vuibeqa, G.B., Hine, D. and Southgate, P.C. 2020. Economic assessment of community-based pearl oyster spat collection and mabé pearl production in the western Pacific. *Aquaculture*. 514: 734505.

Johnston, W., Gordon, S.E., Wingfield, M., Halafihi, T., Hine, D. and Southgate, P.C. 2020. Economic feasibility of small-scale mabé pearl production in Tonga using the winged pearl oyster, *Pteria penguin. Aquaculture Reports*. 17: 100347.

Johnston, W., Wingfield, M., Gordon, S., Halafihi, T. and Southgate, P.C. 2020. Production cost of the farm-ready pearl oyster *Pteria penguin* used for mabé pearl production in the Kingdom of Tonga. *Journal of Shellfish Research*. 39(3): 671-677.

Johnston, W., Gordon, S.E., Wingfield, M., Halafihi, T. and Southgate, P.C. 2022. Influence of production method on the profitability of mabé pearl farming using traditional and research-informed nucleus implanting practices with the winged pearl oyster, *Pteria penguin. Aquaculture*. 546: 737280.

Other publications during candidature

Saidi, I., **Johnston, B.** and Southgate, P.C., 2017. Potential profitability of pearl culture in coastal communities in Tanzania. *Aquaculture Reports*. 5:10-17.

Contributions by others to the thesis

This research was supported by the Australian Centre for International Agriculture Research (ACIAR) as part of the ACIAR project FIS/2014/060: "Developing pearl industry-based livelihoods in the Western Pacific" led by the University of the Sunshine Coast, Queensland, Australia. Further acknowledgement is required for the support of the Queensland Department of Agriculture and Fisheries (QDAF) in allowing me to complete this research as part of my role as Senior Principal Agricultural Economist based in Nambour, Queensland.

My supervisors Professor Paul C. Southgate, Associate Professor Damian Hine, and Professor Steven J.R. Underhill provided academic, scientific, and editorial support.

Logistical and operational support for research and data collection in Fiji was provided by Dr Pranesh Kishore (Pearl Project Scientist) of the University of the Sunshine Coast, Queensland, Australia (based in Suva, Fiji). In Tonga, logistical and operational support and assistance for research and data collection was provided by Max Wingfield (Senior Project Scientist) and Dr Sophie Gordon of the University of the Sunshine Coast, Queensland, Australia (based in Nuku'alofa, Tonga).

Specific co-author contributions for this thesis are outlined by chapter in the table below.

Chapter	Details of publications	Author intellectual inputs and affiliations
1	**Johnston, W.L.**, Hine, D. and Southgate, P.C. 2019. Overview of the development and modern landscape of marine pearl culture in the south Pacific. **Journal of Shellfish Research**.	**William L. Johnston**[1,2] Review of literature, data collection, data analysis, writing, and editing. **Damian Hine**[4] Supervision and technical advice.

		Paul C. Southgate[3] Project concept and funding, supervision, data collection, writing, and editing.
2	**Johnston, W.L.**, Hine, D. and Southgate, P.C. 2018. Economic modeling of round pearl culture in Fiji and assessment of viable farm size. **Journal of Shellfish Research**.	**William L. Johnston**[1,2] Study execution, project design, data collection, data analysis, writing, and editing. **Damian Hine**[4] Supervision, technical advice, and data collection. **Paul C. Southgate**[3] Project concept and funding, supervision, data collection, writing, and editing.
3	**Johnston, B.**, Hine, D., Kishore, P. and Southgate, P.C. 2019. Cost–benefit analysis of two culture methods that influence pearl production from the black-lip pearl oyster, *Pinctada margaritifera*. **Journal of the World Aquaculture Society**.	**William L. Johnston**[1,2] Study execution, project design, data collection, data analysis, writing, and editing. **Damian Hine**[4] Supervision, technical advice, and editing. **Pranesh Kishore**[3,5] Technical advice and data collection. **Paul C. Southgate**[3] Project concept and funding, supervision, data collection, writing, and editing.
4	**Johnston, B.**, Kishore, P., Vuibeqa, G.B., Hine, D. and Southgate, P.C. 2020. Economic assessment of community-based pearl oyster spat collection and mabé pearl production in the western Pacific. **Aquaculture**.	**William L. Johnston**[1,2] Study execution, project design, data collection, data analysis, writing, and editing. **Pranesh Kishore**[3,5] Technical advice and data collection. **Garry B. Vuibeqa**[6] Technical advice and data collection. **Damian Hine**[4] Supervision, technical advice, and editing.

		Paul C. Southgate[3] Project concept and funding, supervision, data collection, writing, and editing.
5	**Johnston, W.**, Gordon, S.E., Wingfield, M., Halafihi, T., Hine, D. and Southgate, P.C. 2020. Economic feasibility of small-scale mabé pearl production in Tonga using the winged pearl oyster, *Pteria penguin*. **Aquaculture Reports**.	**William Johnston**[1,2] Study execution, project design, data collection, data analysis, writing, and editing. **Sophie E. Gordon**[1,3] Technical advice and data collection. **Max Wingfield**[1,3] Technical advice and data collection. **Tu'ikolongahau Halafihi**[7] Technical advice and data collection. **Damian Hine**[4] Supervision, technical advice, data collection, and editing. **Paul C. Southgate**[3] Project concept and funding, supervision, data collection, writing, and editing.
6	**Johnston, W.**, Wingfield, M., Gordon, S., Halafihi, T. and Southgate, P.C. 2020. Production cost of the farm-ready pearl oyster *Pteria penguin* used for mabé pearl production in the Kingdom of Tonga. **Journal of Shellfish Research**.	**William Johnston**[1,2] Study execution, project design, data collection, data analysis, writing, and editing. **Max Wingfield**[1,3] Technical advice and data collection. **Sophie E. Gordon**[1,3] Technical advice and data collection. **Tu'ikolongahau Halafihi**[7] Technical advice and data collection. **Paul C. Southgate**[3] Project concept and funding, supervision, data collection, writing, and editing.
7	**Johnston, W.**, Gordon, S.E., Wingfield, M., Halafihi, T. and Southgate, P.C. 2022.	**William Johnston**[1,2] Study execution, project design,

	Influence of production method on the profitability of mabé pearl farming using traditional and research-informed nucleus implanting practices with the winged pearl oyster, *Pteria penguin*. **Aquaculture**.	data analysis, writing, and editing. **Sophie E. Gordon**[1,3] Technical advice, data collection, data analysis, and editing. **Max Wingfield**[1,3] Technical advice and data collection. **Tu'ikolongahau Halafihi**[7] Technical advice and data collection. **Paul C. Southgate**[3] Project concept and funding, supervision, data collection, writing, and editing.

Author affiliations

[1] School of Science, Technology & Engineering, University of the Sunshine Coast, 90 Sippy Downs Drive, Sippy Downs, Queensland 4556, Australia.

[2] Industry Analytics and Systems, Queensland Department of Agriculture and Fisheries, 47 Mayers Road, Nambour, Queensland 4560, Australia.

[3] Australian Centre for Pacific Islands Research and School of Science, Technology & Engineering, University of the Sunshine Coast, 90 Sippy Downs Drive, Sippy Downs, Queensland 4556, Australia.

[4] Queensland Alliance for Agriculture and Food Innovation, University of Queensland, St Lucia, Queensland 4072, Australia.

[5] School of Marine Studies, University of the South Pacific, Suva, Fiji.

[6] Ministry of Fisheries and Forests, Fisheries Department, Lami, Fiji.

[7] Science Division, Ministry of Fisheries, Nuku'alofa, Tongatapu, Tonga.

Research involving human or animal subjects

"No animal or human subjects were involved in this research".

Acknowledgements

I started my career in 1995 as a fresh-faced agricultural economist working for the Department of Primary Industries (DPI), as it was known back then, in the town of Ayr. The work centred around sugarcane; it is the Burdekin after all. I didn't live in Ayr though, choosing to live in a seaside town close by called Alva Beach. The reason – I love fishing, and this place was a whole new world of fishing opportunities for me. I blame Dr Chris Barlow for the following tome, taking advantage of my fondness for piscatorial pursuits. Then working at the Walkamin aquaculture facility, Dr Barlow contacted me and asked if I would like to be involved in a barramundi project looking at the economics of various diets. I don't think it took me long to reply emphatically. The journey into aquaculture started there, expanding exponentially over time and took me places I never imagined. Thanks Chris.

On my economic journey through various aquaculture commodities, I heard whispers of a mystical figure that worked in pearls, amongst other things he is noted for. People would warn me that he may call on my economic experience in the aquaculture field, but years passed and my belief that he might exist waned. However, one day the phone rang, and it was the mystery man. It has been a completely enjoyable experience working with him, so my sincerest gratitude goes to my primary supervisor Professor Paul Southgate for providing me with the opportunity to be a part of his extraordinary work, and for his significant investment in me and my work, the guidance and support he has provided in a field unfamiliar to him, and most of all, friendship. He's also a great travelling companion and good for a laugh. Thanks Paul.

I would also like to thank my co-supervisor for his support and guidance throughout the years. Associate Professor Damian Hine, thank you for being generous with your time and advice in the field of economics, although my work is applied and sometimes does not fit the academic mould, you kept me grounded with insightful criticism and helped me navigate the pitfalls. In addition, I would like to thank Dr Andrew Zull who is a colleague of mine in the Department of Agriculture and Fisheries (DAF) and an exceptional economist and critical thinker. Without your assistance the publication of my first research paper would not have been possible. Taking my years of applied economic work in agriculture and assisting me in transforming my workings into beautiful equations and methodology was critical in my ability to successfully publish seven papers from this thesis. Thanks Andrew.

I would also like to acknowledge and thank Dr Sophie Gordon, Dr Pranesh Kishore and Max Wingfield for their advice, constructive feedback and input to the field data that underpins this study. Their involvement was invaluable to this study.

Many thanks also goes to all the pearl farmers and communities in Fiji and Tonga that contributed to this study. In particular I would like to thank both Justin Hunter (J Hunter Pearls) and Claude Prevost (Civa Pearls) that were there as a sounding board when I needed them, but also provided a wealth of farming information and data that ensured this study was robust and reflected the true nature of commercial pearl farming.

Dedicated to my family: Joscelyn Lee, Fraser Exton, Isabella Daisy, and Theodore (Teddy)

Financial support

This research was supported by the Australian Centre for International Agriculture Research (ACIAR) as part of the ACIAR project FIS/2014/060: “Developing pearl industry-based livelihoods in the Western Pacific” led by the University of the Sunshine Coast, Queensland, Australia. Further acknowledgement is required for the support of the Queensland Department of Agriculture and Fisheries (QDAF) in allowing me to complete this research as part of my role as Senior Principal Agricultural Economist based in Nambour, Queensland.

In addition, this research was supported by an Australian Government Research Training Program Scholarship.

Keywords

Pearl oyster culture, pearl economics, community-based livelihoods, pearl farm profitability, Fiji, Tonga.

Australian and New Zealand standard research classifications (ANZSRC)

ANZSRC code: 140201, Agricultural Economics

Fields of research (FoR) classification

FoR code: 0704, Fisheries Sciences

FoR code: 0701, Agriculture, Land and Farm Management

Table of contents

List of figures

List of tables

Chapter 1: Overview of the development and modern landscape of marine pearl culture in the south Pacific

Data from this chapter were published as: **Johnston, W.L**, Hine, D. and Southgate, P.C. 2019. Overview of the development and modern landscape of marine pearl culture in the south Pacific. *Journal of Shellfish Research*. 38(3): 499-518.

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers’ comments, submission, and accepted publication in peer reviewed journal.

1.1 Introduction

Natural pearls are mentioned in ancient texts including the Rig Veda (Cariño and Monteforte 2009), the Bible and the Talmud (Silas 2003, Strack 2008). They occur rarely in marine pearl oysters and are largely a valuable by-product of a fishery targeting pearl oyster shells for their mother-of-pearl (MOP) (Strack 2006). Harvesting of marine pearl oyster beds for MOP developed around the world throughout the 18th century (Lintilhac 1987, Strack 2006). MOP industries in Australia and the Pacific islands increased significantly through the 19th century and, with new technologies, came improved underwater vision that enabled pearl oyster fishers to dive to greater depths (Saville-Kent 1893, Farn 1986, Rapaport 1995a). As exploitation of pearl oysters for MOP grew, so did demand for natural pearls. But with global depletion of pearl oyster stocks in the late 19th century, demand for natural pearls far outweighed supply (Taylor and Strack 2008), and it was this that generated interest in developing a method for pearl culture. A French oyster biologist, G. Bouchon-Brandeley, working in French Polynesia in the 1880s, made numerous attempts to culture pearls using the black-lip pearl oyster, *Pinctada margaritifera* (Farn 1986, Friedman 1999, Strack 2006); however, it is widely believed that William Saville-Kent was the first to have perfected marine pearl culture. In his 1893 book 'The Great Barrier Reef of Australia: Its Products and Potentialities' (Saville-Kent 1893), there are images of pearls claimed to be cultured in the Cook Islands using pearl oysters brought from Thursday Island in the Torres Strait (George 1968, Friedman 1999).

Today, pearl culture generates valuable export income and provides livelihood opportunities in a number of developing countries in the Pacific region (Cartier et al. 2012, Southgate et al. 2019). The Pacific includes most of the leading cultured pearl producing nations; China, Japan, French Polynesia, and Australia. While much has been documented about the development of cultured marine pearl industries in these countries, given their history, size and status in the international marketplace (e.g., Southgate et al. 2008, Zhu et al. 2019), the same cannot be said for the smaller cultured pearl producing countries. This chapter focuses on the development of pearl culture in the south-western Pacific region encompassing the island nations south of the equator; French Polynesia, Cook Islands, Fiji Islands (Fiji) and the Kingdom of Tonga (Tonga).

1.2 Japanese development of pearl culture

The pioneering efforts of Kokichi Mikimoto, and his research partner Professor Kakichi Mitsukuri, from the Tokyo Imperial University and Misaki Marine Biological Station, produced the first mabé pearls in 1893 (Nagai 2013). Mabé pearls are produced by attaching hemispherical nuclei to the inner shell surfaces of the pearl oyster where they are covered by successive layers of nacre (MOP) until harvest (Gordon et al. 2018, Kishore et al. 2018). Mabé pearls (Figure 1.1) are also known as half-pearls or blister pearls (Taylor and Strack 2008) and were first produced using the Akoya pearl oyster, *Pinctada fucata*. Mikimoto was granted a patent for the mabé pearl culture technique in 1896 (Gervis and Sims 1992) and, by 1902, he had one million oysters on his farm near Toba in Japan (Taylor and Strack 2008). While Mikimoto continued research towards a method for culturing round pearls, Dr Tokishi Nishikawa, a researcher at the same research station as Mitsukuri, was engaged in similar research. It is likely that he had knowledge of the Saville-Kent technique, which he further developed (Silas 2003), because he did not follow the better-known Chinese techniques. Nishikawa applied for a patent for his round pearl culture method in 1907. Following court battles between Saville-Kent, and Nishikawa and his colleague Tatsuhei Mise, a joint patent was awarded to Mise and Nishikawa in April 1907 (Gervis and Sims 1992, Strack 2006). By 1908 Mikimoto had opened a second pearl farm with ten million oysters. The Mise-Nishikawa method was recognised by Mikimoto as a more suitable technique for round pearl production than his own experimental methods, and he purchased the rights to the method in 1916 (Silas

2003, Taylor and Strack 2008). Mikimoto pioneered commercial pearl culture using Akoya pearl oysters and was trading the much sought-after cultured round pearls in Europe by 1919 (Nagai 2013). With his skills and business acumen, Mikimoto dominated Akoya round pearl culture in Japan from its inception throughout the 20th century (Gervis and Sims 1992).

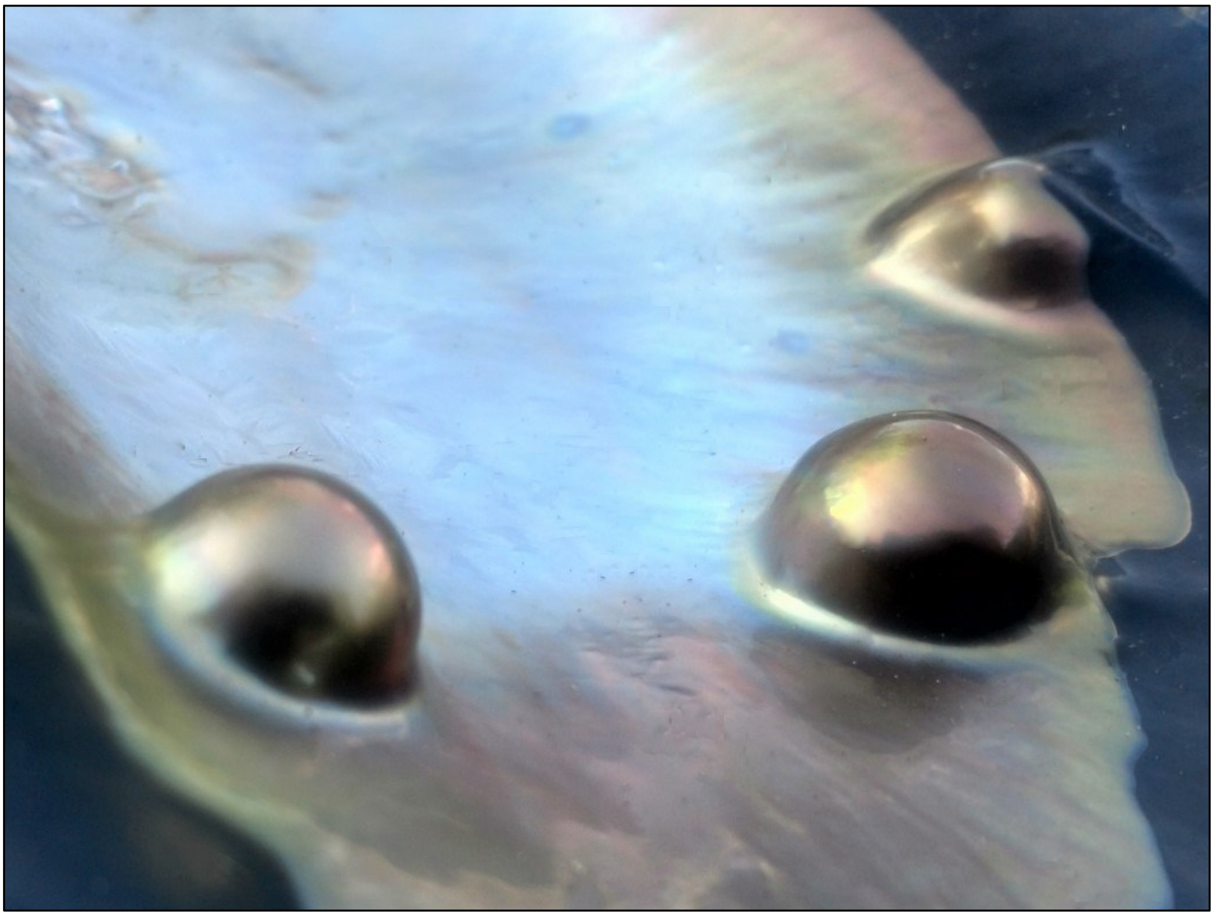

Figure 1.1 Harvested mabé pearls on the inner surface of the shell of *Pteria penguin*. The pearls will be cut from the shells before value-adding takes place. (Photograph by Dr Pranesh Kishore).

1.3 Global expansion of pearl culture

Japan formed the nucleus of the world's cultured pearl industry for many decades (Southgate et al. 2008). China, Vietnam, and India followed Japan, and began cultured Akoya pearl production in the 1960s and 1970s. Australia began pearl culture in the 1950s with the development of 'south sea' pearl culture using the much larger silver- or gold-lip pearl oyster, *Pinctada maxima* (Southgate et al. 2008). In French Polynesia, production of cultured round pearls from the endemic black-lip pearl oyster, *P. margaritifera*, was demonstrated in the 1960s, but commercial production of cultured 'black pearls' was not established until the mid-1970s (Tisdell and Poirine 2008, Southgate et al. 2008). The subsequent flourishing of the French Polynesian cultured round pearl industry provided incentive for research towards similar developments in other Pacific Island countries. The Cook Islands, Fiji, Tonga, Federated States of Micronesia, Kiribati, Solomon Islands and the Republic of the Marshall Islands have all moved towards round pearl culture industries with varying degrees of success (Friedman and Bell 1999, Fong et al. 2005, Tisdell and Poirine 2008, Southgate et al. 2008, Johnston et al. 2014, Johnston et al. 2015).

1.4 Pearl culture in French Polynesia

1.4.1 Brief history and geography

Modern-day French Polynesia is composed of 130 islands within five archipelagos: Society Islands, Marquesas Islands, Tuamotu Archipelago, Gambier Islands, and the Austral Isles (Figure 1.2) (Goebel and Dirlam 1989). The voyage of Dutchman Jacob Roggeveen in 1722 passed through the Polynesian region and recorded extensive use of MOP in pendants, tools, and fishhooks (Rapaport 1995a). Further, the journal of Samuel Wallis, who sailed the Pacific in 1767 on the H.M.S. Dolphin, recorded that the natives he encountered in Tahiti were adorned by feathers, flowers, pieces of shell and natural pearls. The pearls were mostly worn by women. Accounts of pearls were also mentioned in the journal of Lt Cook on board the H.M.S. Endeavour in 1769 which stated that one of the native girls he had encountered had worn three pearls in her ear (Byron et al. 1775). From 1772 to 1776 the Spanish also recorded numerous observations of pearls and pearl shell being used as adornments throughout Polynesia.

"*They all have their ears pierced. Some wear two or three small pearls strung on a thread therethrough. The natives are not unaware that pearls are reckoned precious. Indeed, for a pair of pendants, or for six or eight pearls strung on two threads, she asked what no person in eithers ships could give her.*"

(Corney, 2016)

Figure 1.2 Map of French Polynesia showing pearl culture regions in blue. Map reproduced with the permission of CartoGIS Services, ANU College of Asia and the Pacific, The Australian National University.

The Spanish text indicates that many of the pearls were sourced from Tuamotu Archipelago, specifically, from Rangiroa and Fakarava (Figure 1.2). Many of the pearls described were of poor quality with little lustre, affected by marine borers, or damaged by the fire used to open the oysters.

Apart from utilising natural pearls in body adornment, journals also described the use of MOP for other purposes by Polynesians. In the Journal of the Polynesian Society, a lunate pearl shell breast pendant from the Cook Islands is mentioned (Skinner 1934). As well as utilising MOP from *P. margaritifera* for personal decoration and ceremonial purposes, pearl oyster shells were also fashioned for more practical applications, such as fishing hooks (Strack 2008).

1.4.2 Exploitation of pearl oyster resources

In 1811, MOP (from *P. margaritifera*) harvested from Polynesia was first shipped to Sydney and Auckland, and by 1827 the first organised European traders began large-scale pearl fishing operations in the Tuamotu Archipelago (French Polynesia) even though 'black' MOP was not highly valued at that time (Strack 2008). In 1825, Queen Pomare IV of Tahiti recognised that MOP was an important commodity for the Tuamotus and ordered that a levy be placed upon harvested oyster shells, and that all vessels without a royal license be seized. Foreign diplomatic relations with Europe were strained following overzealous implementation of the policy until the Queen overturned it (Beechey 1831) one year later. The trade in MOP was always dangerous, with many attacks on European vessels and their crews occurring from the early days of trade in the 1700s (Rhodes 1937). Hostilities with Europeans continued in the islands and archipelagos throughout development of the MOP trade, partly due to indigenous Polynesians trying to protect traditional fishing rights, which contradicted the European view that the islands and atoll lagoons were a public resource (Rapaport 1995a). A letter to the

French Governor from the Chiefs of Manihi and Ahe, published in the Messager de Tahiti in 1859 (Rapaport 1995a) stated that: "*What we have to tell you concerns Europeans who bring people to our atolls from other lands in order to dive for our pearl shell*."

It was not until 1842, when the French Protectorate was established followed by the naming of Papeete as the capital in 1843, that attacks on ships ceased. Throughout the expansion of the MOP industry, a wider appeal for natural black pearls from the Pacific developed. By 1850, natural black pearls had begun to appear in Europe (Lintilhac 1987), a fashion trend inspired by Empress Eugenie of France (Strack 2008). Volumes were small because around 15,000 oysters must be harvested to yield a single natural pearl (Tisdell and Poirine 2000). This rarity and the popularity of black MOP for button manufacture in the second half of the 19th century drove prices up, and demand could only be satisfied by expanding pearl oyster collection into the more remote corners of French Polynesia, and by divers exploring greater depths. While price increases 'lined the pockets' of many in the supply chain, from schooner captains to manufacturers in Europe (Lintilhac 1987), indigenous Polynesians were paid little for their harvested shells, and often received only meagre quantities of food or cloth (Salomon and Roudnitska 1986). Oyster resource exploitation was further increased by the granting of the first license for a 'diving machine' (scaphandre) in 1875 (Kunz and Stevenson 1908). This diving suit was predominantly used by well-resourced operations and locals would not see improvements in their technology until 1910 when wooden goggles with glass lenses were introduced to assist oyster collection while free diving (Lintilhac 1987). French Polynesian customs records show that annual harvests of MOP shells from *P. margaritifera* between 1899 and 1948 ranged between 1.25 and 3.25 million shells (Friedman 1999).

A research visit by French oyster biologist G. Bouchon-Brandeley in 1883 was prompted by concerns over pearl oyster stock declines. He recommended that spat collection (Southgate

2008, Kishore et al. 2018) and oyster culture replace harvesting of wild stock, which was overexploited and in decline, and because periodic lagoon closures were an inadequate management measure (Bouchon-Brandeley 1885). Bouchon-Brandeley collected *P. margaritifera* spat from rafts constructed of the wood of *Pemphis adicula*, a halophilic terrestrial flowering plant, and placed them into lagoons to provide substrates to encourage the settlement and growth of pearl oysters. Although this process was slow, with oyster growth taking up to eight years to reach the size required for MOP harvest, it showed that oyster spat collection and cultivation was possible (Friedman 1999). In 1883 Bouchon-Brandeley recommended that strict regulations be applied to oyster bearing lagoons of commercial significance (i.e., those with large accessible oyster populations) and that collected spat and young oysters be placed in protected waters to replenish stocks (Kunz and Stevenson 1908, Goebel and Dirlam 1989). From this point, only certain lagoons would be opened to pearl oyster fishing each year as decreed by the Governor of the French protectorate.

Restrictions were placed on scaphandres or 'diving machines' in the Tuamotu Archipelago (Kunz and Stevenson 1908) in an attempt to limit excessive harvesting by European fishers. Despite the restrictions, a decree in 1890 made the Tuamotu lagoons a public domain. This decree extinguished the traditional fishing rights of local indigenous peoples and allowed exploitation of wild stocks to continue by both French citizens and Polynesians (Rapaport 1995a). Although regulation of the industry began in 1874, in an attempt to protect its most valuable resource (Rapaport 1995a), and some attempts were made to regulate the industry through measures such as rotating lagoon closures, oyster numbers were already too low to allow regeneration of the oyster stock. From the mid-19th century around 450 tonnes (t) of pearl oyster shells were exported annually gradually rising to 1,200 t by 1924 (Andréfouët et al. 2016). Only five lagoons were still open for commercial pearl oyster fishing in 1904, despite it being recognised by government and industry that pearl oyster stocks were overexploited. By the early 20th century much of the pearl oyster resource in the atoll lagoons of French Polynesia was significantly depleted and at an unsustainable level. By 1960, atoll lagoons such as Hikueru, which used to produce 900 t of MOP a year were viewed as irreversibly depleted and the MOP industry had disappeared by the 1970s. Similar situations occurred in other Pacific nations where, for example, MOP fisheries collapsed in New Caledonia in 1910, and in Hawaii in 1930 (Strack 2008). The trade collapsed in many other island nations in the western Pacific where MOP harvesting continued at unsustainable levels. For example, by 1985 the pearl oyster was described as 'rare' in the Cook Islands and Kiribati due to overfishing (Intes and Coeroli 1985, Sims 1992, Benzie and Ballment 1994).

1.4.3 Development of pearl culture

In the 1950s, with the MOP industry in decline, Gilbert Ranson, a French oyster biologist employed by the French administration, began developing wild spat collection techniques using bundles of local hardwoods suspended in the Hikueru atoll lagoon. Unaware of Bouchon-Brandeley's pioneering discovery in the 1880s, he learned from local divers that oyster numbers increased significantly after cyclones, probably as a result of the increase in debris on lagoon floors, providing a substratum for recruitment of pearl oyster spat (Ranson 1962). Following the success of the Ranson's research, French Polynesia expanded spat collection activities and investigated the possibility of developing a round pearl culture industry. In 1961, legislation was introduced by the Territorial Assembly of French Polynesia to promote pearl culture (Rapaport, 1995a). Artificial materials, commonly polypropylene ribbons, replaced the plant materials used for spat collection, and development of spat collection, primarily to boost wild oyster stocks, provided a stable base from which to develop the future French Polynesian pearl culture industry (Cabral 1989, Rapaport 1995b, Southgate et al. 2008).

While some mabé pearl culture was undertaken in the late 1950s it was not until 1961, with the introduction of legislation, that a concerted effort was made to initiate round pearl culture in French Polynesia. Round pearl production involves insertion of a single round nucleus into the gonad of a host pearl oyster, accompanied by a piece of the nacre-secreting mantle tissue from a donor oyster (Taylor and Strack 2008, Kishore and Southgate 2016a). This skilled operation is referred to as 'seeding', 'grafting', or 'nucleation'. In 1961, the Fisheries Service of French Polynesia engaged two companies to provide technical assistance and seeding technicians for a round pearl production trial at Bora Bora. They were the Nippo Pearl Company, which had assisted in early development of the Australian pearl culture industry in the 1950s, and Tayio Gyogo Limited (Strack 2006). Even though round pearls of good quality had been produced by both companies in other countries, there was no ongoing commercial development. In 1962, a French veterinarian Jean-Marie Domard, Director of the Agriculture and Fisheries Department, began experimenting with round pearl culture at Hikueru Atoll and the island of Bora Bora using *P. margaritifera* (Goebel and Dirlam 1989). He was supported by an Australian company, Pearls Pty Ltd, which provided a skilled Japanese seeding technician, Chiroku Muroi (Southgate et al. 2008, Andréfouët et al. 2012). A total of 5,000 pearl oysters were seeded for round pearl production and, in 1965, approximately 1,000 round black pearls of good quality were harvested, but not sold (Lintilhac 1987, Strack 2006).

The first pearl farm was established in French Polynesia in 1966 following the success of the Domard trial. It was established on Manihi Atoll by brothers Jacques and Hubert Rosenthal who were the grandsons of a well-known figure in the French jewellery trade, Leonard Rosenthal, and whose company had long been recognised for its pearl jewellery (Goebel and Dirlam 1989). The Rosenthals were supported financially by the French Polynesian government who hoped to establish a sustainable pearl culture industry following the collapse of the MOP trade; this they hoped would re-establish a degree of economic prosperity to remote parts of the French protectorate. Oysters on the farm were seeded by Japanese technician Renji Wada (Strack 2006). The farm was fully operational by 1968, and the first harvest of 71 pearls took place in 1972 (Southgate et al. 2008). As the industry began to develop, further studies into spat collection by the Fisheries Department in the early 1970s, guided by consultant William Reed, demonstrated that spat collection could be done on a large-scale to reliably supply oysters required for pearl production; this encouraged investor confidence in pearl culture in French Polynesia (Tisdell and Poirine 2000).

William Reed went on to establish his own pearling company, Tahiti Perles, in 1968 on the island of Mangareva. This was later bought in 1974 by the Chinese-Tahitian pearl farmer Robert Wan who, prior to the purchase of the Reed farm, travelled to Japan to increase his knowledge of pearl culture. He met Professor Sato who introduced him to the grandson of Kokichi Mikimoto on Pearl Island. Kichimatsu Mikimoto agreed to purchase pearls produced by Wan if he could deliver a consistent quality and quantity of pearls (www.robertwan.com). From 1974, to the present day, Robert Wan remains a significant producer and exporter of cultured pearls from French Polynesia.

Around the same time (mid-1970s) two other entrepreneurs formed pearl farming companies in French Polynesia; Koko Chaze (former Rosenthal site manager) and Jean Claude Brouillet (Polynesie Perles). The Brouillet pearl farm was based on Marutea Sud which he bought sight unseen (Strack 2006). Brouillet had travelled the world promoting ‘black’ pearls using the pearls produced by the Fisheries Department trial in 1965. Much of his efforts were in vain until he met an eminent jeweller, Salvador Assael, in New York in 1973 (Strack 2006). Assael agreed to promote black pearls among the jewellery houses of Europe and America, in exchange for a stake in the Polynesie Perles farm (Tisdell and Poirine 2000, Southgate et al.

2008). This partnership in the pearl farm was critical to its success largely because he secured the services of Japanese seeding technicians by offering exceptional wages, housing and a cook (Strack 2006). Assael created the brand 'Tahitian black cultured pearl' and, while its profile grew in Europe and America, the largest buyer at auctions held in French Polynesia (starting in 1979) remained Japan (Strack 2006). Japan was the largest pearl trading nation at the time, having reversed its policy of opposing the purchase of black pearls for reasons of competition (Rapaport 1993). From the first harvest of cultured round pearls by the Rosenthals in 1972, and with the entry of new firms into the French Polynesian pearling industry, the output of cultured pearls from French Polynesia had grown to 28,000 by 1977 (Southgate et al. 2008). Of these, 5,600 were produced by the Rosenthal farm (Société Perlière de Manihi) and 14,000 from Brouillet (Polynesie Perles) (Strack 2006).

Robert Wan's business was in its infancy at this time, and his first harvest in 1976 produced 1,770 pearls. He continued to reinvest in his business and, in 1985, purchased his own island, Marutea Sud, previously owned by Brouillet. He separated from the Mikimoto Company and sought new partnerships with Assael and other Japanese dealers (Strack 2006).

By the late 1980s the success of pearl culture in French Polynesia led to a desired demographic response, with the populations that had previously moved to Tahiti seeking employment, returning to their native atolls and islands to access the benefits that the new industry provided (Cochennec-Laureau et al. 2010, Andréfouët et al. 2012). In addition to the resulting population growth in many of the remote islands, entrepreneurs from Tahiti, France and China sought to stake their claim within the burgeoning cultured black pearl industry (Rapaport 1995a).

1.4.4 Modern industry overview

Establishment of the Groupement d'Intérêt Economique (GIE) Poe Rava Nui in 1978 brought the smaller farms together and allowed them to grow a reserve of funds to support development and to organise in-country auctions on behalf of its members (Hisada and Fukuhara 1999). Establishment of the GIE Poe Rava Nui was responsible for a cultured pearl boom in French Polynesia. The number of marine concessions (or leases) granted for the purpose of pearl culture increased rapidly from less than 500 in 1986 to 2,745 by 1999 (Southgate et al. 2008, Andréfouët et al. 2012). While the GIE Poe Rava Nui was the catalyst for the boom, it only represented 20% of pearl production by 1999 because most pearls were sold privately by independent farms to overseas buyers. Data from the Institut de la Statistique de la Polynésie Française (ISPF) show that a rapid increase in concessions lead to a commensurate rise in pearl exports, with peaks of 11,738 kg in 2000 and 16,042 kg in 2010 (www.ispf.pf). Since 2010 more controls have been placed on the quality of exported pearls, leading to a reduction in export quantities (Figure 1.3). For example, 250 kg of pearls were destroyed in 2009 and 400 kg in 2010 (Talvard, 2011), supporting an overall increase in the quality of pearls exported to markets in Asia, America, and Europe (Southgate et al. 2008, Andréfouët et al. 2012). A key quality control measure is a minimum nacre thickness of 0.8 mm (Loesdau et al. 2015). Data presented in Figure 1.3 was current at the start of this study. Subsequent production and value is reported in the summary chapter of this thesis (Chapter 8).

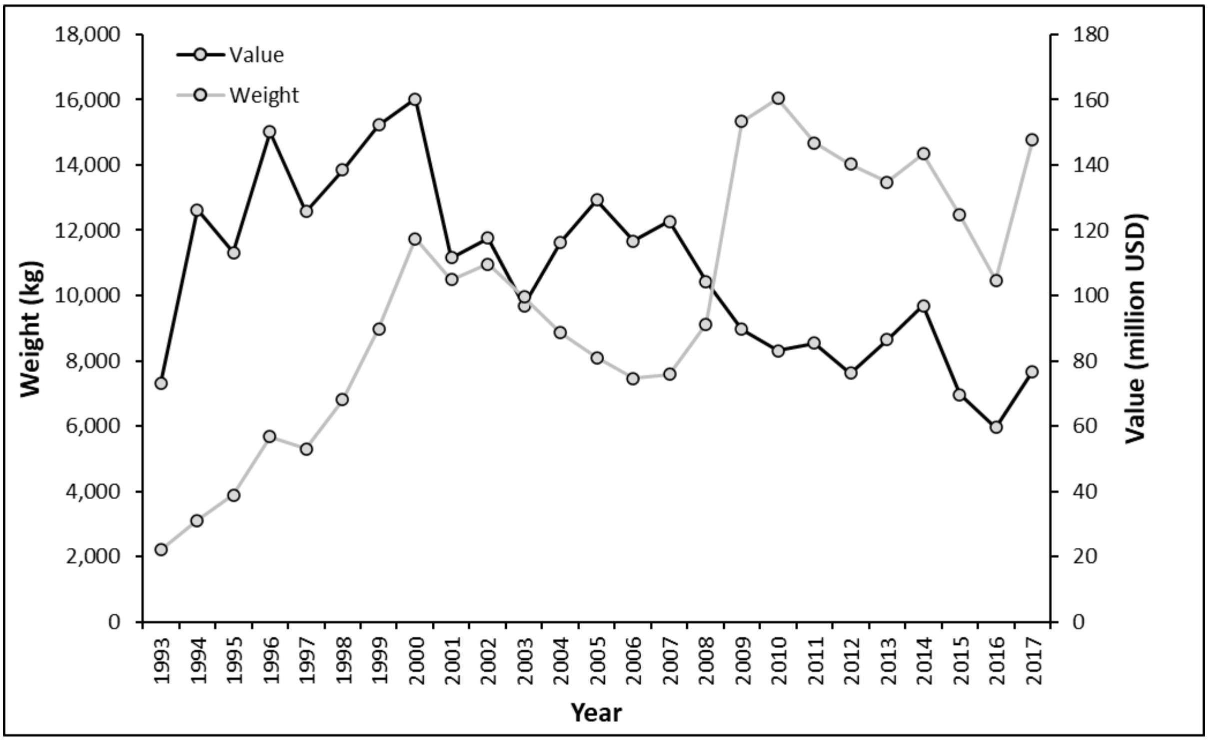

Figure 1.3 Changes in the quantity of raw cultured pearls exported from French Polynesia (ISPF: HS code 71012190), and their value, from 1993 to 2017 (source: ISPF – excludes unreported pearls estimated at 20% of production and domestic sales of around 10%).

Establishment of GIE Perles de Tahiti in 1993 was followed by the formation of numerous other co-operative 'economic interest groups' that supported and promoted their pearl farming members. The largest pearl producing co-operative is the Syndicat Professionnel des Producteurs des Perles (SPPP) (Southgate et al. 2008), of which Robert Wan is the largest shareholder.

1.4.4.1 Pearl grading and quality control

The Tahitian pearl grading system uses a scale of declining quality from A to D. In terms of overall production, the proportion of A-grade (highest grade) pearls in a pearl harvest can be as low as 5% but can account for around 95% of annual gross farm revenue (Haws 2002). A farm producing over 20,000 pearls can generate revenues close to USD 1 million. Despite this potential financial reward, it is associated with significant risk, associated with the unpredictability of pearl quality, high capital investment, extended cashflow lags following farm establishment, significant exposure to production risks such as cyclones, disease and theft, and a requirement for a high level of technical input.

The increase in cultured pearl supply around the turn of the 20th century flooded markets and led to a significant fall in prices; this was exacerbated by a decline in pearl quality (Southgate et al. 2008). The French Polynesian pearl culture agency (Service de la Perliculture) was established in 2002 to regulate the industry and improve the quality of exported pearls (Cochennec-Laureau et al. 2010). In 1985, when pearl production was still in its infancy, prices were approximately USD 100 per gram. Despite attempts to halt declining pearl prices through improved regulation of the industry, after 2007, the price for French Polynesian cultured pearls declined further and, by 2009 had reached close to USD 5 per gram (Andréfouët et al. 2012). Since 2009, the price for French Polynesian cultured pearls has fluctuated between USD 5 and USD 7 per gram (www.ispf.pf). A spike in production in 2009, well beyond the previous peak in 2000 (Figure 1.3), depressed prices which have remained consistently below USD 7 per gram (Figure 1.4). Using average weights of first harvest (0.8 g) and second harvest (1.0 g) pearl (Justin Hunter, J Hunter Pearls, Fiji, *pers. comm.* 2015), and the total weight of pearls exported from French Polynesia in 2017 of 14,759 kg, the estimated average price for pearls exported from French Polynesia was USD 8-10 per pearl. For clarity, once a pearl is harvested by a technician, a second nucleus, commonly larger in size, can be inserted into the existing pearl sac within the oyster to produce a second pearl (Kishore and Southgate 2015). This ‘reseed’ or ‘surgreffe’ process can be done up to four times assuming appropriate quality pearls continue to be produced by the oyster.

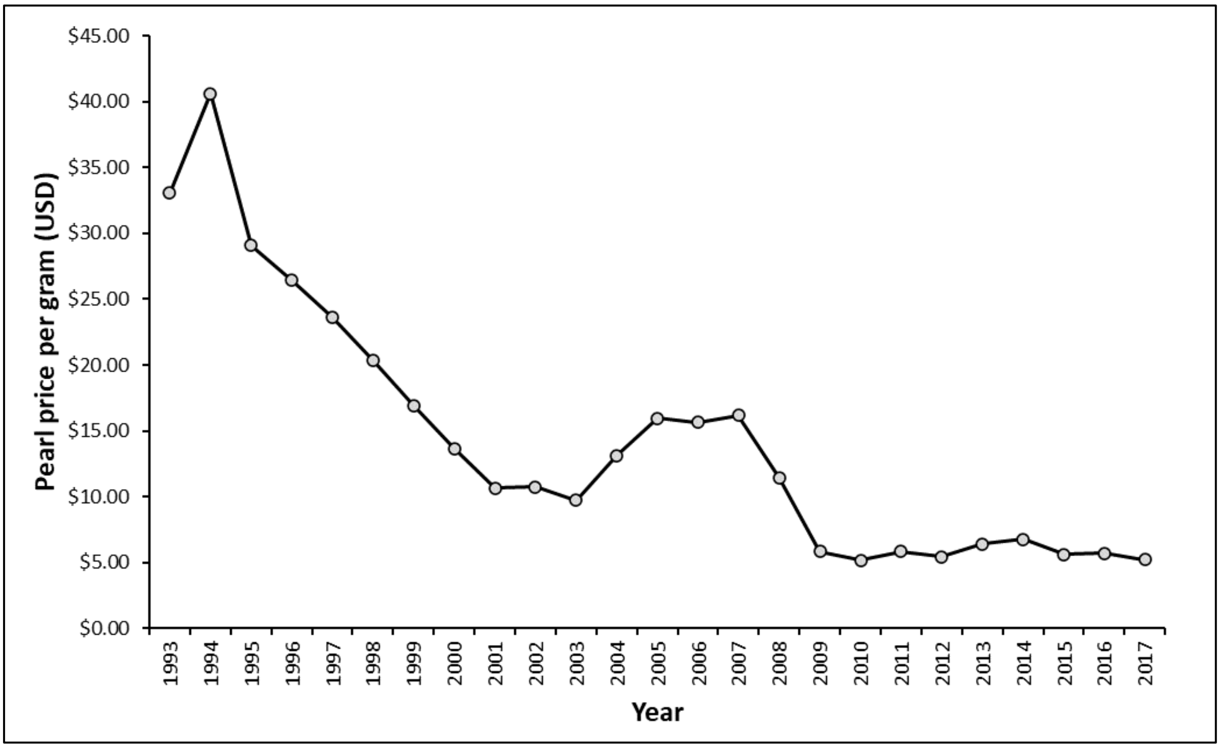

Figure 1.4 Changes in the price of exported cultured pearls from French Polynesia from 1993 to 2017 (source: ISPF).

In 2015, the French Polynesian cultured pearl industry consisted of 487 authorised marine concessions and covered 7,800 hectares of the maximum limit of 10,000 hectares imposed by the government (Ky et al. 2015a, Ky et al. 2016). The pearl industry is currently spread over 26 atolls (of which 15 are designated for spat collecting), and four islands in the Gambier, Society and Tuamotu archipelagos (Andréfouët et al. 2012, Thomas et al. 2012). 'Black' pearl culture remains the largest export commodity for French Polynesia generating approximately 67% of national income (95% of global black pearl production), well ahead of fresh fish (www.ispf.pf), and second only to tourism as the largest contributor to the French Polynesian economy (Southgate et al. 2008, Ky et al. 2016, Table 1.1).

Table 1.1 Most recent published value of pearl production (export or domestic) for pearl producing countries in the south Pacific, where French Polynesia, Cook Islands and Fiji Islands produce primarily round pearls cultured using *Pinctada margaritifera*, and Tonga produces only mabé pearls using *Pteria penguin* ($ in USD).

Country	Estimated Value ($) (Year)	Source
French Polynesia	28,810,429 (2020)	Institut de la Statistique de la Polynésie Française (www.ispf.pf)
Cook Islands	26,157 (2021)	Ministry of Finance and Economic Management (www.mfem.gov.ck)
Fiji Islands	227,000 (2022)	United Nations Comtrade Database (comtradeplus.un.org)
Kingdom of Tonga	325,000 (2018)	Southgate et al. 2023

The cultured pearl sector in French Polynesia provides employment for approximately 5,000 people (Cochennec-Laureau et al. 2010) and is the largest country-based aquaculture industry in the Pacific (Ponia 2010).

1.4.4.2 Environmental impacts

The extent to which intensive pearl culture impacts the atolls and islands of French Polynesia is not fully understood (Niquil et al. 2001, Andréfouët et al. 2012). Mass oyster mortalities occurred across several pearl culture atolls in 1985 when the industry was expanding (Pouvreau et al. 2000a, Pouvreau et al. 2000b). Mortalities have occurred in more recent years, with the underlying issues poorly understood because of the prohibitive costs of monitoring in remote islands and atolls (Andréfouët et al. 2014). The mixing of what were once isolated oyster populations has the potential to spread disease and promote colonisation by epibionts (Lacoste et al. 2014a). In addition, growing pollution problems from tourism and pearl farm waste have exacerbated oyster mortality (Andréfouët et al. 2012, Andréfouët et al. 2014). Following the 1985 mortality event, and similar mortalities of *P. maxima* in Australia from 1974 through to the early 1980s (Pass et al. 1987), a research programme called Programme General de

Recherche sur la Nacre (PGRN) was established to better understand the carrying capacity of lagoons culturing *P. margaritifera* (Pouvreau et al. 2000a, Loret et al. 2000). Pearl farming is generally considered to be a relatively benign form of aquaculture with regard to potential environmental impacts. Pearl oysters are filter feeders so there is no food input to culture systems, and the suspended culture systems used for pearl culture (Southgate 2008) in French Polynesia have been shown to have fish aggregating qualities that potentially improve food security for nearby communities (Cartier and Carpenter 2014).

1.5 Pearl culture in the Cook Islands

1.5.1 Brief history and geography

The Cook Islands are composed of 15 islands located between French Polynesia to the east and American Samoa to the west. Six of the seven islands in the northern group of islands are atolls and Manihiki and Penrhyn form the nucleus of the Cook Island cultured pearl industry (Wood 1967)(Figure 1.5). Pukapuka Island was first sighted by Spaniard Alvaro de Mendana in August 1595 followed by a landing on Rakahanga by Pedro Fernandez de Quiros in 1606 (Coppell 1973). The third voyage of Captain James Cook between 1776 and 1780 lead him through four of the southern group islands, although he never sighted Rarotonga (Quanchi and Robson 2005). The name 'Cook' Islands first appeared on a Russian naval chart in the early 1800s in honour of the famed navigator. In fear of a French takeover, as had occurred to the east, the British annexed the island nation in 1888 and this was followed by a transfer to New Zealand in 1900 (Anon 2016).

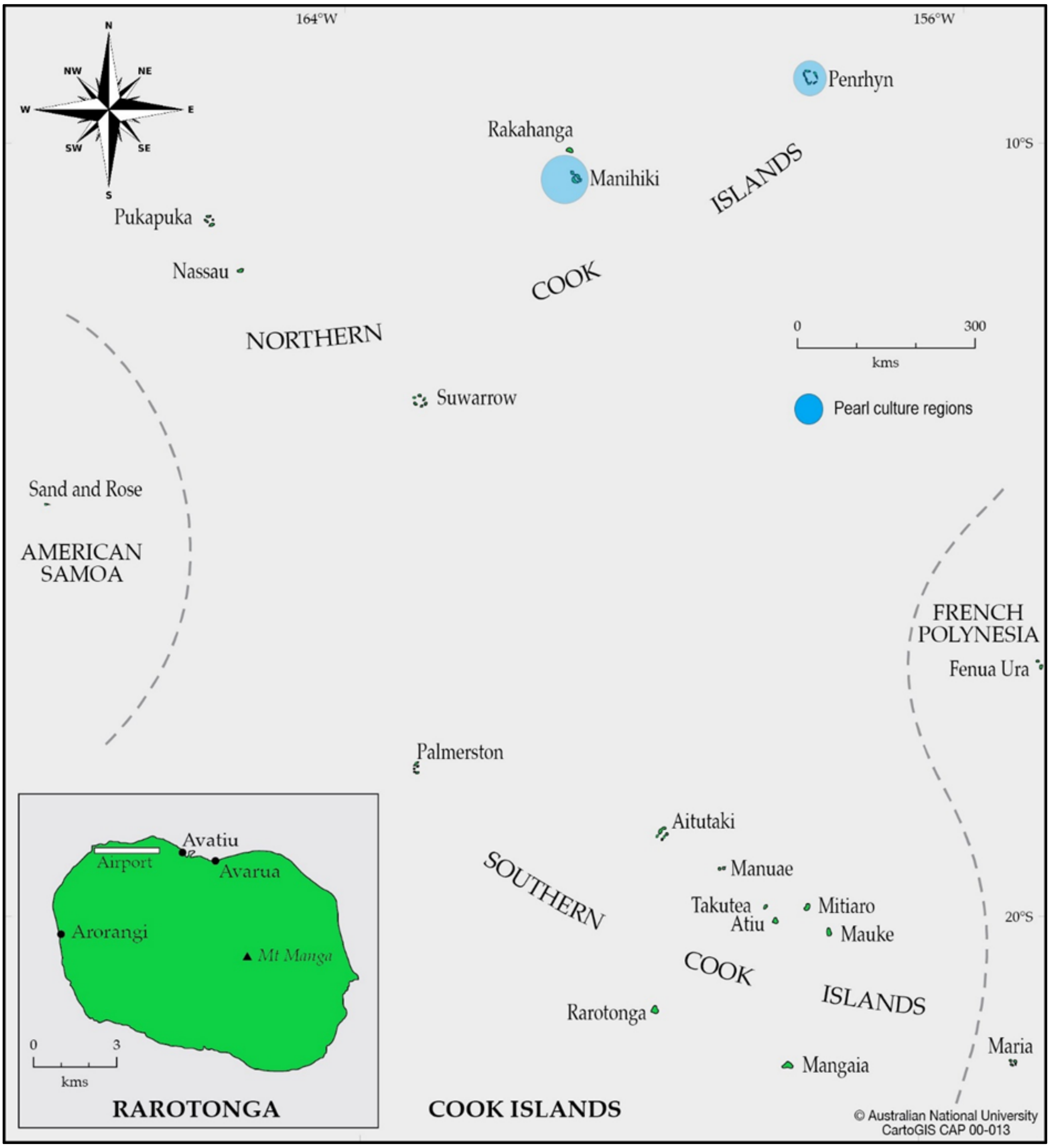

Figure 1.5 Map of the Cook Islands showing pearl culture regions in blue. Map reproduced with the permission of CartoGIS Services, ANU College of Asia and the Pacific, The Australian National University.

1.5.2 Exploitation of pearl oyster resources

As is the case in French Polynesia, *P. margaritifera*, is found in the deep atoll lagoons of Manihiki, Penrhyn and Suwarrow, and these populations formed the basis of a MOP fishery. The fishery, alongside traditional fishing practices, were the two significant forms of income for northern Cook Islanders (Sims 1992, Southgate et al. 2008). While men of the northern Cook Islands have dived for pearl oysters (parau) since the 1870s (Newnham 1989), commercial exploitation of *P. margaritifera* in the Cook Islands began post WWII following development of the French Polynesian MOP industry, and in response to a growing demand for the product in Europe for button manufacture.

Concerns over declining pearl oyster stocks in the mid-1950s lead to the designation of protected areas within lagoons as well as lagoon closures and translocation of oysters to lagoons void of *P. margaritifera* (Anon 1956, Anon 1957). In 1956, Ron Powell an English marine biologist, researched spat collection and growth of *P. margaritifera* on suspended culture lines in the Manihiki lagoon. This was an attempt to populate the uninhabited lagoons of Pukapuka and Rakahanga with *P. margaritifera*, to halt the decline of pearl oyster stocks overfished by MOP divers (Newnham 1989, Macpherson 2000). His results were published in the South Pacific Commission Quarterly Bulletin in 1957 and lead to recommendations to the Manihiki Island Council in 1960 that included lagoon closures and an increase in the minimum harvest size of oysters to 125 mm (Newnham 1989). At around this time, pearl culture using the much smaller *Pinctada maculata* found at Penrhyn Atoll was being investigated. This species produces a small rare natural golden pearl, known locally as 'poe pipi' and known and sold locally world-wide as pipi pearls (Southgate et al. 2008, Anon 2014).

1.5.3 Development of pearl culture

Pearl culture in the Cook Islands is thought to have been first described by Saville-Kent (1893). He describes, and illustrates, pearls reportedly produced in Suwarrow Atoll (Figure 1.5) using silver- or gold-lip pearl oysters, *P. maxima*, imported from the Torres Strait (George 1968). This suggests that pearl culture in the Cook Islands may have occurred much earlier than first recorded in French Polynesia. *P. maxima* was introduced to Suwarrow Atoll in 1904 by British company Lever Brothers (from 1929 the British-Dutch company Unilever). Despite a natural central Indo-Pacific range, from Myanmar to the Solomon Islands (Wada and Temkin 2008), *P. maxima* translocated from Australia to Suwarrow Atoll were able to reproduce and spat-fall was recorded. Significant predation by fish and octopus depleted oyster stocks by 1912, and a cyclone during WWI, eventually caused the closure of the venture (Gervis and Sims 1992, SPC 2012).

No commercial attempts at pearl culture were made until an Australian, Peter Cummings, arrived in the Cook Islands in 1972 (Southgate et al. 2008). He obtained a permit from the Ministry of Marine Resources (MMR) and set up a pearl farm in the lagoon of Manihiki Atoll at Tauhunu village. There was much opposition by the locals to its establishment because it ignored customary rights. The venture failed (Macpherson 2000) and was taken over by Tekake William in 1981 (Strack 2006) who worked with his son Mere (Neil A Sims, *pers. comm.* 2016). They established their own farm in 1987 holding around 15,000 locally collected *P. margaritifera*. Tekake had eleven children, all of whom had some involvement in the cultured pearl farm that would grow to be the second largest, behind that of Yves Chen Pan (Strack 2006, Stanley 2000). His son Peter was well known in the cultured pearl industry as he represented the family and its pearls at international pearl trading events (Strack 2006).

Despite the pioneering efforts of the William family to collect *P. margaritifera* spat and establish pearl oyster culture (Sims 1993), it wasn't until Yves Tchen-Pan from Tahiti set up a farm on Manihiki Atoll in 1986 that pearl culture in the Cook Islands was successfully established on a commercial scale (Southgate et al. 2008). Because of barriers to the establishment of locally owned farms, such as shortage of investment capital and husbandry skills, Ben Toma, a member of the Cook Islands Parliament, encouraged the Manihiki Island

Council to grant a lease to an experienced operator from Tahiti (Macpherson 2000). Despite opposition from Tekake William and the Government, opposed to outsiders and the risk it posed to their communal rights over the lagoon, Yves Tchen-Pan and the Council negotiated a three-hectare lease in the Manihiki Atoll lagoon. The Council believed that foreign investment would provide the catalyst for industry development and, as a result, Cook Islands Pearls Ltd was established in 1986. Within two years, the farm employed as many as 40 staff, and the large foreign owned pearl farm provided a source of capital for locals that they could then invest in their own farms (Macpherson 2000). Demand for oysters by Cook Islands Pearls provided sufficient revenue to support the establishment of another eight locally owned farms by 1987 (Strack 2006). Although the Island Council tried to maintain control over the lagoon and the expansion of pearl farming, support by MMR saw the number of farms rise to 28 by 1988, all having seeded oysters in the lagoon by this time (Newnham 1989). In addition, Yves Tchen-Pan agreed to support these local farms by allowing them to use his pearl seeding technicians (Scott 1991).

Following the expert involvement of Japanese pearl seeding technicians, provided by Yves Tchen-Pan, the Cook Islands Pearl Farmers Association held its first auction of 30,000 pearls in 1991 (Southgate et al. 2008). Although three quarters of the pearls were sold, mostly to Japanese buyers, the quality was poor. Salvador Assael criticised the pearls for their lack of quality, tarnishing the Cook Island pearl industry and its brand in the international market (Strack 2006), a reputation from which the farmers are still trying to recover.

Similar to the French Polynesian experience, development of the Cook Island industry was associated with tensions over lagoon rights. The Manihiki Island Council view that it had the right to manage the lagoon, conflicted with locally owned private farms who believed that they had the right to farm the lagoon (Macpherson 2000). Additionally, when Tekake William attempted to break away from the hold that Yves Tchen-Pan and Cook Islands Pearls Ltd had over the local industry, by seeking to use his own seeding technician, tensions rose rapidly between the two prominent figures. When the plane carrying the pearl seeding technician was on its way to Manihiki Atoll, Ben Toma, the aforementioned Member of Parliament, instructed the Public Works Department on the island to block the runway with a bulldozer (Neil A Sims, *pers. comm.* 2016). Legal action followed, and local farms gained the right to seek their own pearl seeding technicians, leading Yves Tchen-Pan to rescind his technical support to all farmers (Scott 1991). Despite tensions over the rights to the lagoon, eight pearl farming operations developed alongside the Cook Islands Pearl company (Macpherson 2000).

Following financial support from the US Agency for International Development, the Tongareva Research Station was established on Penrhyn Island (Figure 1.5) in 1994. Successful production of *P. margaritifera* larvae by the hatchery facility in 1996 led to a harvest of 8,000 saleable pearls. The pearl farms established on Penrhyn saw the return of many New Zealand emigrants. The Penrhyn Island Council managed industry expansion on the island and assisted in contracting Japanese pearl seeding technicians (Strack 2006). In 1996, there were approximately 150 farms on Manihiki and Penrhyn with over 200,000 seeded oysters (Macpherson 2000). By the end of the 1990s a community farm was established on Rakahanga (SPC 2012), but despite establishment of pearl farms on other islands, Manihiki remains the largest producer of cultured black pearls in the Cook Islands and is responsible for more than 90% of production (McKenzie 2004).

Tropical Cyclone Martin devastated the pearl industry on Manihiki in 1997, sweeping away most of the farms and killing 19 people. With loans from the Asian Development Bank, and continued support by the Cook Island Government through MMR and the larger farms, there was an 80 percent recovery of pearl farming by 1999 (Strack 2006). In late 2000, when the industry was at its peak, calm weather conditions over a two-month period reduced lagoon flushing and increased water temperatures. Overstocking, combined with a massive oyster spawning event, triggered a *Vibrio* bacteria outbreak that caused mass pearl oyster mortalities (Diggles and Hine 2001, Heffernan 2006). Before this disease outbreak, the Cook Islands pearl industry in 2000 generated USD 8.4 million in export revenue per annum from 81 farms (SPC 2012), an income second only to tourism. During the late 1990s French Polynesia grew its exports significantly, driving down international prices. While still recovering from the mass mortality event in late 2000, pearl export revenue dropped significantly in the Cook Islands and, by 2004, was approximately 10% of that recorded in 2000, dropping to just over USD 80,000 (Figure 1.6) (Heffernan 2006).

The Cook Islands, which had followed the methods and policies used in French Polynesia, had not learned from the mistakes made by them. Even though the Cook Islands Pearl Authority (CIPA) was established in 1994 and given authority in 1998 under the CIPA Act to regulate the industry through quality and export controls (Anon 2018), it lacked control over the developing industry.

1.5.4 Modern industry overview

Following the decline of the industry from 2000, it was clear that better monitoring and understanding of the Manihiki Atoll lagoon ecosystem was required in order to provide a stable sustainable basis for the cultured pearl industry. Working with agencies such as the Secretariat of the Pacific Community (SPC) and NZAID, the Cook Islands MMR began numerous projects to address industry shortcomings. These included lagoon monitoring buoys to collect biophysical data from remote lagoon locations (Heffernan 2006), and a Pearl Farming

Management Plan that was introduced in 2006 to regulate pearl farming practices and minimise preventable shocks to the Cook Islands pearl industry.

By 2007 the industry had stabilised somewhat and was buoyed by an increase in domestic pearl sales to the tourism market. Nonetheless, production remained significantly below 2000 levels; an estimated 186,725 pearls weighing 280 kg were harvested in 2007 with an export value of USD 2.4 million (Figure 1.6) (Ponia 2010).

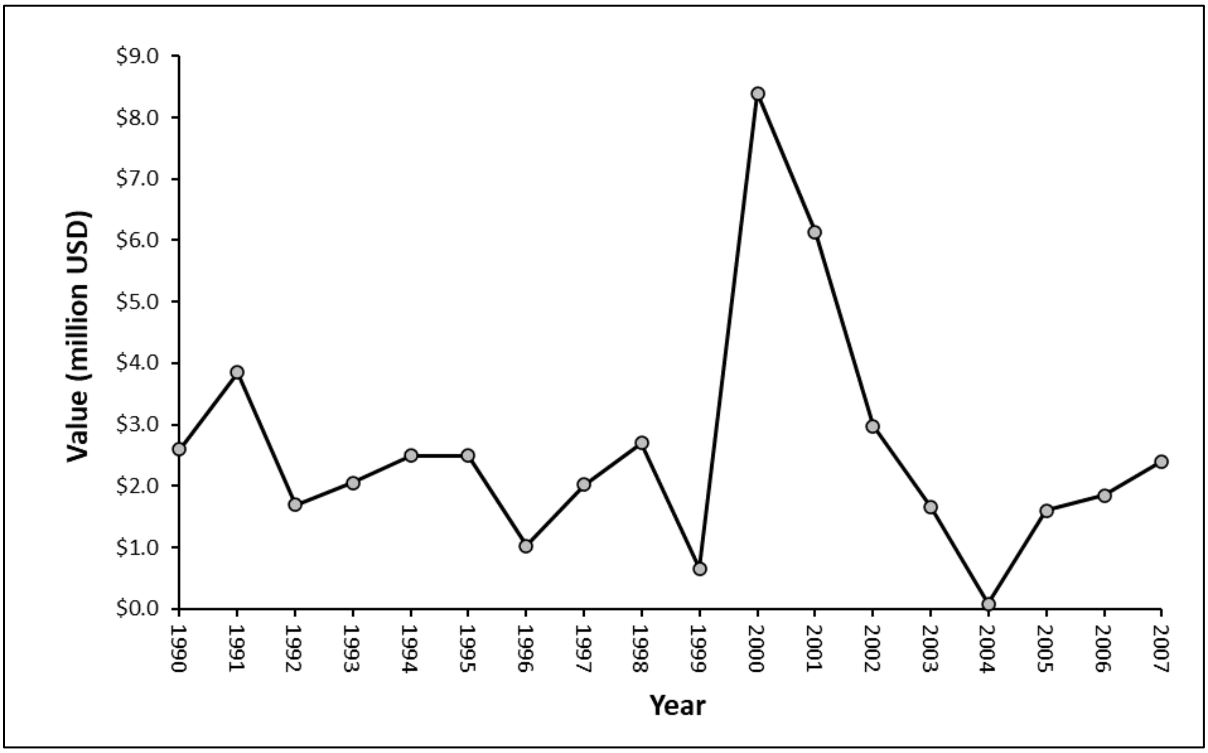

Figure 1.6 Value of saleable cultured pearls from the Cook Islands from 1990 to 2007 (source: Ministry of Marine Resources and the Secretariat of the Pacific Community).

The CIPA regular surveys of the pearl industry were discontinued in 2010 (Gillett 2009) resulting in wide ranging variation in reported cultured pearl export numbers and values from the Cook Islands. Figures since 2010 are the official budget estimates of the Government and are used in this review (Figure 1.7). The export statistics are not truly reflective of industry production in the Cook Islands because pearls sold to tourists in the growing domestic market are not recorded, and those taken out of the country by industry participants are not declared

(Gillett 2009). It is estimated by the United Nations Food and Agriculture Organisation (FAO) that the value of pearl exports from the Cook Islands could be as high as USD 781,250 (2014) compared to the budget estimate of USD 302,000 for that year (www.fao.org). Another report suggests that the Cook Islands Ministry of Marine Resources estimates pearl production in 2014 at 50,000 pearls with an estimated value of USD 650,000, similar to the value estimate by the FAO in the same year (Gillett 2016).

The Cook Islands pearl culture industry has implemented strategies to control pearl quality to establish a premium product in the international market; these include provision of improved scientific and technical support for pearl farmers, better monitoring and management of lagoons for long-term sustainability and ensuring sufficient availability of oysters (spat) to support future industry growth (SPC 2012, Gillett and Tauati 2018). Whether these measures are effective in supporting both the recovery and growth of the Cook Islands pearl industry is difficult to assess given inadequate reporting. As such, the true status of the industry is unlikely to be completely understood because around half of all pearls are estimated to be sold domestically, and a further portion are informally exported (Gillett 2016).

According to the 2016/17 budget estimates report by the Cook Islands Government, pearl farming is still the leading economic activity on Manihiki, while on Penrhyn the harvesting of natural pipi pearls is the main source of income. The same report indicates that there is a low production base of around ten active farmers and a further 14 artisanal farms that contribute little to pearl production output (www.mfem.gov.ck). The 2017/18 budget estimates describe a significant shift away from exports as illustrated in Figure 1.7. A New Zealand funded pearl revitalisation programme, targeting pearl farmers on Manihiki, provides ongoing support to the industry in the form of subsidised grants for new equipment to increase production and pearl quality. As part of this programme farmers are required to be involved and to implement a lagoon management plan (www.mfem.gov.ck).

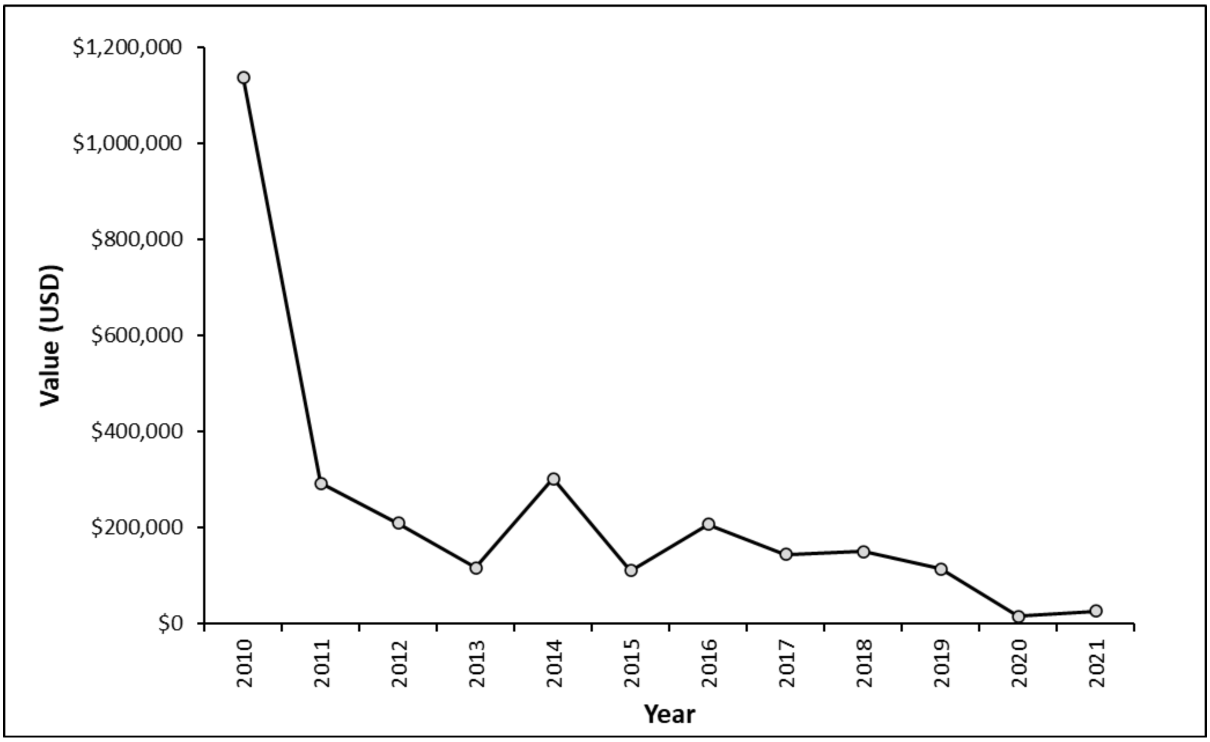

Figure 1.7 Changes in production value of exported cultured pearls from the Cook Islands from 2010 to 2021 (Government of Cook Islands 2022).

With export figures declining since 2009 and production remaining relatively stable (Figure 1.7), indications are that there is a significant shift toward the domestic market for cultured pearl sales in the Cook Islands, along with related value-added handicraft production. It was previously estimated that up to 30% of pearl production was sold domestically (Reeves 2012, Ben Ponia, Secretary of Marine Resources, Cook Islands, *pers. comm.* 2017), but is likely to be higher although the statistics is unverifiable due to lack of data collection concerning domestic sales of pearls, that are categorised with fish production in official government statistics. Investment in infrastructure for the pearl industry by New Zealand and China has seen a rise in production from 20,987 pearls in 2013 to a peak of 40,611 pearls in 2014 (Figure

1.7). The most recent value (2021) of cultured pearl exports in the Cook Islands was estimated to be USD 26,157 (Table 1.1).

Available statistics for pearl production and values in the western Pacific are notoriously unreliable with irregular or inaccurate data collection and reporting. For example, an article in the Pacific Island Report in 2012 titled “Cook Islands Pearl Industry Shortfalls Buffered by Fishery Revenues” indicated that total production was in the range of 100,000 to 150,000 pearls, in sharp contrast to government reports that production in that year was only 20,199 pearls. According to recent budget documents released by the Cook Islands Government (Government of Cook Islands 2018), the industry has shifted its focus from export to domestic and tourism markets. The pearl industry in the Cook Islands is now considered a low value contributor to the Gross Domestic Product (GDP) of the country.

1.6 Emerging pearl culture nations

1.6.1 Fiji Islands

1.6.1.1 Brief history and geography

The Melanesian nation of the Fiji Islands (Fiji) lies to the east of Vanuatu and New Caledonia and to the west of Tonga and Wallis and Futuna. It is an archipelago of 333 islands of which 150 are inhabited. Of the two major islands, Viti Levu is the most populated and has the capital Suva, with Vanua Levu located to the northwest (Figure 1.8). The first European sighting of the Fiji Islands was in 1643 by the Dutch explorer Abel Tasman in his quest to find the great southern land. Although Captain James Cook sailed through the islands it wasn’t until Captain William Bligh, following the mutiny on the Bounty, that much of the Fiji Islands (previously called the Bligh Islands) were accurately documented in 1789 (Quanchi and Robson 2005).

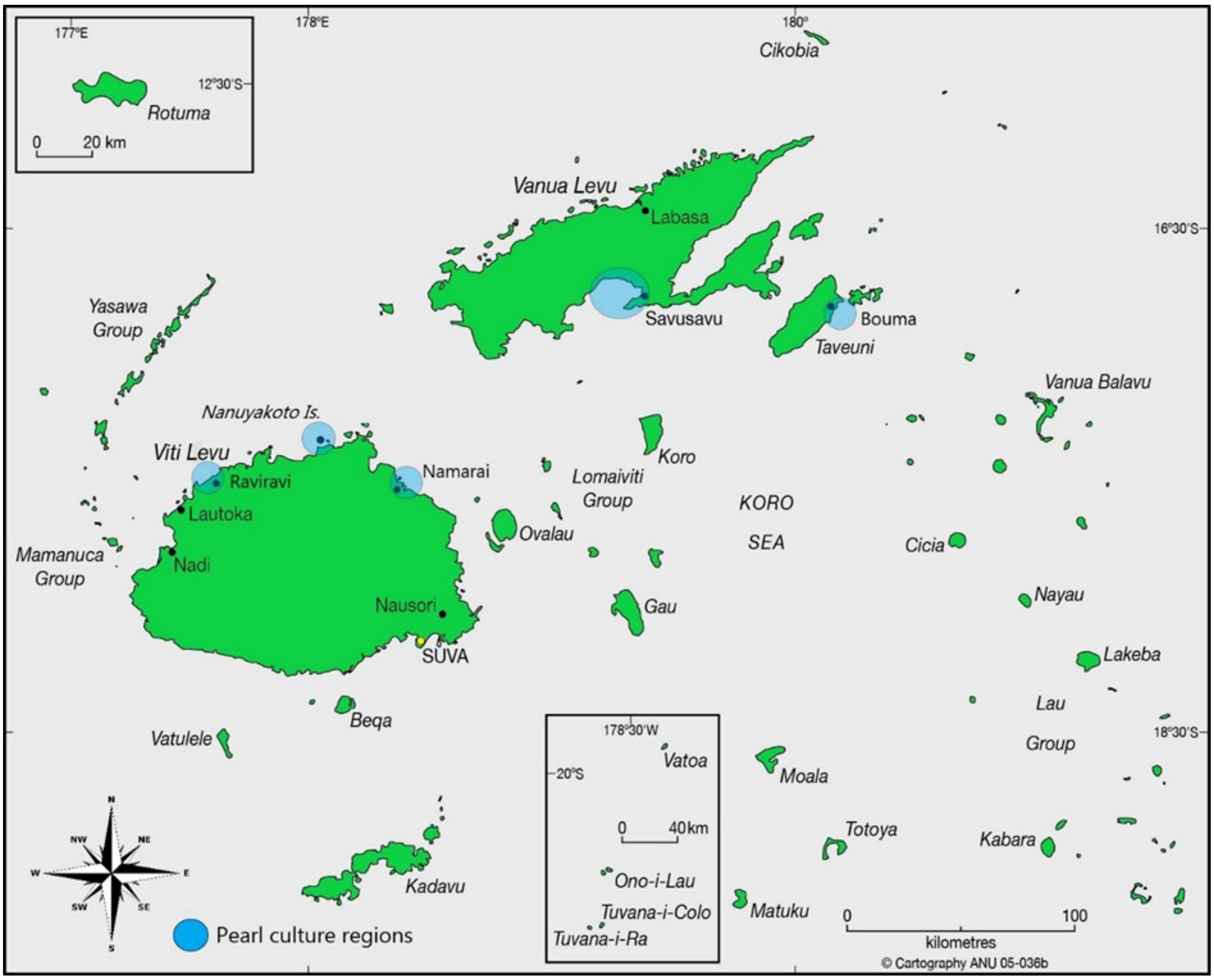

Figure 1.8 Map of the Fiji Islands showing past and present pearl culture regions in blue. Map reproduced with the permission of CartoGIS Services, ANU College of Asia and the Pacific, The Australian National University.

Although there is mention of pearling operations in the Fiji Islands in the 1950s (Strack 2006) it is more likely that the origins of pearl culture began in the early 1960s when Japanese pearling companies were looking to expand into the south Pacific and pearl farms were established in the Fiji Islands and Papua New Guinea during this period (George1968).

1.6.1.2 Development of pearl culture

In 1963, Dr Koji Wada, a pearl seeding technician, travelled to the Fiji Islands and was employed by the Pacific Fishing Company (PAFCO) in Levuka on the island of Ovalau (Tevita Taumaipeau, *pers. comm.* 2018). Identifying an opportunity to establish a pearl culture venture, Wada along with Yasuharu Tokito, established the 'Asia Pearl Company'. Wada had worked in the burgeoning Australian pearl culture industry and Tokito had many years of experience working in the Japanese industry. Wada departed the Fiji Islands in 1966, travelling to Tahiti to assist with development of first pearl farm in French Polynesia established by the Rosenthals (Anon 2012). Following the departure of Wada, Tokito moved the pearl farm to neighbouring Gau Island, renaming the company 'Tokino Pearls'. The pearl farm produced mabé pearls from *P. margaritifera* and the winged pearl oyster, *Pt. penguin*, in Vukanicula Bay on Gau Island (Uwate et al. 1984, Southgate et al. 2008) and, following the success of the mabé culture trials, the company began producing round pearls from *P. margaritifera* in 1968 (Chand et al. 2011). The company moved again to Namarai Bay in the Western Division (Viti Levu) but by the late 1970s it had ceased operations because of issues with the local villagers and poor progress. Tokino Pearls finally relocated to Nanuyakoto Island (near the town of Rakiraki on the north coast of Viti Levu) where the farm operates today on a small scale, focusing predominantly on mabé pearl production (Chand et al. 2011).

In 1993, an Australian Centre for International Agricultural Research (ACIAR) funded project, in partnership with Fiji Fisheries, assessed natural stocks of *P. margaritifera* in the Fiji Islands. Surveys were carried out at a number of locations in 1995 and the results showed that populations of pearl oysters were low in the surveyed reefs. In 1997, ACIAR commissioned further research to assess potential of pearl oyster spat collection and to conduct further surveys of pearl oyster stocks (Southgate 1997), this research was begun in 1998 and overseen by the International Centre for Living Aquatic Resources (ICLARM), now Worldfish. Pearl culture was included in a new 'Commodity Development Framework' (CDP) initiative of the Fijian Government in 1998. As the process of culturing round pearls became better understood, and more was revealed about the best locations for pearl oyster spat collection and pearl culture, the Fijian Fisheries Department, under the CDP initiative, established an experimental farm in Savusavu Bay on the island of Vanua Levu (Figure 1.8) in 1998 to promote development of the industry (Anon 2007). Savusavu Bay is deep (40 metres) and supports an abundance of phytoplankton, the food required for growth of the pearl oysters (Southgate et al. 2008). The objective of the farm was to show that black pearl production was possible in the Fiji Islands and to train potential industry participants. The farm was initially established using wild collected *P. margaritifera* from Bua (Vanua Levu), but the main hurdle was the need for experienced pearl seeding technicians. Local fisheries officer, Tevita Taumaipeau, arranged a visit to Tahiti where he met a Japanese seeding technician, Yushihiro Kazama, who agreed to seed oysters at the Savusavu Bay pearl farm. In 2000, the first small harvest of pearls was sold to Jack's Handicrafts, a recognised retail outlet throughout the Fiji Islands (Tevita Taumaipeau, *pers. comm.* 2016).

1.6.1.3 Modern industry overview

Research by Fiji Fisheries in the late 1990s involved spat collection and pearl production trials with *P. margaritifera* and, in conjunction with the 'Pearl Oyster Program' that provided small grants to farmers, heralded the beginning of the Fijian cultured pearl industry. By 2000, Marama Fiji Pearls (Marama translates as 'Lady' in Fijian) had begun operation in Savusavu Bay. The company was established by Taylor Shellfish Farms from the United States, with the assistance of local man Justin Hunter, a relative of the Taylor family. The company developed a close working relationship with the Japanese seeding technician, Mr Kazama, employing him for their venture.

Marama Fiji Pearls offered 38,855 round pearls (*P. margaritifera*) for auction in Japan in 2005 (Tevita Taumaipeau, *pers. comm.* 2016) and, following the sale, Marama Fiji Pearls became J

Hunter Pearls, with Taylor Shellfish remaining as a partner in the venture. Considerable marketing effort was invested by J Hunter Pearls in to differentiating Fijian cultured pearls from those of Polynesian producers and towards creating a unique brand image around ‘Fiji Pearls’. This significant effort in marketing and promotional strategies have ensured that ‘Fiji Pearls’ is synonymous with high quality round pearls with a wide variety of colours, some of which are unique to Fiji (Figure 1.9).

Figure 1.9 Cultured round pearls from *Pinctada margaritifera* in Fiji generate strong market demand because of their high quality and unique colour range. (Photograph by Claude Prevost, Civa Fiji Pearls, Fiji).

The larger pearl farms in the Fiji Islands, J Hunter Pearls, Valili Pearls and Civa Fiji Pearls, initially marketed their pearls as combined lots at pearl auctions, predominantly held in Hong Kong and Japan; but since 2009, Gellner, a German jewellery house, has exclusively purchased pearls from J Hunter Pearls for use in its fine jewellery lines, circumventing the more popular auctions. The opening of direct access to the European market created broader export opportunities for other larger Fijian pearl producers to market their pearls outside of the more common auctions in Asia (Johnston et al. 2014).

By 2011 there were eight operating round pearl farms, four of which were based on Vanua Levu, two on the island of Taveuni, and two on the largest island of Viti Levu near the town of Rakiraki (Chand et al. 2011). The number of farms had declined to six by 2016: J Hunter Pearls (Savusavu Bay, Vanua Levu); Valili Pearls (Savusavu Bay, Vanua Levu); Navatadua Pearls (Raviravi Village, Vanua Levu); Civa Fiji Pearls (Bouma, Taveuni); Desci Namarai Pearls (Namarai, Viti Levu); and Tokino Pearls (Nanuyakoto Island, Rakiraki) (Johnston et al. 2014). The number of round pearl farms is currently static at two, J Hunter Pearls and Civa Fiji Pearls.

In 2016 100,000 oysters were seeded for pearl production by J Hunter Pearls (Justin Hunter, J Hunter Pearls, Fiji, *pers. comm.* 2016), which by 2019 had become by far the largest pearl farm in the Fiji Islands; however, subsequent attempts to expand the J Hunter Pearls pearling operation were unsuccessful and apparently affected by disease outbreaks and the impacts of tropical cyclones. Large commercial farms are critical to the local economy, and they support local communities through income generating activities such as oyster spat collection operations (Kishore et al. 2018) and value-added handicrafts from discarded pearl oyster shells (Southgate et al. 2019). Larger farms also provide direct employment of local people and ideally, nurture the development of existing small-scale and newly established pearl farms in the region through sharing of resources and knowledge. Ongoing research in Fiji supports development of upstream and downstream pearl industry-based livelihoods that include development of local spat collection operations and skill development in the manufacture of handicrafts and jewellery (Kishore et al. 2018, Southgate et al. 2019). For example, 28 communities now generate significant income from spat collection and the sale of spat to round pearl farms (Southgate et al. 2023).

1.6.1.4 Barriers to pearl culture development

The pearl industry is still incipient in the Fiji Islands and will take time to increase production and to maintain a stable output of pearls. The Ministry of National Planning in Fiji highlighted in 2009 that constraints to industry development included a paucity of technical expertise, lack of appropriate technology and infrastructure, market and capital access, an unfavourable investment climate, and export standards compliance. In 2013, The Ministry of Fisheries Permanent Secretary, Inoke Wainiqolo, speculated that the industry would contribute at least FJD 50 million to the Fijian national domestic product by 2014, but added that there were a number of significant barriers to this progress (Fiji Government 2013). According to the United Nations (Comtrade), the Fijian cultured pearl industry contributed USD 227,000 to the national economy in 2022 through exports. The economic contribution to the national economy is likely to be greater given anecdotal evidence of significant domestic sales of pearls and pearl products (Claude Prevost, Civa Pearls, *pers. comm.* 2023) that are not distinguishable in the national accounts. While the larger farms, which are financed from overseas, can overcome some of these barriers, smaller indigenous owned operations struggle to establish and maintain their businesses.

Following the global economic crisis, issues of high production, disease and declining demand, fragmentation at supply and distribution levels, and rising competition from Chinese freshwater cultured pearl production (Zhu et al. 2019), the expansion of the marine cultured pearl industry in the Fiji Islands remained slow (Johnston et al. 2014). Improved access to oysters resulting from a well-coordinated national spat collection program (Kishore et al. 2018) has supported an estimated 40% increase in the number of oysters seeded for pearl production, on some Fijian pearl farms. Despite modest recovery from the global financial crisis (GFC), more recently, Fiji's cultured pearl sector was impacted by the global pandemic (COVID-19) which closed borders followed by a significant decline in domestic demand. At the time of this studies completion, formal assessment of production and financial impacts of the pandemic to the Fijian pearl sector was not available. However, as an indicator of the impact of the pandemic, one farm (Civa Pearls) provided sales data from 2013 to 2022. From 2013 to 2018 revenues from pearl sales remained stable and provides the reference base for the impact of the pandemic. From 2019 to 2021 sales pearls declined steadily, reaching a low of 70% revenue loss in 2021 compared to pre-2019 levels. The lifting of border restrictions and resumption of international travel saw pearl revenues rebound significantly being 30% above pre-2019 levels in 2022 (Claude Prevost, Civa Pearls, *pers. comm.* 2023).

1.6.2 Kingdom of Tonga

1.6.2.1 Brief history and geography

The Polynesian Kingdom of Tonga (Tonga) lies between the Fiji Islands to the west and Niue to the east. It has 150 islands in three main groups of which 36 are inhabited. The capital Nuku'alofa is on the main island of Tongatapu in the southernmost group of islands. The other two island groups are Ha'apai (central) and Vava'u (north) (Figure 1.10). Although the first European sighting of Tonga was by Le Maire in 1616, and documented by Tasman and Wallis, it wasn't until Captain Cook visited Tonga twice (1773 and 1774) during his second voyage to the region from 1772 to 1775 that Tongan culture was first documented (Kaeppler 1971, Quanchi and Robson 2005).

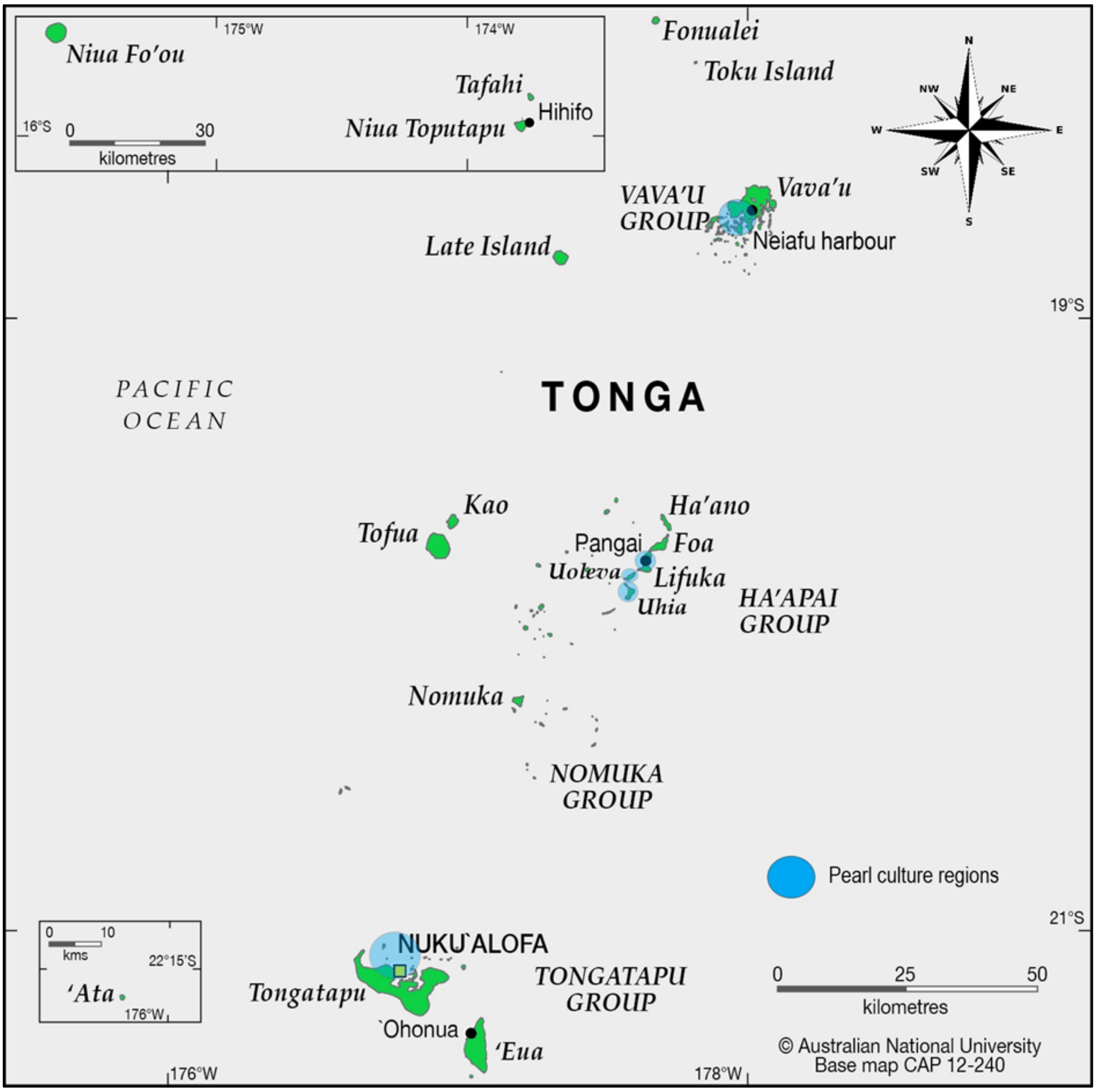

Figure 1.10 Map of Tonga island group showing pearl culture regions in blue. Map reproduced with the permission of CartoGIS Services, ANU College of Asia and the Pacific, The Australian National University.

1.6.2.2 Development of pearl culture

While round pearl oyster culture was present in Tonga in the 1960s (Teitelbaum and Fale 2008), it wasn't until the 1970s when Tonga conducted numerous trials with pearl oysters and coordinated research began into pearl culture. These trials led to little commercialisation due to factors such as lack of infrastructure, lack of capital and skilled labour, and limited domestic markets (Adams et al. 2001). At the behest of Prince Tungi of the Kingdom of Tonga, a range of pearl oyster species were introduced to Tongan waters during these trials. Between 1975 and 1979, Tasaki Shinju from the Japan-based Tasaki Pearl Company, conducted feasibility studies and oversaw the introduction of *P. maxima*, *P. fucata*, *Pinctada martensii*, *P. margaritifera* and *Pt. penguin* (Gervis and Sims 1992). More importantly, the company introduced 220 *Pt. penguin* to Vava'u as part of an investigation into mabé pearl farming and was followed by further introductions to Vava'u between 1975 and 1979 (Yamamoto and Tanaka 1997). While the trials were mostly unsuccessful it was noted that *Pt. penguin* grew the best of all species trialled in Neiafu Bay (Vava'u) and that it had established. The study concluded that *Pt. penguin* had the potential to form the basis of a future mabé pearl culture industry in Tonga (Adams et al. 2001). The Tasaki Pearl company closed operations following damage caused to the farm by cyclone Isaac in 1982 (Yamamoto and Tanaka 1997).

The Fisheries Division of Tonga ran further pearl oyster cultivation trials in the Vava'u island group (Figure 1.10) from 1986 to 1988 as one of its research priorities. The Ministry of Fisheries, supported by the FAO South Pacific Aquaculture Development Project (SPADP), conducted research into pearl oyster spat collection in 1988. The spat collection trials were successful, describing a 'mass' spawning and subsequent recruitment of *Pt. penguin* to spat collectors in Vava'u (Tanaka 1990). A stock assessment for *Pt. penguin* followed and trials of mabé pearl production were initiated in Vava'u (Teitelbaum and Fale 2008, Johnston and Hine 2015). By 1993 an investigation into the commercial feasibility of a potential mabé pearl industry reported a number of key bottlenecks including oyster supply to farms, under capitalisation, and lack of a marketing strategy. A five-year pearl development plan was drawn up by the Ministry of Fisheries in 1994 to support mabé pearl culture in preference to development of a round pearl industry, because it utilised a locally available species in *Pt.*

penguin and was more likely to be taken up by small-scale family groups and coastal communities (Johnston and Hine 2015).

1.6.2.3 Modern industry overview

Tonga officially began to record the export of mabé pearls in 2000 (Ponia 2010) because prior to this, the trade was primarily domestic and focused on the local tourist market. In 1990, the Weekly Pearl Newspaper reported that 155 pearls were imported from Tonga and sold in Japan (Anon 1990) and, in 1996, the Ministry of Fisheries in Tonga documented the export of local pearls valued at USD 10,000. The pearls sold by the Government resulted from oysters collected from the deployment of spat collectors under the FAO-SPADP initiative that were set after 1989. Prior to the sale in 1996, they had collected 73,000 juveniles that produced two lots of mabé pearls for sale, 345 pearls in 1992 and 550 pearls sold in 1996. The report indicates that the first lot of 345 mabé pearls were sold in the year they were produced and those sold in 1996 were from accumulated stocks from 1993 to 1996 (Yamamoto and Tanaka 1997). Given the estimated revenues, the 1996 price was approximately USD 20 per pearl.

In 1997, an FAO report was commissioned into the potential for commercial development of mabé pearl farming in Vava'u. The Japanese consultant that worked on the report, Tetsu Yamamoto was a pioneer of mabé farming in Japan and operated one of the largest farms. He estimated that Vava'u had the potential to dedicate up to 850 hectares to mabé pearl culture, with a potential annual harvest of 750,000 pearls of which one third would be of a high quality. At that time, each high quality mabé was valued at USD 30 and, on this basis, the estimated 250,000 good quality mabé pearls could generate around USD 7,500,000 and make a significant contribution to the national GDP (Yamamoto and Tanaka 1997).

Mabé pearl production offered considerable opportunities for coastal communities in Tonga, and by the end of 2000, 25 small scale operations had been established based wholly on the collection of wild stock (Southgate et al. 2008). Despite this potential, and over-optimistic predictions (Yamamoto and Tanaka 1997), aquaculture staff from the Ministry of Fisheries indicated that in 2008, four farmers from Vava'u (Figure 1.10) were producing mabé pearls, equating to an annual production of around 200 pieces (Gillett and Tauati 2018). The industry had contracted significantly due to an unreliable supply of juvenile pearl oysters resulting from over-harvesting of wild oysters and unfavourable recruitment conditions. In 2013, there were only three small farms in Vava'u but collaborative research between Tonga Fisheries and James Cook University, Australia, funded by the Australian Centre for International Agricultural Research (ACIAR) attempted to address this situation through hatchery production of *Pt. penguin* spat. Successful and simplified hatchery culture methods were developed (Southgate et al. 2016), and supply of hatchery produced pearl oyster spat to pearl farmers stimulated expansion of pearl farming in Vava'u, and eventually, to the introduction of mabé pearl farming to the other island groups in Tonga.

In 2015 there were nine operational mabé pearl farms in Tonga situated mainly around the Tongatapu group. By 2022, this figure had increased by a further 15 mabé pearl producing communities across the Tongan island groups of Vava'u, Tongatapu, and Ha'apai (Figure 1.10) (Southgate et al. 2023). From 2015 to 2018 mabé farms saw a growth in production from 2,700 pieces, generating a revenue of USD 125,000, to 4,680 pieces valued at USD 325,000. This represents an average price increase from USD 46 per piece to USD 70 per piece (Southgate et al. 2023). Reporting by the MoF raised concerns over the inconsistent and variable range of prices for AAA-grade mabé pearls (Gordon et al. 2018), between USD 30 and USD 100 per piece, and that this may result from incorrect grading. More training has been initiated by projects funded by ACIAR to support development of an accurate grading system and appropriate training facilities (Gordon et al. 2018). It is encouraging that some local mabé pearl farmers use up to 90% of their lower grade pearls to produce valuable handicrafts and jewellery. Further handicraft skills training will continue to improve returns to the local pearl farms (Hales 2015, Southgate 2018).

1.6.2.4 Barriers to pearl culture development

While aquaculture research has been conducted in Tonga for nearly 50 years, there have been few significant commercial developments in the pearl industry. A suggested cause for this was highlighted in a 2011 FAO report which concluded that much of the research was biology-based and did not include essential economic feasibility studies which could lead to the secure establishment of aquaculture industries (Gillett and Tauti 2018).

One of the major bottlenecks to the development of a mabé pearl industry in Tonga was initial reliance on the collection of wild spat for culture stock. While a small industry survived in Vava'u based on spat collection, poor recruitment to spat collectors forced pearl farmers to collect adult oysters from the wild (Southgate et al. 2016); a practice that no doubt resulted in further declines in oyster recruitment to spat collectors. The Government addressed this issue by establishing a pearl oyster hatchery on the main island of Tongatapu at Nuku'alofa in 2007, and operation of the hatchery was supported by an ACIAR-funded project that began in 2007. This initiative to assist pearl industry development in Tonga was further supported by the ACIAR project titled 'Pacific Agribusiness Research for Development Initiative' that began in Tonga in 2010 and targeted industry development issues such as market and value chain analysis, industry organisation, and business skilling (Moorhead 2015). In 2013, the hatchery produced 44,000 spat that were grown to maturity and distributed to farmers. Hatchery production had increased to 690,000 by 2014 (Johnston and Hine 2015), and in the period of 2014-2017, annual production from the hatchery ranged from around 300,000 to 650,000.

Hatchery production of *Pt. penguin* by the Ministry of Fisheries has supported, and continues to support, development of the mabé pearl industry in Tonga. Pearl sector reliance on hatchery production of culture stock in Tonga is unique among the pearl producing countries in the Pacific; while some hatchery production of *P. margaritifera* occurs in French Polynesia, Cook Islands and Fiji, the pearl sectors in these countries relies primarily on spat collection for oyster supply. Although hatchery production is technically demanding and unsuitable in many countries that lack the technical resources and skills required for successful hatchery operation, research investment in Tonga has supported development of simplified, more appropriate hatchery culture methods for pearl oysters (Southgate et al. 2016), and institutional capacity building that has supported export development in Tongan mabé pearls (Southgate 2009, Wassnig and Southgate 2016). Tongan mabé pearls are considered high quality internationally, however, similar to the Cook Islands, there has been a shift toward domestic sales in the tourism market in recent years (Figure 1.11). Reporting of domestic sales is not yet a requirement of licensed mabé pearl farms in Tonga but is likely to be introduced in the near future to capture the full extent of industry growth, or contraction, to better inform Government policy and guide industry development initiatives.

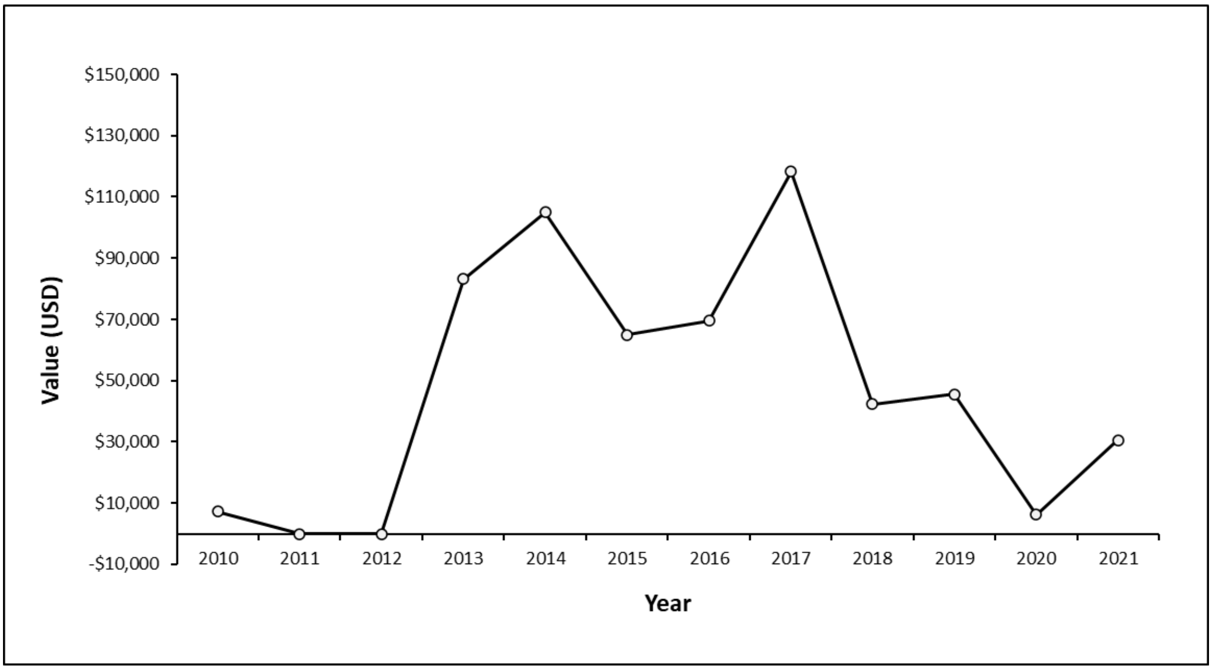

Figure 1.11 Value of exported raw mabé pearls from the Kingdom of Tonga (HS code XIV) from 2010 to 2021 (source: Tonga Statistics Department).

Although Tonga is the only western Pacific nation to focus primarily on mabé pearl culture using *Pt. penguin*, other pearl producing Pacific nations have recently begun investigating the use of half-pearl techniques to diversify production. Widespread throughout the western Pacific (Wada and Temkin 2008, Kishore et al. 2015), *Pt. penguin* is now used to culture mabé pearls in Fiji (Southgate et al. 2019). Mabé pearls are traditionally produced using *Pt. penguin* (Strack 2006, Southgate et al. 2008) but today the term 'mabé' is also applied to half-pearls cultured using other pearl oyster species (Gordon et al. 2019). Half-pearls are commonly cultured using *P. margaritifera* in Fiji, French Polynesia and Cook Islands, and production of half-pearls, simultaneously with round pearls, from *P. margaritifera* producing their final round pearl, is practiced in Fiji and French Polynesia, and offers further product diversification options for pearl farmers (i.e., production of both round and half pearls from the same oyster, harvested at the same time). Although production of half-pearls in other Pacific Island countries increases regional competition within the pearl and pearl handicraft sector, Tongan mabé pearls are usually value-added by shaping and carving of traditional patterns and motifs into the MOP surrounding the pearl, to create a uniquely Tongan product (Gordon et al. 2018, 2019, Figure 1.12). Mabé pearl culture offers coastal communities in Tonga a low-cost, low-tech, income generating opportunity and provides the country with significant export income. Further expansion and development of the Tongan mabé pearl sector is likely to require greater focus on marketing of pearls and pearl products, through improved quality control, branding and certification, and targeting of specific export and domestic market sectors.

Figure 1.12 Tongan mabé pearls are typically value-added using carving or shaping of the mother-of-pearl surrounding the pearl to create unique products. These particular items were presented to HRH Duke and Duchess of Sussex on their visit to the Kingdom of Tonga in October 2018. (Photograph by Sophie Gordon)

1.7 Round pearl or mabé pearl culture?

Although French Polynesia, the Cook Islands and Fiji have well-established round pearl culture industries, there are significant barriers to entry to this industry for local people. This is because, round pearl culture requires significant initial investment and has high operational costs. Round pearl culture also relies on skilled seeding technicians, commonly travelling from Japan, to seed the oysters twice a year for pearl production. This process is costly but provides no guarantee of a quality harvest. For many communities, these factors prevent entry to round pearl production, and limit their role in the industry to that of supplying pearl oysters obtained from spat collection, to larger round pearl farms (Southgate et al. 2019).

Spat collection, and the possession of oysters that results, does however provide opportunity for community level mabé pearl production. In Fiji, for example, community spat collection activities generate both *P. margaritifera*, that can be sold to pearl farms, and *Pt. penguin* (Kishore et al. 2018) that can be retained for mabé pearl production following training of prospective pearl farmers (Southgate et al. 2019). Although not as valuable as high-grade round pearls, mabé pearls are simpler and cheaper to produce, and they require around half the culture time (~ 10-12 months) of round pearls (Southgate et al. 2006, Kripa et al. 2008); mabé pearl culture requires fewer technical skills and they can be produced by local people following appropriate training (Ruiz-Rubio et al. 2006, Southgate et al. 2019). A further advantage of mabé pearl production, compared to round pearl production, is that multiple mabé pearls (usually 3-5) can be produced from a single oyster (Haws et al. 2006, Taylor and Strack 2008, Gordon et al. 2018) which, collectively, may exceed the value of a good quality round pearl, which are produced singly by an oyster.

Mabé pearl farms can be established on a small scale, require much less capital in the establishment phase, and the shorter culture period compared to round pearl production reduces potential cash-flow stress. Furthermore, mabé pearl culture can generate the funds and experience necessary for community members to consider future transition to round pearl farming.

1.8 Socio-economic benefits of Pacific pearl culture

Aquaculture provides opportunities for livelihoods diversification in rural and remote communities throughout the Pacific. Appropriate aquaculture commodities are generally those requiring minimal husbandry inputs so that culture activities are compatible with local lifestyles. Pearl oyster culture matches these requirements and, as a result, has become the Pacific regions most valuable and highest priority aquaculture activity (SPC 2007, Ponia 2010). Across the broader Pacific region, aquaculture production is valued at around USD 116 million per annum (Gillett 2016). The value of pearl production in the countries discussed in this chapter is currently estimated to be around USD 30 million and makes up a significant portion of total aquaculture production in the region, dominated by French Polynesia (Table 1.1). Pearls as products are small, lightweight, easily stored and transported, and of high value, with significant export demand for round pearls and mabé pearls, major domestic markets for pearl and pearl shell handicrafts.

A major advantage of pearl culture, compared to other forms of aquaculture, is that it offers livelihood opportunities (upstream and downstream) to coastal communities at a number of levels including collection of oysters through spat collection, for on-selling to pearl farms (Haws and Ellis 2000, Kishore et al. 2018, Southgate et al. 2019), mabé pearl production, and jewellery and MOP shell craft production (Southgate et al. 2019), creating a broader economic base and a more sustainable and high value industry (Fong et al. 2005, Preston 2008). Spat collection and other pearl farming activities, for example, has been actively introduced to remote islands and atolls in French Polynesia where they support local communities (Arnaud-Haond et al. 2003, Southgate et al. 2008, Andréfouët et al. 2012). It is also possible for local communities to diversify income generating opportunities associated with pearl culture by transitioning to increasingly complex pearl farming activities. For example, communities involved in spat collecting in Fiji can be trained to produce high quality mabé pearls from the oysters they collect and to produce pearl and pearl shell handicraft items (Southgate et al. 2019). Diversification of round pearl farms into mabé pearl production, or the establishment of stand-alone mabé pearl farms, is increasingly prevalent in Pacific pearl producing nations (Gordon et al. 2017), motivated by risk minimisation, a broader market base and a much simpler and less costly industry entry pathway.

1.9 Thesis overview

This study forms part of a broader research program to support the development of pearl-based livelihoods in the western Pacific region. This economic study has a particular focus on the pearl sectors of Fiji and Tonga but with the intent that it is a catalyst for broader adoption within the region. While pearl culture based on *P. margaritifera* and *Pt. penguin* is well documented in the Pacific region, its sustainable development is hampered by a paucity of knowledge around the economics of pearl culture activities, which is critical to inform decision making for private and government investment, business and sector growth, sector policy, and the development and adoption of new technologies etc. Economic information and resulting decision making tools are essential in guiding long-term sustainable development of the pearl culture sector (Hambrey Consulting 2011).

The underlying driver of the study was to demonstrate the critical role economics plays in understanding the viability of the pearl sector in the Pacific and the impact of interventions. Economics supports the decision-making of stakeholders, including the establishment of farm viability thresholds, documenting operational costs and inputs, assessing the impacts and supporting adoption of new technologies and practices, broader value chain opportunities, and improving the knowledge base around the impediments and bottlenecks to sector development.

This study ultimately provides an example for the benefits associated with the inclusion of rigorous economics in future development programs in the Pacific region.

This above goals were addressed through the following base objectives:

i. to develop whole-farm economic models for both round and mabé pearl culture that can be used to establish a baseline scale of production required for profitability, considering the inherent risks within pearl culture value chains;
ii. to investigate the viability and profitability of spat supply operations on which farm and industry growth relies; and
iii. to assess recent advances in production methodology to improve efficiencies and product quality.

These objectives provide the basis for the following research chapters in this thesis.

Chapter 2 is the first study to investigate the economics of round pearl culture in Fiji based on the collection of wild *P. margaritifera*. To undertake the economic assessment a detailed whole-farm economic model was built using discounted cashflow analysis over a 20-year period and populated using data gathered from existing farmers and key stakeholders. The study was a significant advancement in understanding the impediments to sector development, such as the need for high levels of capital investment and technical requirements, which had led to a high turnover of small to medium size farms in Fiji at the time. Additionally, establishment of viable-scale benchmark for round pearl culture in Fiji assisted in the understanding of capital and input costs, production and price risks, and production levels required for profitability long-term viability. The model also provided the basis for a training and education program. The success of pearl culture is important given that round pearl culture offers significant economic opportunity and socioeconomic benefits for rural communities in upstream (oyster stock supply) and downstream (handicrafts, jewellery, and tourism) activities.

Chapter 3 is a cost-benefit analysis of alternative methods of pearl production using chaplet-based and panel net-based culture methods. This study used whole farm data, including gross revenues and annual production costs, fixed and variable, to analyse the two methods. There are no prior reports in the primary literature assessing the relative economic benefits of different culture methods for round pearl culture from *P. margaritifera*. Given this is the first economic analysis of different pearl culture methods, evidence of profitability will inform decision making processes and support further development of the black-lip pearl industry in the Indo-Pacific region.

Chapter 4 is the first economic assessment of community-based pearl oyster spat collection and mabé pearl production in the Fiji with broader implications for the western Pacific. Cultured pearl production, and associated activities, are of crucial social and economic importance to remote coastal communities in Polynesia and the western Pacific. This study determined the potential profitability of (1) community-based pearl oyster spat collection operations targeting *P. margaritifera*, and the subsequent sale of pearl oysters to round pearl farms; and (2) the use of *Pt. penguin*, collected incidentally from *P. margaritifera* spat collection operations, for mabé pearl production.

Chapter 5 is the first study to investigate the economic feasibility of small-scale mabé pearl production in Tonga using *Pteria penguin*. This study determined establishment and operational costs of subsistence-level mabé pearl farming in Tonga and developed a whole-farm economic model to assess required scale and potential profitability of such operations. The modelled mabé pearl farm offers insight into the significant economic opportunity provided by mabé pearl culture and additional socio-economic benefits for rural communities involved in downstream activities (handicrafts, jewellery production, tourism). The economic model is an extension and training tool used in the sector and by government.

Chapter 6 reports the production cost of farm ready *Pt. penguin* oysters incurred by the Government used for mabé pearl culture in Tonga. The Tongan mabé pearl sector is developing rapidly, but its growth is tied to a routine supply of spat to mabé pearl farmers from the government hatchery, currently at no cost to the farmer. This is the first study to determine the costs of operating the government pearl oyster hatchery in Tonga and developed an economic model to assess the production cost of juvenile oysters (hatchery and nursery phase). The results will be valuable to key stakeholders and informs future government policy while having regional relevance for hatchery production of high-value aquaculture opportunities.

Chapter 7 provides the first economic comparison undertaken of two nucleus implanting arrangements, traditional and research-informed, that influences both mabé pearl production and profitability of mabé pearl farming in Tonga using *Pteria penguin*. The results of this study will help define the most profitable option for mabé pearl production in Tonga, supporting further development of the sector with broader regional significance.

This thesis is presented in a thesis-by-publication format. Each research chapter represents a succinct study that has been published. On this basis, there may be some repetition of content between chapters.

Chapter 2: Economic modelling of round pearl culture in Fiji and assessment of viable farm size

Data from this chapter were published as: **Johnston, W.L**, Hine, D. and Southgate, P.C. 2018. Economic modeling of round pearl culture in Fiji and assessment of viable farm size. *Journal of Shellfish Research*. 37(1): 79-91.

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers' comments, submission, and accepted publication in peer reviewed journal.

2.1 Introduction

The black-lip pearl oyster *Pinctada margaritifera* has a broad Indo-Pacific distribution from East Africa and the Red Sea to eastern Polynesia (Wada and Tëmkin 2008). Since the mid-1970s it has supported cultured pearl production in French Polynesia and the Cook Islands that was previously valued at up to USD 170 million per annum (Southgate et al. 2008). Pearl culture provides opportunity for export income and is the second largest contributor to GDP in French Polynesia after tourism. It also supports socio-economic benefits and employment in remote rural locations. On this basis, pearl farming is the Pacific regions most valuable and highest priority aquaculture activity (SPC 2007). Based on the success of pearl culture in Polynesia, recent years have seen development of pearl culture in western Pacific countries such as the Fiji Islands (Fiji) which, since 2000, has developed a round pearl export industry valued at up to USD 13 million per annum (Bolatagici 2016). The developing cultured pearl industry in Fiji has quickly gained a reputation for high quality pearls with a unique range of colours (Southgate et al. 2008, Kishore and Southgate 2016b). There is considerable opportunity for further expansion of the industry in Fiji and this is strongly supported by the Fiji Islands Government.

Round pearl production requires a skilled operation, generally called ‘seeding’, ‘grafting’ or ‘nucleation’, which is usually conducted by experienced overseas technicians. This involves the insertion of a single round nucleus into the gonad of a host pearl oyster, accompanied by a piece of the nacre secreting mantle tissue from a donor oyster (Taylor and Strack 2008). However, not all oysters presented by the farmer to the technicians are appropriate for pearl production and some may be rejected. Even after seeding, it is still common for oysters to reject the nucleus during subsequent culture, an occurrence referred to in the industry as a ‘vomit’. Successful seeding results in proliferation of the grafted mantle tissue around the nucleus to form the pearl sac (Kishore and Southgate 2016b), which begins nacre secretion onto the nucleus. A period of 18 to 24 months is usually required to produce a cultured pearl with appropriate nacre thickness (Blay et al. 2014). Once a pearl is harvested by a technician, a second nucleus may be inserted into the existing pearl sac, to produce a second pearl (Kishore and Southgate 2015; Demmer et al. 2016). This ‘reseed’ process can be done up to four times assuming appropriate quality pearls continue to be produced by the oyster. During the pearl culture period, oysters are tied to a rope using fishing line in series to form a ‘chaplet’ (Southgate 2008, Kishore and Southgate 2016b). Chaplets are then suspended from a longline holding the oysters in suspended culture, where they are periodically cleaned of fouling (Southgate 2008).

The grading of pearls is determined by the five characteristics of shape, size, lustre, colour, and surface perfection (Strack 2006, Matlins 2008). Quality of a cultured pearl relies on the skill of the technician and his/her seeding technique (Cochennec-Laureau et al. 2010, Ky et al. 2014). These skills influence post operation mortality of oysters, the nucleus rejection rate, and the quality (colour and grade) of the resulting pearls, reflecting appropriate selection of host oysters and saibo tissue from donor oysters (Scoones 1996, Wada and Komaru 1996, O’Connor 2002, Mamangkey et al. 2010). Pearls are the only gem without an internationally recognised grading system and therefore pearl grading is considered subjective (Strack 2006, Matlins 2008). The Tahitian system grades pearls from A to D, with descending quality, and is the common grading system for most cultured pearls produced in the south Pacific. Table 2.1 outlines the grading system used for round pearls.

Table 2.1 Overall grading of round pearls produced by *Pinctada margaritifera* incorporating assessment within five grading categories (shape, lustre, size, surface perfection and colour) (Strack 2006, Taylor and Strack 2008, Kishore et al. 2014).

Grade	**Shape**	**Lustre**	**Size (8-20 mm)**	**Surface Perfection**	**Colour**
A	Round	Very high lustre	Often larger than pearls in other grades	Very minor or no imperfection usually <5% of the total surface	Very bright and attractive colour
B	Round to Semi-round, Semi Baroque	High lustre	Variable, but generally larger than pearls in C and D grades	Minor surface imperfections usually <30% of the total surface	Brightly coloured
C	Baroque	Variable (medium) lustre	Variable	Notable surface imperfections that may include blemishes, dents, bulges and circles	Variable
D	Uneven shapes / presence of circles	Dull	Variable	Major surface imperfections. More than 60%	Variable

In terms of overall production, the proportion of 'A' grade pearls in a harvest might only be around 3%, and it is generally acknowledged that around 5% of pearls produced by a pearl farm in the Pacific generates around 95% of farm revenue (Haws 2000). The potential financial reward of pearl farming is coupled with significant risk, from factors other than pearl quality. Production of round pearls is commonly characterised by high capital investment, extended cashflow lags following establishment, significant exposure to production risks such as cyclones, disease and theft, and requires a high level of technical input. A major impediment to further development of this industry in Fiji is a lack of knowledge relating to establishment and operational cost of pearl farms, potential profitability compared to other rural activities, and inherent production and financial risks.

Few studies have investigated the economics of pearl farming worldwide, yet such information is of vital importance as a basis for long-term sector viability. For example, economic modelling recently demonstrated that potential profitability from half-pearl culture is far greater than that from spat collection and sales of pearl oysters to pearl farmers (Fong et al. 2005, Saidi et al. 2017). The aim of this study was to determine establishment and operational costs of active cultured round pearl farms in Fiji through a series of workshops attended by industry stakeholders. Workshops were held in 2013 and 2015 and yielded pearl farm economic data. The resulting information was used to develop whole farm economic models for round pearl production in Fiji, incorporating risk analysis, and provided a basis for determining minimum viable pearl farm size. The information generated will assist the Fijian Government in policy development for the sector, facilitate business establishment and industry expansion, and assist regional agencies and donor research organisations in prioritising funding and research activities.

2.2 Materials and methods

2.2.1 Generating inputs for the economic model

The information needed for the modelling was generated through a series of workshops with pearl farmers and other stakeholders, and one-on-one interviews.

2.2.2 Development of the economic model

The economic model was developed using cost-benefit analysis methodology incorporating a discounted cashflow framework over a 20-year period to ensure the model achieved a steady state, given the complexity of the production system (Johnston and Ponia 2006). The approach estimates the benefits and costs of an investment, or potential investment, to identify whether the benefits outweigh the costs of undertaking the investment. This method is also applied when choosing among a range of investment or project options (Nas 2016).

The economic model for round pearl culture uses a number of financial indicators to assess viability of the investment in this venture. The present value (PV) of the future stream of costs and benefits is calculated using the compound interest method. The rate used to calculate that present value is the discount rate. Subtracting the future value of costs from the future value of benefits is the Net Present Value (NPV), represented by the following equation (Kay et al. 2020):

$$\mathrm{NPV} = -\mathrm{INV} + \sum_{t=1}^{n} \frac{\mathrm{NCF}_t}{(1+i)^t} + \frac{\mathrm{SV}_n}{(1+i)^n} \tag{1}$$

where

INV is the initial investment;

NCF is the net cashflow (annual revenues less total fixed and variable costs, including capital costs);

n is the number of years for the life of the investment;

i is the discount rate;

t is time; and

SV is the salvage value.

The NPV was utilised to derive an equivalent annual return (EAR), or annual profit, for the pearl farm using the following equation:

$$\mathrm{EAR} = \frac{i * \mathrm{NPV}}{1 - (1+i)^n} \tag{2}$$

For the purpose of this modelling exercise, the discount rate was set at 6%, a reflection of the long-term domestic bond market in Fiji at the time of the modelling (cbonds.com). The Internal Rate of Return (IRR) provides an indication of the sensitivity of the project to changes in the discount rate, and is another financial indicator used in this study. The IRR defines the discount rate *i* at which the NPV in Equation 1 is set to zero. More simply, the IRR represents the maximum rate of interest that could be paid on all capital invested in a project. If all the funds were borrowed, and interest charged at the IRR, the borrower would break even, i.e., recover the capital invested in the project.

Annual benefits were estimated using revenues generated from the sale of pearls both internationally and domestically. Average prices across grades and types of pearls were estimated from a number of interviews with existing pearl farmers in Fiji. Sale of value-added products such as jewellery and handicrafts were not included in the analysis. All capital, variable and fixed costs were also estimated based on data collected from a range of business skilling workshops and one-on-one interviews with pearl farmers in Fiji between 2011 and 2015.

Finally, the stochasticity of the project was explored using Monte Carlo simulation. This method is used to assess risk in situations where significant uncertainty exists in multiple variables that are required to make a forecast or estimate. Monte Carlo simulations have a vast array of applications in fields that are characterised by random variables, such as agriculture and aquaculture production systems (Metropolis and Ulam 1949, Hardaker et al. 1997). In this instance, the critical and uncertain parameters of farm yield and average pearl price are used in the simulation which had five-point probability distributions applied. The simulations used data collected from the workshops and informed the assessment of risk for the 'viable scale' round pearl farm.

The equation for the Monte Carlo simulation used in this research is as follows:

$$\pi_i = \left(y_j + \left(\frac{y_{j+1} - y_j}{a_{k+1} - a_k} * (\mathrm{RY}_i - a_k) \right) \right) * \left(p_l + \left(\frac{p_{l+1} - p_l}{b_{m+1} - b_m} * (\mathrm{RP}_i - b_m) \right) \right) - \mathrm{TC} \qquad (3)$$

where

$$j\{k\{\mathrm{RY}_i\}\}\ and\ \ l\{m\{\mathrm{RP}_i\}\}$$

Profit is denoted π; *y* and *p* represent the two distributions of yield and price, respectively; *a* and *b* represent the probability distributions for *y* and *p*, respectively; RY represents the random number for yield; RP represents the random number for price; and TC represents the total annual cost of the pearl farming operation. The values *j* and *k* represent the distribution intervals, or 'bins', for yield and its associated probability distribution, where *j*+1 and *k*+1 are the upper limits of the bin. Similarly, *l* and *m* represent the same for the price distribution and its associated probability distribution, respectively. The sampled results for price and yield were then multiplied to generate a revenue sample from which all annual costs were deducted to produce an EAR. The simulation runs 10,000 iterations.

The round pearl whole farm tool developed in Excel was used in business skilling workshops in Fiji and incorporated a risk analysis model developed internally by the authors using Visual Basic language. This supported distribution amongst target coastal communities, associated government agencies and organisations, without requiring additional commercial risk analysis software. Incorporation of internal risk analysis software within the spreadsheet model greatly enhances the extension capability of the program throughout the Pacific, improving adoption and application.

Various methods have been employed to assist estimation of input risk distributions with a degree of confidence to reflect the risky environment of pearl farming. There were varying degrees of success. To improve the understanding of risk, and adoption of the model as a business tool, a separate Excel® tool was developed to better assist in the development of the price and production risk distributions. A 'Pearl Farming Risk Calculator' was developed, both as a training tool, and to improve autonomous risk assessments by pearl farmers. The risk calculator categorises price and production risk from severe to low as shown in Table 2.2.

Table 2.2 Risk categories for price and production.

Risk Category	**Description**
Severe	delivers 'zero' to 'poor' production or a minimum to poor price
Significant	delivers 'poor' to 'average' production and price outcomes
Moderate	delivers 'average' to 'good' production and price outcomes
Low	delivers 'good' to 'maximum' production and price outcomes

As an example, production risks that were identified as 'significant' during the workshops, delivering a 'poor' to 'average' production result included category 3 to 4 cyclones, significant flood events that reduced salinity to <25 ppt, chronic disease of oyster stock, and problems with oyster availability. Each was assigned a probability of occurrence and combined to provide the probability in the related distribution.

2.2.3 Modelling oyster flow

Modelling was based on the French Polynesian chaplet culture method (Southgate, 2008). One of the major challenges encountered in developing the economic model was the dynamic and complex nature of the progression of oysters through the farming operation over time (Figure 2.1). Modelling was based on the categories of oysters on farm as outlined in Table 2.3.

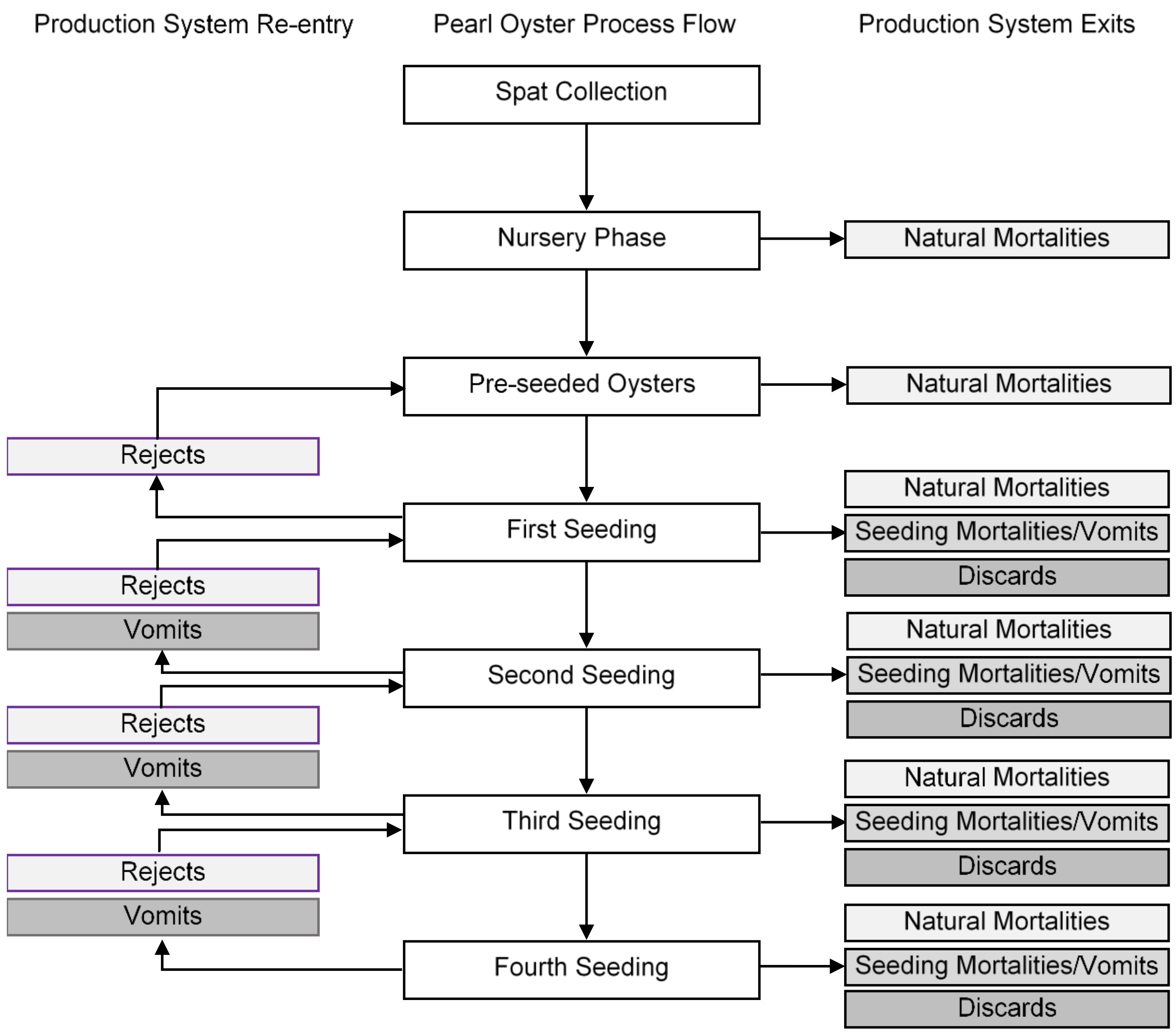

Figure 2.1 Process flowchart for pearl oysters through the farms production system for round pearl production in Fiji.

Table 2.3 Farm oyster categories.

Oyster Category	Description
Spat and Juveniles	Oysters that range from spat (small oysters taken from collectors in the wild) to a size that is almost ready for seeding. Age ranges from 1 to 24 months.
Pre-seedable	Oysters that have moved through the nursery phase on farm and are ready to be seeded at the next seeding or grafting event (commonly held twice a year). Age ranges from 24 to 36 months.
Seeded (first)	Oysters that have undergone their first seeding operation.
Seeded (second)	Oysters that have had their first pearl removed and a second larger nucleus implanted during seeding.
Seeded (third)	Oysters that have had their second pearl removed and a third larger nucleus implanted during seeding.
Seeded (fourth)	Oysters that have had their third pearl removed and a fourth larger nucleus implanted during seeding.

Given that there are six categories of oysters on the farm at any one time (Table 2.3), further complexity is added when considering other factors that determine whether an oyster is re-seeded. When an oyster enters the seeding shed for the first time a range of decisions will follow, that determine its flow through the farm during its life (Figure 2.1). If oyster condition is unsuitable for seeding it is rejected and reconsidered at the next seeding event or discarded. Seeded oysters are placed back out on the farm (Taylor and Strack 2008) for 18 months before pearls are harvested at the next seeding event. The seeding operation creates a level of mortality, due to the stress caused by the operation (Gervis and Sims 1992), which is considered in the modelling. If an oyster survives on the farm, and assuming nucleus retention, it will be return to the seeding shed for pearl harvest. The technician will again open the oyster to remove the pearl from the developed pearl sac. Further decisions based upon condition, quality of pearl harvested, and nucleus rejection are made at this time to determine whether the oyster is re-seeded with another nucleus, rejected, or discarded. This process will continue through the oyster's life on the pearl farm until it dies naturally or is discarded. A discarded oyster can be harvested for its meat and MOP (shell) (Chand et al. 2011).

Flow of oysters through the production system drives related elements of the modelling including the number juvenile oysters needed to maintain the desired farm scale, the number of nuclei required for seeding and the number of seeding operations. In Fiji, two annual seeding events occur, generally in March and September. The production system achieves steady state at approximately the 10-year point beyond which the proportions of first, second, third and fourth harvest pearls are stable.

2.2.4 Components of the economic model

2.2.4.1 Physical parameters

The scale of the model is set by entering a figure for the number of juvenile oysters that will enter the production system at inception of the farming project. The economic model calculates the number of pre-seedable and seeded oysters, estimating the total number of oysters required on the farm at any point in time. Other physical parameters set in the model include details of farming infrastructure, e.g., longlines including rope, anchors, buoys, and chaplets or panel nets (Southgate 2008). Information entered in this section of the model informs the capital requirements section of the economic model and sets area and density measures for the farm.

2.2.4.2 Farm labour

Farm labour is divided into four categories in the economic model:

- Technical assistants – casual or part time labour that is hired to assist seeding technicians during bi-annual seeding events. Payment is based on a weekly wage.

- Cleaning labour – casual or part-time labour hired to regularly clean oysters on the farm. Biofouling is a significant issue that increases operational and economic costs associated with pearl production and requires a significant proportion of farm labour to control (Pit and Southgate 2003, de Nys and Ison 2008, Bertucci et al. 2016).
- Permanent staff – full time labour hired to perform key farm duties, i.e., farm manager.
- Owner – drawings of the owner are accounted for in the farms total labour costs.

2.2.4.3 Seeding technician labour

Seeding technicians are brought in for bi-annual seeding events and are paid in numerous ways. The economic model allows for three options including payments based on a percentage of gross revenue received at harvest, a set value per oyster seeded with an optional bonus, or a set wage that can also include additional payment to cover travel, food, and accommodation. The most common form of technician payment in Fiji uses a set price per seeded oyster with an optional bonus based on pearl quality targets. Generic parameters are set in the model including the number of technicians required, seeding operations completed per day, harvest operations completed per day and the average number of days a seeding technician is required per year.

2.2.4.4 Marketing

The marketing section of the economic model sets out the breakdown of the harvest in terms of the types (shapes) of pearls harvested (Table 2.4), size of pearls harvested, and their quality based on the Tahitian grading system. The model provides additional capacity for users to describe pearls utilising the basic shape categories of cultured pearls based on the Akoya system (Lintilhac 1987, Strack 2006, Taylor and Strack 2008, Matlins 2008, Kishore 2015). Also considered in this section of the model are the marketing costs including advertising, auction, brokerage, and commission costs.

Table 2.4 Basic shape categories for round pearls. Modified from Strack 2006, Taylor and Strack 2008, Kishore and Southgate 2016b.

Shape	Description
Round and semi-round	A round pearl is one that is perfect, or close to perfect, spherical shape (considered rare and valuable) while a semi-round pearl looks round to the eye, appears symmetrical, but has some minor flaws where diameter varies by 2% to 5%.
Semi-baroque	Includes drop shapes (commonly described as teardrop shape – the neck or extension at one end of the pearl is generally caused by the incision by the grafting technician), pear shapes, and oval and button shapes (a pearl that has a flat surface on one side and is rounded on the remainder).
Baroque	Pearls that have a distinctly irregular shape and are asymmetrical.
Circles	A symmetrical pearl that has one or more parallel furrows running around the pearl perpendicular to its long axis (evidence suggests the shells byssus creates the phenomenon).
Keshi	A non-nucleated pearl with many unique shapes that is created when the nucleus is vomited.

2.2.4.5 Additional operating costs

This section of the economic model accounts for any additional operating costs not captured in the wider modelling exercise. These include fuel and oil, electricity, repairs and maintenance, accounting and legal, office and administration, government fees and charges, phone, travel, vehicle registrations and insurances.

2.2.4.6 Capital expenditure

Capital costs of round pearl farms are divided into nine main components: (1) land and buildings; (2) vehicles and machinery; (3) longlines, buoys and anchors; (4) culture units; (5) watercraft and associated equipment; (6) diving equipment; (7) lab and associated equipment; (8) seeding equipment; and (9) miscellaneous (e.g., tools). Capital equipment bought at farm inception is replaced at pre-determined periods over the 20-year life of the farming project. Replacement costs are estimated as the amount of money required to replace capital items, net of its salvage or trade-in value. The initial year of capital purchase is year-0, and the model assumes that all relevant capital is sold, and proceeds enter the cashflow as a revenue stream in year-20.

2.3 Results

2.3.1 Farming parameter inputs for the economic model

The information in this section describes outputs from workshops attended by Fijian pearl farmers and industry stakeholders and provides details of inputs used in the economic modelling exercise. All monetary values are expressed in US dollars (USD).

2.3.1.1 Physical parameters

An establishment phase of nine months was factored into the modelling that assumes first seeding occurred in September of the first year. A production period from seeding to harvest was selected at 18 months and the production method used was based on chaplets (Southgate 2008). Critical to the economic model is determination of the number of juvenile oysters present at the beginning of the farming operation; this was set at 60,000. An additional input requirement was to set the number of oysters required for each seeding event; this was set at 15,000 (excluding older oysters returning for re-seeding operations). Tables 2.5 and 2.6, respectively, outline the physical parameters related to oyster numbers and the production infrastructure required to support them.

Table 2.5 Farm oyster numbers at steady state.

Oyster Category	Number of Oysters
Total number of oysters on farm	112,906
Number of juvenile oysters	60,000
Number of pre-seedable oysters	15,000
Number of seeded	37,906

Table 2.6 Longline infrastructure and associated oyster numbers.

	Seeded	Pre-seedable	Juveniles
Number of longlines	38	8	1
Total length of longlines (metres)	3,800	800	100
Number of oysters per longline	998	1,875	60,000

2.3.1.2 Seeding and mortality

The economic model sets seeding parameters relating to progression of oysters through the production system including seeding mortalities, retention rates and number of saleable pearls resulting from a seeding event. Table 2.7 shows the parameters used in the modelling. It is not until year three that any pearls are harvested, and it is not until mid-way through the farms life that pearl production achieves a steady state (Figure 2.2).

Table 2.7 Seeding parameters and grow out mortality.

	Seeding Number	
	First Seeding (%)	**Reseeds (2-4) (%)**
Rejects	10	6
Vomits	10	6
Seeding mortality	15	10
Grow out mortality	5	3
Retention rate	35	16.2
Saleable pearls	50	20

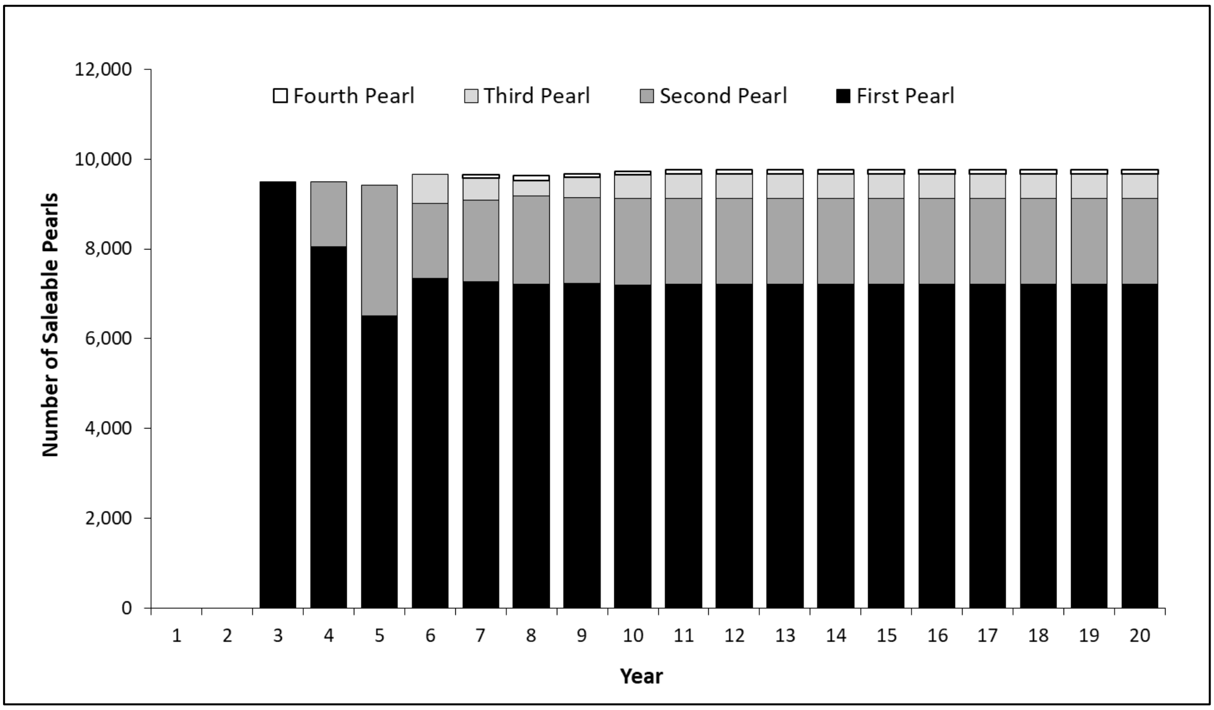

Figure 2.2 Number of saleable pearls produced over the life of the farming operation.

2.3.2 Cost inputs for the economic model

2.3.2.1 Juvenile requirements

New juveniles are required each year to replenish the farms oyster stocks. The number of juveniles required is based on the estimated number of pre-seedable oysters required at future seeding events, with a correction for losses. An expected survival rate was set at 60%, i.e., if 10,000 oysters are required at seeding and only 60% are expected to survive to be seeded, then

16,667 (10,000 / 0.6) would be required to achieve the desired target. Juveniles are sourced from external spat collection operators and supplied at a cost of USD 1.00 per juvenile. The number of juveniles required annually over the life of the farm are shown in Figure 2.3.

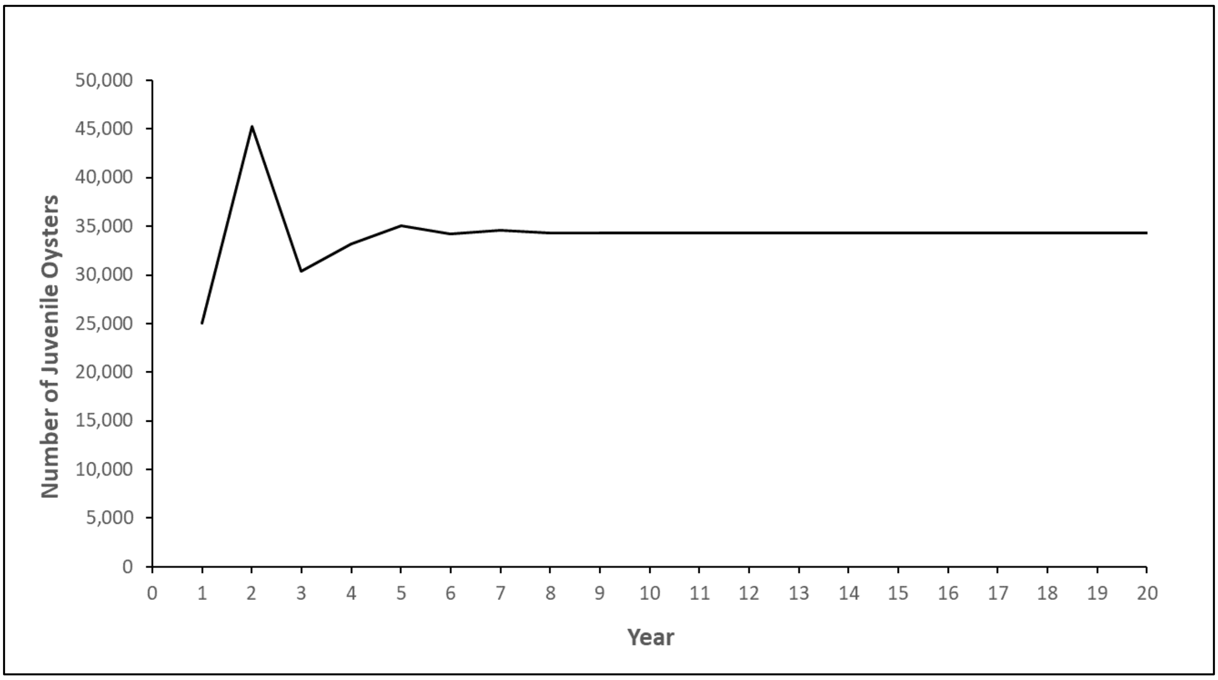

Figure 2.3 Annual number of juvenile oysters required to supply seeding events.

2.3.2.2 Nuclei

The modelled dynamic production system estimated the number of nuclei required at each seeding event from first implant through to numbers required for a fourth implant. Estimated cost of nuclei over this period are shown in Table 2.8. The total number of nuclei required annually, and their cost is shown in Figure 2.4.

Table 2.8 Cost per nucleus across seeding sizes ($ in USD).

Nuclei Seeding Category	Price per Nucleus ($)
Nuclei for first seeding	0.51
Nuclei for second seeding	1.08
Nuclei for third seeding	1.67
Nuclei for fourth seeding	5.00

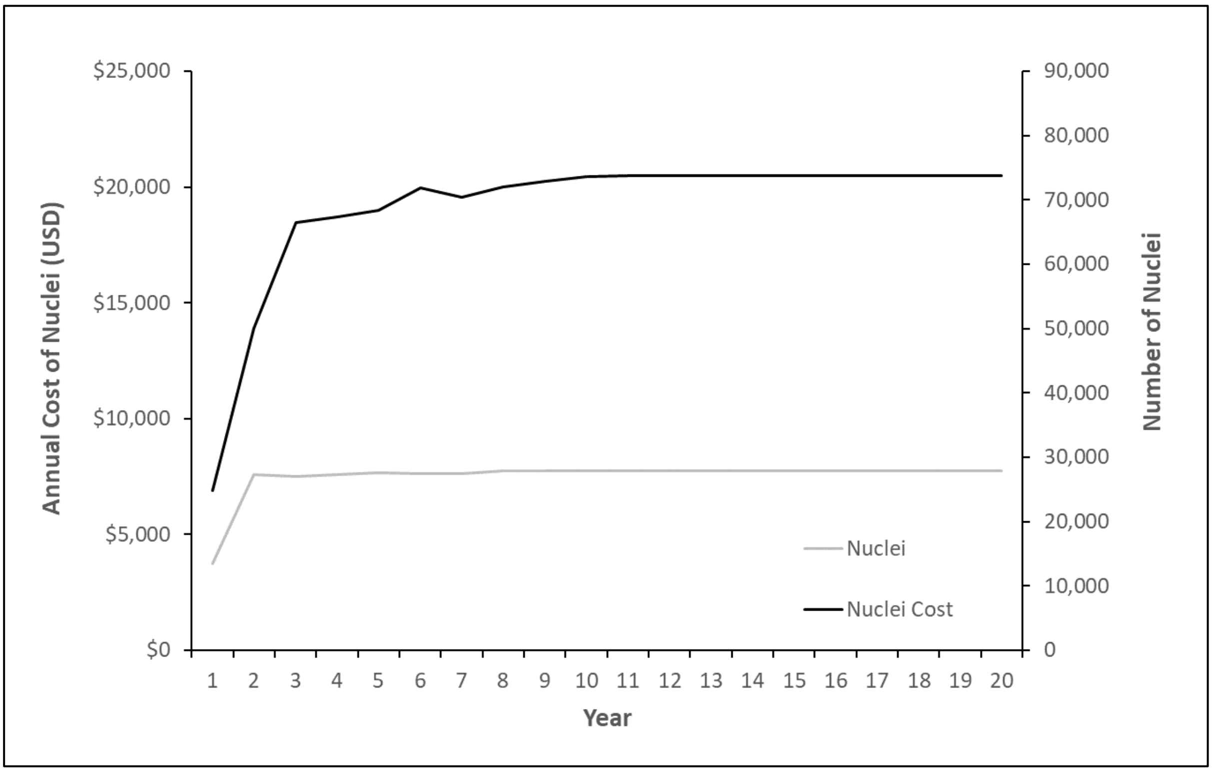

Figure 2.4 Annual number and cost of nuclei required for seeding events ($ in USD).

2.3.2.3 Marketing

Marketing of Fiji pearls is split in to two market segments, with A-grade and B-grade pearls, across all shapes, sold to international buyers. Pearl size also influences price and the average size of Fijian pearls from first to fourth pearls, i.e., first seed of an oyster through to its third re-seed that produces a fourth pearl are shown in Table 2.9. Many harvested pearls are of a low quality and high quality flawless round pearls represent only around 5% of saleable pearls (Kishore and Southgate 2016b). The highest average price used in the model was USD 650 for an A-grade 14 mm round pearl, while the lowest price was USD 8 for a B-grade 10 mm baroque pearl. Across all pearl sizes, 25% A-grade and 50% B-grade were assumed for the purpose of this model. The remaining 25%, graded C and D, are sold domestically. The average wholesale prices for various pearl shapes and sizes used in the model are shown in Table 2.10.

Table 2.9 Average size and weight of saleable pearls.

Seeding Number	Size (mm)	Weight (g)
First	10.0	0.80
Second	11.5	1.00
Third	12.5	1.10
Fourth	14.0	1.30

Table 2.10 Average wholesale prices for Fijian black pearls from first pearl to fourth pearl ($ in USD).

Shape	First ($)	Second ($)	Third ($)	Fourth ($)
Rounds	50.00	87.50	162.50	275.00
Semi-baroques	32.50	62.50	112.50	162.50
Circles	20.25	26.25	37.50	50.00
Baroques	21.50	26.25	37.50	50.00

2.3.2.4 Seeding technicians

For the purpose of this modelling exercise, a flat rate of USD 2.56 per operation was used to cover all costs including the seeding operation, airfares, accommodation, food, visas and any taxes a technician may incur. On an annualised basis, the model round pearl farm spends USD 67,812 per year (USD 7.77 per saleable pearl) on seeding technicians, and this represents the largest portion of annual operating costs at 35.45% (Figure 2.5).

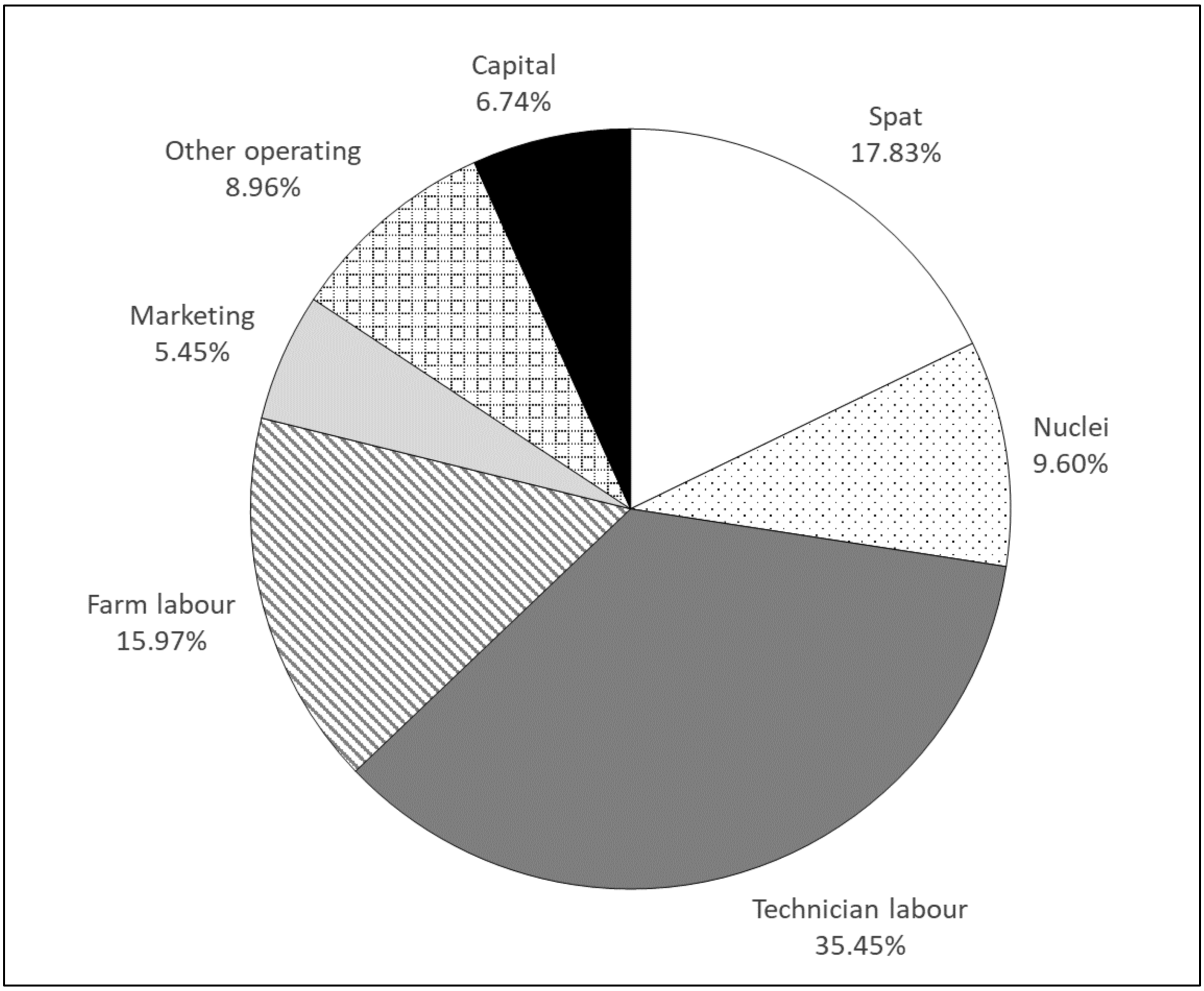

Figure 2.5 Proportion of total annual costs attributable to key cost items.

2.3.2.5 Other labour

The remaining labour component of the model farm consists of six permanent employees paid USD 80 for a 40-hour working week (average wage rate in Fiji is USD 2.00 per hour), equating to an annual cost of USD 23,040 (allowing for four weeks of holiday). In addition, the model assumes the owner will draw USD 7,500 per annum. In the Pacific, labour is treated as non-value good, assuming that drawings will only be realised when the business generates sufficient profit (Johnston and Pickering 2003). This approach underestimates the true cost of labour. If the enterprise returns a profit solely based on unpaid labour, then the decision to undertake that enterprise would be based on false economies (Johnston and Pickering 2003).

2.3.2.6 Other operating

All miscellaneous costs used in the model are shown in Table 2.11.

Table 2.11 Additional annual operating expenditure ($ in USD).

Cost Item	**Annual Cost ($)**
Fuel, oil, and electricity	3,150
Repairs and maintenance	4,538
Training	1,000
Travel	5,000
Lease fees	2,500
Vehicle expenses	400
Sundries	450
Total	**17,038**

2.3.2.7 Capital expenditure

Capital costs of the pearl farm comprised three main components: land and buildings, production infrastructure and equipment, and vehicles and machinery. A small parcel of land is purchased for storage of equipment, office space and other onshore activities. The remainder was allocated to infrastructure such as living quarters and a pearl seeding facility. The total cost of land and buildings is USD 20,050. Additional equipment and infrastructure required for the model farm are shown in Table 2.12. Vehicles and machinery required for the model farm are listed in Table 2.13 and are purchased second hand. The residual value, representing the total cash salvaged at the end of the project from the sale of capital items, was USD 21,515.

Table 2.12 Infrastructure and equipment costs ($ in USD).

Item	Purchased Value ($)	Salvage Value (%)	Year of Purchase / Replacement
Longline rope	2,820	0	0,10
Anchor rope	9,024	0	0,10
Anchor blocks	2,840	0	0
Buoys (large)	1,880	0	0,10
Buoys (small)	1,880	0	0,5,10,15
Chaplet rope	5,738	0	0,10
Chaplet other	3,405	0	0,5,15
Juvenile Centre Turn Knot	10	0	0,5,10,15
Diving air compressor	15,000	20	0,10
Scuba tanks	1,600	0	0,3,6,…,18
Wet suits	400	0	0,2,4,…,18
Personal diving equipment	500	0	0,5,10,15
Microscope	500	0	0,10
Computer	1,000	0	0,5,10,15
Seeding tables	100	0	0,5,10,15
Workshop tools and equipment	250	10	0,5,10,15
Water pressure cleaner	400	10	0,5,10,15
Miscellaneous	270	0	0,2,4,…,18
Total	**47,617**		

Table 2.13 Vehicle and machinery costs ($ in USD).

Item	Purchased Value ($)	Salvage Value (%)	Year of Purchase / Replacement
Utility	10,000	40	0,10
Boat(s)	7,000	40	0,10
Outboard(s)	8,000	20	0,5,10,15
Total	**25,000**		

2.3.3 Economic model output summary and economic indicators

2.3.3.1 Farm output summary

The Fijian viable scale pearl farm produced 8,723 saleable pearls annually. Of the saleable pearls produced 32% were rounds, 21% were semi-baroque, 33% were circles, and 14% were baroque. Annual gross revenue from the sale of pearls totalled USD 347,634 (USD 39.85 per saleable pearl), while annual production costs totalled USD 191,271 (USD 21.93 per saleable pearl) (Table 2.14).

Table 2.14 Breakdown of annual production costs ($ in USD).

Cost Item	Annual Cost ($)	Cost per Pearl ($)
Oyster stock	34,095	3.91
Nuclei	18,362	2.11
Technicians	67,812	7.77
Farm labour and drawings	30,540	3.50
Marketing	10,429	1.20
Other annual operating	17,133	1.96
Capital purchase and replacement	12,900	1.48
Total	**191,271**	**21.93**

2.3.3.2 Net Present Value (NPV)

NPV over the 20-year life of the project, using a set discount rate of 6% (based on the long-term rate at the time of study in Fiji), was USD 1,793,465. As shown in Figure 2.6, the model indicates that it would take five years to recoup the original investment in the project.

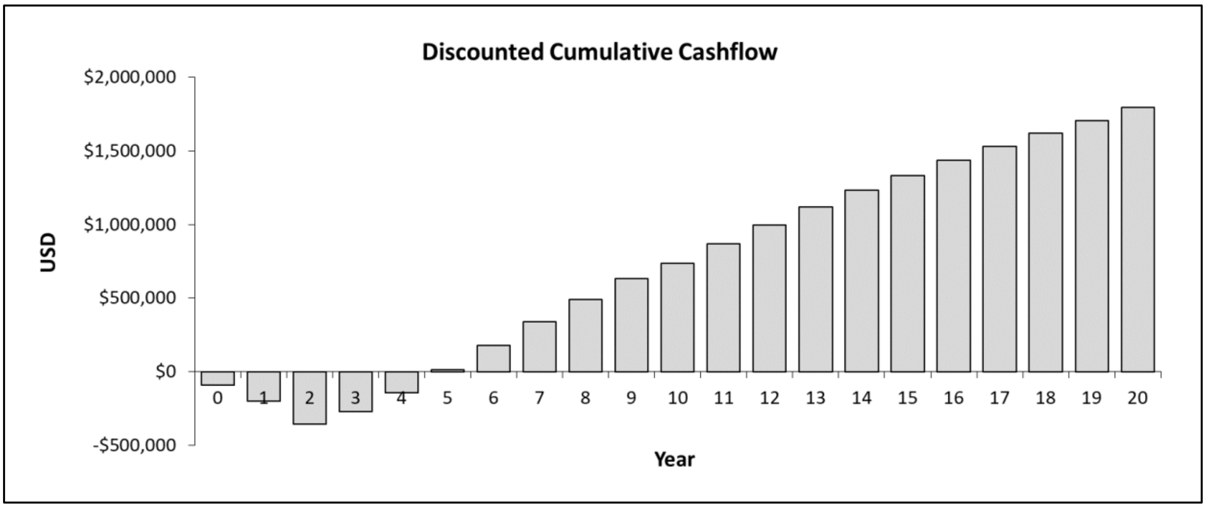

Figure 2.6 Discounted cumulative cashflow for the Fijian viable scale pearl farm ($ in USD).

2.3.3.3 Annual profitability

Measurement of pearl farm profitability was based on equivalent annual return (EAR = annualised NPV) and IRR. The results of the analysis are shown in Table 2.15 with some additional economic indicators. EAR was USD 156,362 and the IRR was 36.12%. The benefit-cost ratio (BCR) was 1.83 meaning that for every dollar (USD) invested in the project USD 1.83 is returned. The payback period, at the point where discounted cashflow becomes positive, was five years (Table 2.15).

Table 2.15 Summary of profitability results and other economic indicators ($ in USD).

Measure	Result
EAR ($)	156,362
IRR	36.12%
BCR	1.83
Payback period	5 years

2.3.3.4 Risk analysis

Risk analysis focused to two key parameters, price and production and five-point distributions were used for both variables (Table 2.16). In both distributions, the average point is derived from the outcomes already described in the farm output summary above. Minimum production is zero because in Fiji, cyclones and disease could potentially wipe out annual pearl farm production. Pearl farmers indicated that a 'poor' production result would be approximately 10% of expected production levels, hence 872 saleable pearls. The 'maximum' point in the distribution of pearls was set at 10,000 as the pearl farmers indicated that the models expected outcome of 8,723 pearls would be difficult to exceed in both number of pearls produced and the number of years that it might occur. The 'good' point in the distribution for production was estimated as the midpoint between the 'average' point and the 'maximum' point.

Table 2.16 Production and price distributions with associated cumulative probabilities ($ in USD).

Description	**Production (No. of Pearls)**	**Cumulative Probability (%)**
Minimum	0	0
Poor	872	15
Average	8,723	65
Good	9,200	85
Maximum	10,000	100
Description	**Price per Pearl ($)**	**Cumulative Probability (%)**
Minimum	29.70	0
Poor	34.78	15
Average	39.85	65
Good	44.93	85
Maximum	50.00	100

The average price for a saleable pearl from the viable scale pearl farm was USD 39.85. This was used to set the 'average' point in the distribution. The maximum price to be received for a saleable pearl was set at USD 50.00, based on stakeholder inputs. Remaining distribution points were based on midpoints between the 'average' and the 'maximum', and the 'average' and the 'minimum'. Probabilities were determined following stakeholder input to identify and categorise risks from severe to mild, and their probabilities of occurrence. Simulation output is the EAR. The highest EAR was USD 295,406, while the lowest was -USD 190,765 (Figure 2.7). The average EAR produced by the simulation was USD 29,463. Incorporation of production and price risk reduced the expected EAR from USD 156,362 per annum to USD 29,463. The probability of the viable scale pearl farm making a loss (where the distribution intersects the y-axis; Figure 2.7) is approximately 42%.

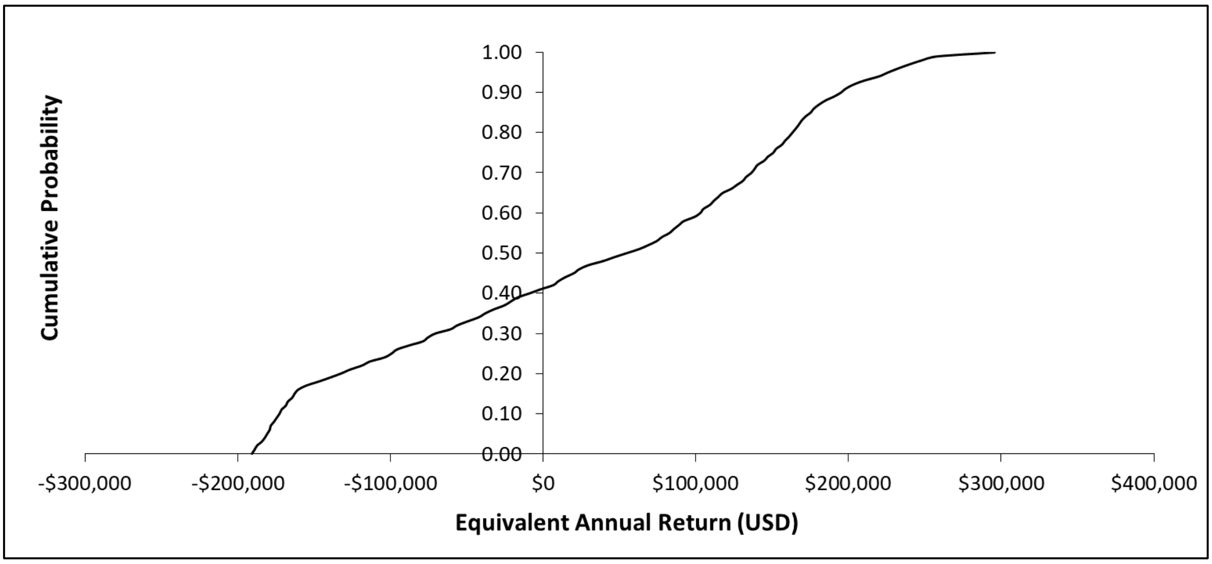

Figure 2.7 Cumulative probability distribution for EAR (variables: price and production) ($ in USD).

2.4 Discussion

The aim of this chapter was to determine establishment and operational costs for round pearl culture in Fiji, and to estimate a viable scale farm size. Development of a viable scale whole farm model was initiated to serve as a guide to industry participants, stakeholders, government departments, research organisations and donors, regional extension agencies and NGOs, describing the inputs required to establish and maintain a viable round pearl farm in Fiji. Economic information pertaining to pearl farming in the south Pacific is sparse, providing little or no guidance in the development of a farming profile. On this basis, the information generated in this study is vital for sustainable development of the Fijian cultured pearl industry. It will assist in the establishment of new farms, expansion of current farms, and will inform development of a policy framework by the Government of Fiji to support industry expansion. To provide some context, the largest farm in Fiji, J Hunter Pearls (Fiji), seeded approximately 100,000 oysters in 2016 (Justin Hunter, J Hunter Pearls, Fiji, *pers. comm.* 2016). The second largest, Civa Fiji Pearls, seeded only 7,000 oysters in 2015 (Claude Prevost, Civa Pearls, *pers. comm.* 2015). The results of this study suggest a viable scale farm requires annual seeding of a minimum of 30,000 oysters per year.

Only one prior study (Fong et al. 2005) discusses the economic feasibility of black-lip round pearl culture in the Pacific (Republic of the Marshall Islands and the Federated States of Micronesia). The motivation for their study was to stimulate private sector economic development with a view to reducing reliance on foreign aid and government support (Fong et al. 2005). The basis for their economic modelling was a pearl farm containing 25,000 seeded oysters at any point in time, which is similar to the scale of the Fijian pearl farming model developed in the current study. Similar to the current study, Fong et al. (2005) used a 20-year timeframe, but with a higher discount rate of 8%. Some of the key findings from their study were an upfront capital investment of USD 202,076, producing an NPV of USD 102,944 with an IRR of 9.6% (Fong et al. 2005). This capital investment is nearly twice that reported here for the Fijian viable scale farm, but it included over USD 100,000 for land and buildings, including living quarters for technicians and 12 labourers. The estimated Fijian investment in similar items in the present study, was USD 23,000 in wages for six labourers, with seeding technicians building in the cost of hotel accommodation or similar. Although the capital investment is higher in the Fong et al. (2005) model, the analysis showed that it is profitable, but margins were smaller due to the significant costs of labour and seeding that represented 66% of the total production cost, compared to 51% in the present Fijian model. With an NPV of USD 102,944, and using the 8% discount rate, the EAR for the Fong et al. (2005) model farm was USD 10,485. The NPV for the Fijian model, using a 6% discount rate, was considerably higher at over USD 1.7 million with an EAR of USD 156,362. Recalculation of the Fijian model using the same discount rate as the Fong et al. (2005) model (8%), only reduced the EAR by 7.7% to USD 144,309. An IRR of 36.12% in the Fijian model developed in the current study indicates that an investor could borrow the capital required at that interest rate and still break-even. Additionally, the Micronesian model of Fong et al. (2005) had a four-year lag before any cash inflow is realised compared to three years for the Fijian model developed in the current study.

The Micronesian pearl farming model (Fong et al. 2005) and the Fijian model developed in the present study have similar production costs of USD 19.15 per pearl in Micronesia, and USD 21.93 per pearl in Fiji. The average price per pearl, across all grades, shapes and implant number for the Fijian model is USD 39.85, while the average price across first to third implants was approximately USD 21.42 in Micronesia. Fong et al. (2005) stated that the market prices used were conservative, with a 50% discount, based on saleable pearl quality from two farms in the region and international pearl prices at the time. The Fijian pearl pricing matrix used in the present study is based on actual sales data from all Fijian pearl farmers that attended the workshops in 2013, with follow-up one-on-one interviews in 2015. Fijian pearl farmers and Government have invested significant time and effort into differentiation of their product, from that of mass-produced (measured in tonnes) pearls from French Polynesia, through colour and quality (Figure 1.9). Targeted marketing campaigns by Fijian stakeholders, and tight controls over the quality of exported pearls sold in the international marketplace (Johnston et al. 2014), meant no discounts were applied to Fijian pearl prices.

Fong et al. (2005) recognised that low potential profitability could be reduced by training locals in pearl seeding techniques to reduce reliance on specialist and costly overseas technicians. A similar approach has been trialled in Fiji with at least two farms; both demonstrated limited success and poor pearl yield and quality. The Fijian pearl sector is likely to be reliant on overseas pearl seeding technicians for many years into the future, although training of local seeding technicians is a desirable development and is likely to be an increasingly important consideration in a number of Pacific nations.

2.4.1 Considering risk for pearl farming in Fiji

Future development of the round pearl farming sector in Fiji is unlikely to attract significant new entrants, and farms that do establish are likely to have some level of foreign interest. The Fijian viable scale farm model developed in this study sets the bar high in terms of production compared to current farming effort and provides a robust blueprint for round pearl farming in Fiji. At the expected production level where everything goes to plan, the Fijian model generates a significant annual income of USD 156,362. The Fijian model has a payback period of five years and generates a benefit cost ratio of 1.83. That is, for every dollar invested in the project, USD 1.83 is returned. These results do not consider the riskiness of the activity. Profit margins are susceptible to the significant risks including disease events, destructive cyclones, theft, and fluctuating market prices. A pearl farm, while potentially facing losses in some years, must compensate for those potential losses with consistent cashflows in other years. The potential impacts of risks were accounted for in this study using stochastic modelling (Monte Carlo simulation), that showed the Fijian viable scale pearl farm could still generate an average income of USD 29,463 and realise losses in four in ten years despite facing significant risks. While 81% is a significant drop in the EAR, it represents significant profit, above all costs, for an operation in the context of other aquaculture and agricultural practices in Fiji. For example, according to the most recent survey in 2008-09 by the Fiji Bureau of Statistics, rural household incomes were approximately USD 5,800.

2.4.2 Constraints to pearl farm establishment in Fiji

The common denominator for the stifled expansion of the Fijian cultured pearl industry since 2000 was a lack of access to capital to establish effective operations, grow their businesses, and survive the early years when cashflow is lacking. New entrants do not often have the scale to attract technicians, or purchase resources at reasonable market prices because they cannot buy in bulk. Commonly, small pearling operations rely on larger operations for support, access to skilled technicians and resources, as well as imparting knowledge and skills. In French Polynesia, many pearl farms are grouped in relatively close proximity, forming economic interest groups, or Groupement d'Intérêt Economique (GIE) (Hisada and Fukuhara 1999); however Fijian round pearl farms are spatially dispersed which limits potential benefits relating to scale and resource sharing. This is complicated further by the lack of clear title and tenure for marine farming areas that are often subject to traditional access rights. Interestingly, the four current round pearl exporting farms have some degree of foreign investment and support which assists access to resources, but most importantly, capital. Indigenous Fijians find it difficult to access capital from local lending institutions, particularly for aquaculture businesses. In Fiji, a business is required to have appropriate insurances, their business accounts certified, and some level of collateral appropriate to the size of their loan.

Chapter 3: Cost-benefit analysis of two culture methods that influence pearl production from the black-lip pearl oyster, *Pinctada margaritifera*

Data from this chapter were published as: **Johnston, B.**, Hine, D., Kishore, P. and Southgate, P.C. 2019. Cost–benefit analysis of two culture methods that influence pearl production from the black-lip pearl oyster, *Pinctada margaritifera*. *Journal of the World Aquaculture Society*. 50(3): 510-521

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers' comments, submission, and accepted publication in peer reviewed journal.

3.1 Introduction

Cultured round pearl production using the black-lip pearl oyster, *P. margaritifera*, in Polynesia, relies primarily on collection of oysters from the wild using spat collectors (Arnaud-Haond et al. 2003, 2004; Southgate et al. 2008), and subsequent grow-out of the resulting oysters to pearl-producing size. Oysters are then 'seeded' or 'grafted' for pearl production (Taylor and Strack 2008; Blay et al. 2014), then typically cultured for a further 18-24 months before resulting pearls are harvested. Once a pearl is harvested by a technician, a second nucleus can be inserted into the existing pearl sac, to produce a second pearl (Kishore and Southgate 2015; Demmer et al. 2016). This 'reseed' process, referred to as 'surgreffe' in French Polynesia, can be done up to four times assuming appropriate quality pearls continue to be produced by an oyster.

Pearl farmers have a number of options regarding the culture method and culture units, used to hold pearl oysters during the pearl production phase of their operation (Gervis and Sims 1992, Southgate 2008). Perhaps the simplest is the "ear-hanging" method which was adapted initially from the Japanese scallop culture industry (Gervis and Sims 1992). It involves drilling a small hole (2–3 mm) through the base of the pearl oyster shell in the dorsal-posterior region, which is used to attach the oyster to a rope using monofilament fishing line or wire (Gervis and Sims 1992, Southgate 2008). A number of oysters are usually attached to a single rope, either singly or in pairs, to form a 'chaplet' (Friedman and Southgate 1999, Ky et al. 2016), and chaplets are attached directly to either a raft or surface longline (Gervis and Sims 1992, Southgate 2008). The advantages of this chaplet-based culture method include low set-up and maintenance costs, due to greatly reduced equipment outlay, and improved water flow and food availability because oysters are not enclosed within a culture unit. Chaplet-based pearl oyster culture is widely practiced in French Polynesia and has provided a basis for a considerable volume of pearl industry specific research, reported over recent years by the French Research Institute for Exploitation of the Sea (Ifremer) and associated agencies, working towards pearl industry improvement in French Polynesia (e.g., Ky et al. 2016 and related publications). Chaplet-based pearl oyster culture is well suited to the relatively protected atolls of Polynesia where predation is minimal. However, chaplet-based pearl oyster culture is less suited to other pearl culture regions where pearl oysters are exposed to both adverse environmental conditions and greater threats from predators such as fish, crustaceans, molluscs, and turtles (Humphrey 2008; Pit and Southgate 2003). In Australia and south-east Asian countries, for example, pearl oysters are predominantly cultured using panel (pocket) nets that are made from strong steel or galvanized frames supporting mesh pockets that hold the oysters (Gervis and Sims 1992, Southgate 2008).

Commercial round pearl production using *P. margaritifera* was established in Fiji in 2000, using spat collection and chaplet-based culture methods, similar to those used in French Polynesia (Kishore and Southgate 2016b, Kishore et al. 2018). Like French Polynesia, the overall quality of round pearls produced in Fiji is reduced by the occurrence of pearls with ‘circles’ (Kishore and Southgate 2016b); concentric depressions or grooves on their surfaces (Ito 2009), that can considerably reduce the value of a pearl crop. In the Tuamotu Archipelago of French Polynesia, for example, circled pearls account for 23% of production volume but only 6% of their value (Ky et al. 2015b). Prior research has shown that *P. margaritifera* cultured on chaplets produce a higher proportion of pearls with circles than oysters held in panel nets (Kishore and Southgate 2016b). Pearl farmers seek to produce high quality ‘A-grade’ round pearls (very high lustre, very minor or no surface imperfections, and are bright and colourful) as opposed to other shapes and grades (B to D). The proportion of round shaped pearls resulting from panel net-based culture was 6.25% compared to 5.34% for chaplet-based culture, and panel net-based culture produced a much higher proportion of ‘A-grade’ pearls

(Kishore and Southgate 2016b). This difference between culture methods was thought to result from increased byssus secretion by oysters held on chaplets because of their reduced stability compared to those in panel nets. The authors argued that pearls produced by pearl oysters held in panel nets would provide better returns and higher profit margins for pearl farmers, but they noted the greater capital outlays for infrastructure and potentially higher operational costs of this method may be prohibitive for prospective farmers (Kishore and Southgate 2016b).

Whole-farm modeling supports the determination of set-up and operational costs of round pearl farming in Fiji and can ultimately provide assessments of minimum viable farm size (Chapter 2). The model does not include lease costs of marine production space but includes land purchases for terrestrial operations. Such models allow prediction of the economic impacts of changes in culture methodology, a potentially valuable decision-making tool for pearl farmers (Saidi et al. 2017). While Kishore and Southgate (2016b) confirmed that panel net-based culture of *P. margaritifera* resulted in improved pearl quality and value compared to chaplet-based culture, they also suggested that a detailed cost-benefit analysis of the two husbandry options would be beneficial to round pearl farmers. There are no prior reports in the primary literature assessing the relative economic benefits of different culture methods for round pearl culture from *P. margaritifera*. Based on a minimum farm size of approximately 50,000 mature oysters (Chapter 2), the aim of this study was to compare the relative economic benefits of pearl production in Fiji employing chaplet-based and panel net-based culture methods using cost-benefit analysis. Given the broad use of chaplet-based pearl oyster culture in a number of countries (Southgate 2008, Ky et al. 2016) our results will have broad application in assisting both existing and prospective pearl farmers with decision making about appropriate culture method, in the context of upfront capital investment, technical skill level required and operational costs, and potential profits generated.

3.2 Materials and methods

The economic model developed in this study used data generated by Kishore and Southgate (2016b) that reported relative quality of pearls produced, from a first pearl harvest, by *P. margaritifera* cultured using both chaplet-based and panel net-based culture methods. The life of the pearl farms modelled in this study was set at 20 years, and therefore had to account for subsequent pearl reseeds. However, because Kishore and Southgate (2016b) only reported first harvest results, actual production quality data from other current Fijian pearl farms were used in the model to represent production from second, third and fourth pearl harvests. These data accounted only for differences in operational and infrastructure costs between methods and did not account for pearl production differences between methods.

3.2.1 Data collection

Data for this study were collected through a series of interactive workshops attended by pearl farmers and pearl industry stakeholders in Fiji, which yielded baseline pearl farm economic data reported in section 2.2.2. The resulting data were used in this Chapter to develop representative economic models to compare chaplet-based and panel net-based culture methods. A chaplet consists of ten seeded oysters, each suspended by 25 cm of fishing line on a 1.5 m dropper rope from the main longline which is 100 m in length (Southgate 2008). In comparison, panel nets hold eight oysters and are suspended directly from the main longline in a similar fashion. As detailed in the preceding section, the models were based on comparative pearl production data from chaplet-based culture and panel net-based culture reported by Kishore and Southgate (2016b) and included gross revenue from pearl sales and annual production costs, both fixed and variable. From these data, the model generated comparative results for net present value (NPV), equivalent annual return (EAR, a derivative of NPV and a measure of annual profitability), internal rate of return (IRR), BCR and payback period as defined in section 2.2.2.

3.2.2 Modeling software and analysis

The modeling software used in this study is an extension of a model developed by Johnston and Ponia (2006) for analysis of cultured round pearl production in Pacific Island nations (Tisdell and Poirine 2008, Johnston et al. 2014, Queensland Department of Agriculture and Fisheries 2023). The economic model used for the cost-benefit analysis incorporates a discounted cashflow analysis over a twenty-year period to ensure the model achieves a steady state, given the complexity of the round pearl production system (Saidi et al. 2017, Chen et al. 2017, section 2.2.2).

The economic model for round pearl culture uses a number of financial indicators to assess the viability of investment in a venture. The present value (PV) of the future stream of cost outflows and cash inflows over twenty years is calculated using the compound interest method. Subtracting the future sum of cost outflows from the sum of future cash inflows generates the NPV (Shang 1990, Saidi et al. 2017, Chen et al. 2017, section 2.2.2), and the annuity of this figure provides the EAR, a measure of annual profitability. This method is commonly applied when choosing among a range of investment or project options (Nas 2016). The rate used to calculate present values is known as the discount rate (opportunity cost of funds). For the purpose of this modeling exercise, the discount rate was set at 6%, a reflection of the long-term domestic bond market in Fiji at the time of the study (cbonds.com, 2018). Additionally, the IRR provides an indication of the sensitivity of the project to changes in the discount rate, and is another financial indicator used in this study (Saidi et al. 2017, Chen et al. 2017, section 2.2.2). More simply, the IRR represents the maximum rate of interest that could be paid on all capital invested in a project. For example, if all the funds were borrowed, and interest charged at the IRR, the borrower would break even, that is, recover the costs of the project. Thus, IRR is an important indicator of the 'investability' of a venture.

Data inputs to the model include the costs associated with longline farming infrastructure (e.g., ropes, floats, anchors, etc.), pearl production and husbandry (e.g., panel nets or chaplets, pearl nuclei, pearl technicians, oyster cleaning tools etc.), marketing, labour and farm operating costs. Values shown in this study are United States dollars (USD) with values calculated from actual costs in Fijian dollars (FJD) using an exchange rate of 1 USD = 2 FJD.

3.2.3 Comparative economic models

Kishore and Southgate (2016b) implanted 600 first seed oysters for pearl production (mean 112 mm dorso-ventral measurement); 300 were then held using the chaplet-based method and 300 using the panel net-based method. Pearls were harvested after 18 months of oyster culture and graded (Kishore and Southgate 2016b). The resulting pearl grades are described in Table 3.1, and these data provide a basis for the cost-benefit analysis comparison of the two culture methods undertaken in this study.

Table 3.1 The percentage (%) of saleable pearls across grades (A, B, C, D) and four pearl shapes resulting from chaplet-based and panel net-based pearl oyster culture methods, reported by Kishore and Southgate (2016b).

Pearl Shape [a]	Grade			
	A	B	C	D
Chaplet-based Culture				
Round / semi-round	3.05	2.29	0	0
Semi-baroque	0	16.41	0	0
Circles	0	11.07	47.33	0.38
Baroque	0	0	1.53	17.94
Panel Net-based Culture				
Round / semi-round	6.25	0	0	0
Semi-baroque	2.21	23.16	0	0
Circles	0	23.53	21.69	0
Baroque	0	0	16.18	6.99

[a] Pearl shape descriptions: round/semi-round - a round pearl is one that is perfect, or close to perfect, spherical shape (diameter varies by 2-5%); semi-baroque - includes drop shapes, pear shapes, and oval and button shapes; baroque - have a distinctly irregular shape and are asymmetrical; circles - symmetrical pearl that has one or more parallel furrows running around the pearl perpendicular to its long axis (Strack 2006).

The average wholesale (raw pearl – without value adding) prices across grades and types of pearls used in this study are drawn from data supplied by Fijian pearl farmers. The market for round Fijian *P. margaritifera* pearls is considered 'niche' where global demand exceeds supply, creating a market environment where pearl prices are relatively stable. The prices used in this analysis represent wholesale long-term averages (since 2011) for Fijian round pearls sold on the international market. Sale of value-added pearl products such as jewellery and handicrafts are not included in the analysis. All capital, variable and fixed costs are also estimated based on data collected from stakeholder workshops, including follow-up one-on-one interviews with pearl farmers in Fiji.

The two different culture methods require a different level of investment and influence the operational costs of the pearl farm. Key economic inputs that vary between culture methods include capital investment, preparation and cleaning time for labourers, marketing (calculated as% of revenue earned) and repairs and maintenance (% of capital investment). Costs for panel nets were provided by the pearl farmer who operates the farm that collaborated in the study by Kishore and Southgate (2016b), and who is experienced in both culture methods.

3.3 Results

A summary of the production and infrastructure inputs and key costs for the modelled chaplet-based and panel net-based farms is provided in Table 3.2. General differences in infrastructure and operational costs between the two culture methods impact a number of areas. The capital cost of making chaplets (USD 0.75) is less expensive than the upfront purchase of panel nets (USD 9.00). A key husbandry requirement for both culture methods is regular cleaning of oysters (removal of biofouling) to maintain their health (de Nys and Ison 2008). Cleaning of oysters is carried out every two months (6 times per year) regardless of the culture method. Using panel net-based culture reduces the time (4 min per panel net) required to clean oysters, compared to chaplets (10 min), which reduces estimated annual farm labour costs by USD 6,861 (Table 3.3 and Table 3.4). The cost of repairs and maintenance, calculated annually as a percentage of capital investment, is higher for the panel net-based farm (USD 7,008) compared to the chaplet-based farm (USD 4,500). International marketing costs of pearls is calculated as a percentage of annual gross revenue. The correlate between pearl value and marketing cost stems from the reality that auction and brokering costs are set as a percentage of value, making them variable and linked to quality. Due to the improved shape and grade of pearls, the marketing cost is higher for the panel net-based farm (USD 8,544) compared to USD 7,611 for the chaplet-based farm (Table 3.4).

Repairs and maintenance costs, and marketing costs, were both calculated as direct percentages in the whole-farm modeling and vary directly with shifts in revenue and capital investment. While changes in repairs and maintenance, and marketing costs are important factors, it is the upfront expenditure (and future replacement costs) required for panel net-based culture, and the impact they have on labour resources that will likely influence a change in farming practice for round pearl farmers.

3.3.1 Capital impacts

The chaplet-based method had an initial capital outlay of USD 3,405, compared to panel nets that require an upfront investment of USD 49,394 (Table 3.2). Importation of panel nets to Fiji cost USD 6.80 per net with a total cost of USD 9.00, after duties and taxes. Considering the requirement for dropper ropes are the same for the two methods, in this study chaplets are costed on the basis of drilling (including labour) and materials only. Considering wear on the drill, drill bits, and electricity, the cost of each chaplet is set at USD 0.75. The traditional chaplet-based culture method is relatively inexpensive at establishment (USD 90,033) compared to panel net culture (USD 140,163) (Table 3.2). Annualized farm costs show that capital expenses (including upfront purchase and replacement costs over the 20-year life of the modelled farms) for chaplet-based culture (USD 12,538) are approximately half that of panel net-base culture (USD 24,033) (Table 3.4).

Table 3.2 Production parameters, infrastructure, and other key costs and inputs used to develop whole-farm economic models for round pearl farming in Fiji ($ in USD).

Parameter	Number or Value
Production Parameter	
Total number of oysters on farm	112,906
Number of seeded oysters on farm	37,906
Production time (months) from seeding to harvest	18
Seeding events per year	2
Number of nuclei required annually	27,915
Total hectares of farm production area	7.95
Percent mortality of seeded oysters after first implant	20%
Percentage of saleable pearls in the first harvest	50%
Number of annual cleaning events	6
Capital Investment	
Upfront capital required for chaplet-based culture ($)	90,003
Upfront capital required for panel net-based culture ($)	140,163
Culture Infrastructure	
Number of longlines required	47
Number of buoys required	470
Number of anchors required	454
Number of chaplets required	3,791
Number of panel nets required	4,738
Total upfront cost of materials to build chaplets ($)	3,405
Upfront purchase cost of panel nets ($)	49,394
Labour	
Number of seeding technicians required per event	2
Seeding cost per oyster ($)	2.56
Number of farm labourers employed	6
Weekly wage per labourer ($)	80
Annual drawings of owner ($)	7,500
Annual Production Costs	
Chaplet-based culture ($)	187,958
Panel net-based culture ($)	196,033
Other Infrastructure Required	
Land and buildings	
Vehicles and boats	
Diving equipment	
Lab and seeding equipment	

3.3.2 Farm labour impacts

The chaplet-based pearl farm (with approximately 50,000 mature oysters) employs six permanent staff to assist in the day-to-day operations of the farm. Table 3.3 summarizes the time required to build a chaplet or fill a panel net and maintain them (cleaning – removal of biofouling) each year. Both panel nets and chaplets are cleaned nine times over the production cycle of 18 months i.e., cleaning events occur every two months, or six times per year.

Table 3.3 Differences in annual labour resources for chaplet-based and panel net-based pearl culture methods required to construct (chaplet) or fill (panel net) pearl production apparatus and annual maintenance (cleaning - removal of biofouling), and their costs for round pearl culture in Fiji ($ in USD).

	Chaplet-based	**Panel net-based**
Construction (minutes)	24	8
Annual cleaning (minutes)	60	24
Total number of apparatuses on-farm	4,541	5,488
Total labour minutes – build and clean	381,444	175,625
Total labour hours – build and clean	6,357	2,927
Cleaning labour cost ($)	12,715	5,854
Total annual farm labour cost ($)	**30,540**	**23,679**

Table 3.4 Annualised cost structure for chaplet-based and panel net-based culture methods for round pearl farming operations in Fiji ($ in USD).

Commodity / Activity	**Chaplet-based ($)**	**Panel Net-based ($)**
Juvenile oysters	34,095	34,095
Nuclei	18,362	18,362
Seeding technicians	67,812	67,812
Farm labour	30,540	23,679
Marketing	7,611	8,544
Fuel and energy	3,150	3,150
Repairs and maintenance	4,500	7,008
Other operating	9,350	9,350
Capital	12,538	24,033
Farm total	**187,958**	**196,033**
Total per pearl	**21.55**	**22.47**

The Fijian wage rate used in this study is USD 2.00 per hour and, although the length of a typical working week can vary for pearl farm employees, a working week of 40 hours was assumed in our modelling. Use of panel nets, compared to chaplets, saves an estimated 3,430 hours (USD 6,860) of labour per year over six cleaning events, equivalent to 1.8 labourers (Table 3.3).

3.3.3 Economic modelling output summary and economic indicators - comparative output summaries

The comparative annual cost structures of chaplet-based and panel net-based pearl farms are shown in Table 3.4. The revenue generated from each farm is based on the same number of harvested pearls which is 8,723 annually (Chapter 2). Based on results from Kishore and Southgate (2016b), shown in Table 3.1, the composition of the pearl harvest, in terms of pearl shape and grade, is improved when using panel nets. Table 3.5 describes the total annual harvest of saleable pearls, across pearl shapes, and apportioned revenues.

The average annual production cost per pearl, across all grades and shapes, is USD 22.47 for the panel net-based farm and USD 21.55 for the chaplet-based farm (Table 3.4). Average revenues per saleable pearl for the panel net-based farm and chaplet-based farm are USD 32.65 and USD 29.08, respectively (Table 3.5).

3.3.4 Net Present Value (NPV)

NPV over the 20-year life of the project, using a discount rate of 6%, is USD 754,005 for the chaplet-based farming operation, and USD 1,018,227 for the panel net-based operation. The model indicates that it would take eight years to recoup the original investment in the chaplet-based farm (Figure 3.1), and seven years for the panel net-based farm (Figure 3.2).

Table 3.5 Distribution of harvested pearls across graded shapes and associated annual revenues for chaplet-based and panel net-based pearl oyster culture methods ($ in USD).

	Chaplet-based		Panel net-based	
Pearl Shape	**Number**	**Gross Revenue ($)**	**Number**	**Gross Revenue ($)**
Round	1,824	142,795	1,844	153,772
Semi-baroque	1,297	32,055	1,890	46,013
Circle	4,103	38,313	3,205	28,398
Baroque	1,499	40,532	1,744	56,624
Farm total	8,723	253,695	8,723	284,807
Total per pearl		**29.08**		**32.65**

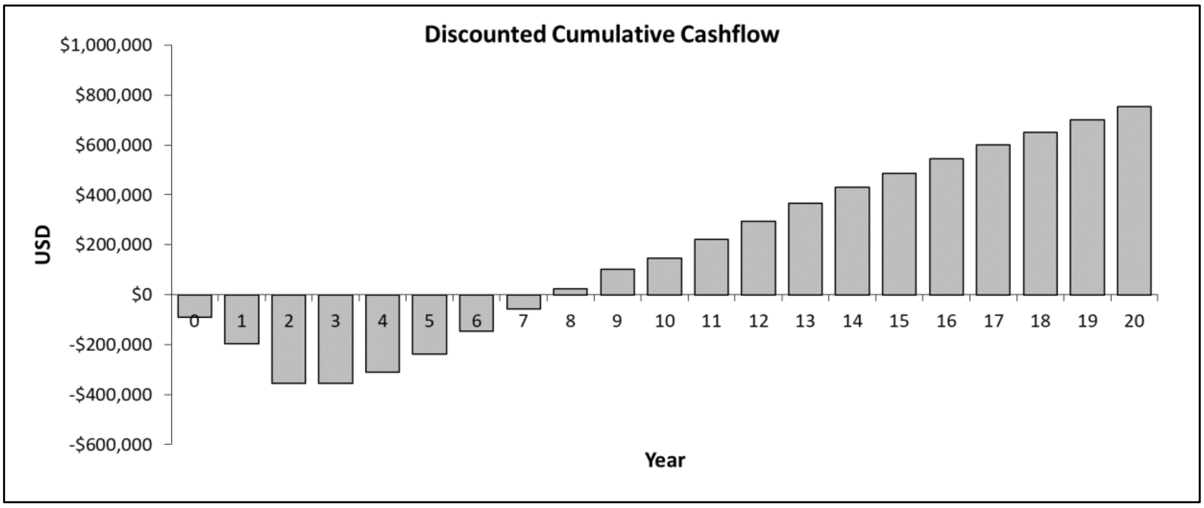

Figure 3.1 Discounted cumulative cashflow for the chaplet-based round pearl-farming operation (Fiji) modelled in this study ($ in USD).

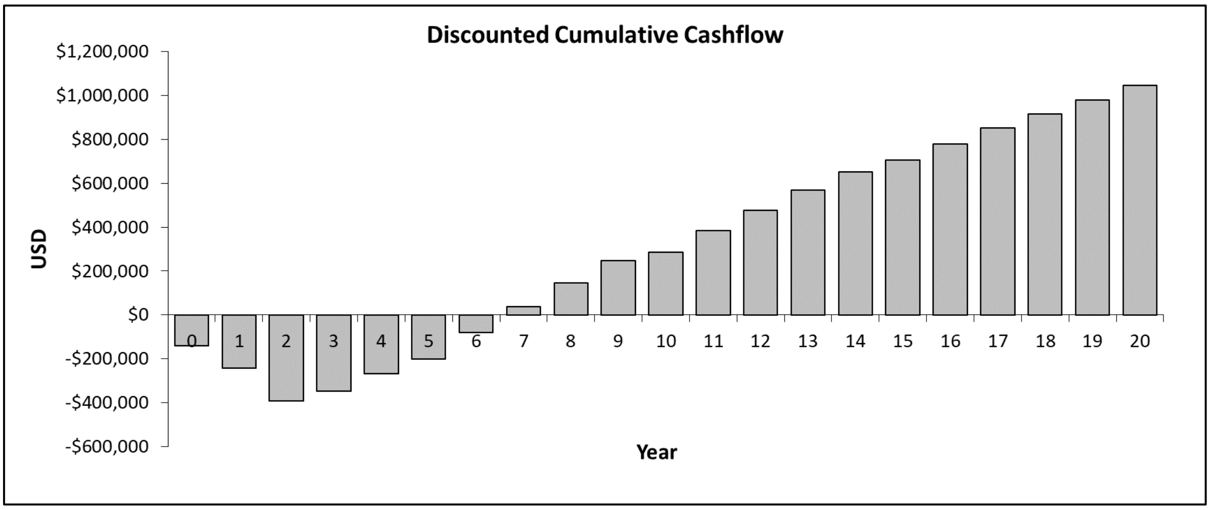

Figure 3.2 Discounted cumulative cashflow for the panel net-based round pearl-farming operation (Fiji) modelled in this study ($ in USD).

3.3.5 Annual profitability

Measurement of pearl farm profitability is based on EAR and IRR. The results of these analyses are shown in Table 3.6 with some additional economic indicators. For the chaplet-based and panel net-based farms the EAR is USD 65,738 and USD 88,774, respectively, IRR is 20.35% and 23.10%, respectively, and the BCR (total benefits divided by total costs) is 1.35 and 1.45, respectively, that is, every dollar invested in the chaplet-based farm would return USD 1.35 over the life of the farm. These figures present reasonable returns on investment, though what is presented in the model are operational values that do not account for the purchase price or lease cost of the space occupied by the farm.

Table 3.6 Summary of profitability results and other economic indicators for chaplet-based and panel net-based pearl oyster culture methods in Fiji ($ in USD).

Economic Measure	Chaplet-based	Panel Net-based
EAR	65,738	88,774
IRR	20.35%	23.10%
BCR	1.35	1.45
Payback period	8 years	7 years

3.4 Discussion

Economic information relating to establishment and maintenance costs, and potential profitability of pearl farming is very scarce (Tisdell and Poirine 2008). This is the first comparison in the primary literature of the relative economic benefits of pearl production by *P. margaritifera* using different culture methods. Results showed that pearl farming using both chaplet-based and panel net-based culture methods would recover the initial upfront capital investment and make a profit, supporting the viability of the two culture-based ventures. The payback period of the panel net-based farm (7 years) is one year ahead of the chaplet-based operation (8 years), despite higher upfront capital investment and increased maintenance associated with panel net-based culture. In terms of annual profit, the panel net-based farm would generate an EAR 35% higher than the chaplet-based farm. Kishore and Southgate (2016b) showed that culture method has an impact on the shape and quality of resulting pearls, and on overall pearl grades. Substitution of these harvest results into the whole-farm viable scale model, described in Chapter 2, shows that panel net-based culture of *P. margaritifera* improved gross revenues by 12%. As mentioned above, our economic modeling was based on pearl quality and production data from first seeded *P. margaritifera* (Kishore and Southgate 2016b) and actual production data from other current Fijian pearl farms was used in the model to represent subsequent pearl production. This approach will likely underestimate the revenue generated using panel net-based culture, compared to chaplet-based culture. Size, quality and value of cultured pearls generally improves subsequent to the first harvest (Kishore and Southgate 2015) and would likely further improve annual revenue streams for panel net-based culture compared to chaplet-based culture, beyond first pearl harvest.

Differences between chaplet-based and panel net-based pearl oyster culture are most evident for farm labour resources used in cleaning of culture apparatus, upfront capital purchase and replacement costs, marketing, and repairs and maintenance costs. Increases in marketing costs and repairs and maintenance costs are a linear function of the increase in revenues and capital costs of the operation. The panel net-based farm, compared to the chaplet-based farm, had increased marketing costs (calculated as 3% of gross sales for both modelled farms) of 12%, and higher repairs and maintenance costs of 56%, based on the greater upfront purchase cost of panel nets. The upfront capital cost of purchasing and importing panel nets is USD 49,394 compared to the capital cost of constructing chaplets (USD 3,405). Total capital expenditure, including land, but excluding the lease cost of marine production space, for a panel net-based farm at inception is USD 140,163, of which panel nets comprise 35.2%. In comparison, upfront capital expenditure for a chaplet-based farming operation is USD 90,003, of which chaplets compose 3.8%.

Chapter 1 identified significant barriers to entry into round pearl farming in Fiji of relevance to the broader western Pacific. Many smaller operators struggle to access the capital they require to establish farms and overcome the significant cashflow lags that exist in the initial years of a round pearl farming operation. Considering lower upfront capital investment, smaller operations are likely to maintain the traditional chaplet-based culture method, despite the higher potential long-term profitability of panel net-based culture. It may however be feasible to gradually replace chaplets and transition to panel net-based culture as the venture progresses toward profitability. In this way the venture could reinvest returns, rather than rely on debt financing, which comes at a high interest rate (often 18-25%) throughout the Pacific, which is similar to the IRR indicated in this study.

One of the major husbandry activities associated with marine pearl farming is removal of biofouling from oysters (de Nys and Ison 2008, Lacoste et al. 2014b, Pit and Southgate 2003). Most pearl farms in Fiji employ local indigenous labourers to remove epibionts attached to oyster shells and culture infrastructure. As chaplets comprise oysters attached to a dropper line, suspended from a longline, they are more difficult to handle and take longer to clean. Each chaplet takes ten minutes to clean (one minute per oyster), while panel nets which hold oysters in pockets, within a rigid frame, require four minutes to clean (30 sec per oyster). This efficiency gain in farm labour is significant and reduces annual farm labour cost by 22.5% (Table 3.3), or 1.8 full-time equivalent staff. While labour efficiency is not beneficial for local employment opportunities, particularly in rural Fiji, efficiencies gained here allow resources to be deployed to other areas of the pearl farming operation such as collection of oyster spat (Kishore et al. 2018), half-pearl production (Kishore et al. 2014), or scaling-up the farm. Small family groups or coastal communities that operate small-scale pearl culture operations could benefit from panel net-based culture because the time saved, compared to chaplet-based culture, could be utilized elsewhere to support the family or community group (i.e., terrestrial farming, fishing, and other livelihood activities).

3.5 Conclusions

Established and prospective pearl farmers in the Pacific have options regarding the culture methodology they adopt. Results of this study show that pearl production from *P. margaritifera* housed in panel nets provides direct long-term economic benefits, compared to traditional chaplet-based culture. While farm operating costs were similar between the two culture methods, labour efficiencies in panel net-based culture offset the higher capital, maintenance, and marketing costs of this culture method. The improved quality of first pearls from panel net-based culture, provided a 12% increase in revenue, compared to chaplet-based culture, overcoming the greater annual operating costs (4.3% higher than chaplet-based culture).

Establishment of a round pearl farm in the western Pacific would be better placed to utilise panel nets rather than chaplets, given the greater profitability that it generates over the longer term. However, investment decisions are not only guided by long-term profitability. Consideration must be given to entry barriers such as significant upfront capital investment and the reality that capital to fund pearl farms is inherently difficult to access, particularly in Fiji (Chapter 2). The fact that chaplet-based operations would generate over USD 65,000 in annual profits, compared to the average annual rural household income of USD 5,800 in Fiji (Fiji Bureau of Statistics, 2008-09), does not make this investment choice redundant for potential entrants (Johnston and Pickering, 2003).

Chapter 4: Economic assessment of community-based pearl oyster spat collection and mabé pearl production in the western Pacific

Data from this chapter were published as: **Johnston, B.,** Kishore, P., Vuibeqa, G.B., Hine, D. and Southgate, P.C. 2020. Economic assessment of community-based pearl oyster spat collection and mabé pearl production in the western Pacific. *Aquaculture*. 514: 734505.

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers' comments, submission, and accepted publication in peer reviewed journal.

4.1 . Introduction

Pearl farming is the Pacific's regions most valuable and highest priority aquaculture activity (SPC, 2007; Ponia 2010). Round pearl production from the black-lip pearl oyster, *Pinctada margaritifera*, has been well established in Polynesia since the mid-1970s but has only been established commercially in Fiji since 2000 (Southgate et al. 2008). Hatchery production of *P. margaritifera* pearl oysters makes a relatively small contribution to culture stock in both French Polynesia and Fiji, and round pearl production throughout the south Pacific relies almost exclusively on collection of oysters from the wild using spat collectors. Methods for pearl oyster spat collection are simple and well established (Haws and Ellis 2000, Southgate 2008, Kishore et al. 2018), and involve deployment of 'spat collectors' made from appropriate materials (such as rope, frayed rope and shade-cloth) to a depth of 2-8 m at a suitable oceanic site. Spat collectors provide a substrate for pearl oyster recruitment, and after a period of 6-15 months, juvenile oysters can be harvested from them. This activity can be accomplished by groups of local people, commonly coastal communities, with minimal training using cheap and readily available materials. It provides opportunity for income generation through the sale of resulting *P. margaritifera* oysters to pearl farms for round pearl production (Arnaud-Haond et al. 2003, Andréfouët et al. 2012, Kishore et al. 2018, Southgate et al. 2019). Recent expansion of the round pearl sector in Fiji generated increasing demand from pearl farmers for *P. margaritifera*, and stimulated development of a national pearl oyster spat collection program to improve supply of oysters to the sector (Kishore et al. 2018). Nearly 30 Fijian community groups, many driven by organised women's collectives, now generate income from the sale of *P. margaritifera* to round pearl farms, with incomes ranging from USD 520-2,640 per crop (Southgate et al. 2019, Southgate et al. 2023).

Together with *P. margaritifera*, a second species of pearl oyster, the winged pearl oyster *Pteria penguin*, also recruits to spat collectors in Fiji (Kishore et al. 2018). *Pt. penguin* has limited value to round pearl farmers but is traditionally used for production of 'half-pearls' or mabé pearls (Gordon et al. 2019; Taylor and Strack 2008). The availability of *Pt. penguin* as a by-product of spat collection activities in Fiji, provides potential for community-based mabé pearl production (Southgate et al. 2019). Mabé pearls are produced by adhesion of hemi-spherical nuclei to the inside surface of *Pt. penguin* shells, and subsequent coverage of the nuclei with nacre during a culture period of up to 15 months (Gordon et al. 2019). Compared to round pearl production, mabé pearl production is uncomplicated and can be taught to community members with appropriate training (Southgate et al. 2019). Seven Fijian coastal communities have so far been trained for mabé pearl production and five of these have produced at least one crop of pearls. Women's groups make up 57% of the communities currently engaged in mabé pearl farming in Fiji with each crop generating more than USD 1,200 (Southgate et al. 2019).

Prior economic assessment of pearl production in the Pacific has been poorly reported in scientific literature and is generally limited to broad overviews of regional or country-specific round pearl production (e.g., Tisdell and Poirine 2008). Pearl oyster culture, and associated activities such as spat collection, is of crucial social and economic importance in supporting habitation of remote and isolated islands in French Polynesia (Arnaud-Haond et al. 2003). Similarly, in Fiji, spat collection and associated mabé pearl production offers considerable income generating opportunities supporting livelihoods for rural coastal communities in remote parts of the country (Southgate et al. 2019). Yet despite this potential, no prior study has reported set-up costs, operational costs or potential profitability of either pearl oyster spat collection or mabé pearl production in the Pacific, nor investigated the potential cumulative benefits of vertically integrated operations that undertake both activities.

The aim of research in this Chapter was therefore to develop economic models to assess the feasibility of two pearl industry-based livelihoods activities in Fiji: (1) community-based pearl oyster spat collection operations targeting *P. margaritifera*, and the sale of resulting oysters to round pearl farms; and (2) the use of incidentally collected *Pt. penguin* for mabé pearl production. The models estimate potential income generation from these community activities over a 20-year horizon and the outputs provide valuable new information for prospective pearl oyster spat and mabé pearl farmers, donors, funding bodies and other stakeholders. The models provide valuable extension tools supporting further development of the pearl sector in Fiji with relevance to pearl producing counties in the broader Indo-Pacific region.

4.2 Material and methods

The fundamental basis for the economic modelling utilised in this study was first applied to assess round pearl production in Fiji and mabé pearl production in Tonga (Johnston et al. 2014, Johnston et al. 2015, section 2.2.2), as well as subsistence level pearl oyster spat collection and mabé pearl production in Tanzania (Saidi et al. 2017). The cost and price data used to inform the economic modelling was based on information collected during recent surveys in 2018 and 2019 and contemporary knowledge of ongoing community-based spat collection operations and working mabé pearl farms in Fiji.

4.2.1 Development of the economic model

Economic models for spat collection and mabé pearl production in Fiji were developed using cost benefit analysis (CBA) methodology incorporating a discounted cashflow framework over a twenty-year period with a standard discount rate as outlined in section 2.2.2. The economic indicators used in this Chapter include the NPV, EAR, BCR and the payback period (years) (section 2.2.2). However, the IRR methodology applied in section 2.2.2 was replaced with a

Modified Internal Rate of Return (MIRR) in this chapter. This more accurately reflects expected rates of return around cash outlays as it takes in to account the expected finance rate in the business environment, and the expected rate of return on invested positive cash inflows. The MIRR in this Chapter is calculated using micro-credit loan rates in Fiji that were at 19% (Bank of the south Pacific, www.bsp.com.fj, 2019) and business savings interest rates that were 0.50% at the time of this study.

Estimated benefits for both economic models were developed using revenues generated from the sales of black-lip pearl oyster (*P. margaritifera*) juveniles to round pearl farms, and the sale of mabé pearls, in separate models. All capital, variable and fixed costs were estimated based on data collected directly from established spat collection farms and mabé pearl producers in Fiji.

Finally, the stochasticity of the mabé pearl farm was explored using Monte Carlo analysis (section 2.2.2). The critical and uncertain parameters of pearl farm yield and average pearl prices had five-point probability distributions applied, utilising data collected from operational farms (Southgate et al. 2019), that was used to inform the risk assessment framework for mabé pearl production. The sampled results from the simulation for price and yield were then multiplied to generate a revenue sample from which all costs were deducted to produce an estimate of NPV.

Whole farm modelling incorporating risk analysis was developed internally by the authors using the Visual Basic language (section 2.2.2). Incorporation of internal risk analysis programming within the spreadsheet model greatly enhanced the extension capability of the program, avoiding commercial software requirements while improving adoption and application in rural areas of the Pacific.

4.2.2 Spat collection methods and infrastructure requirements

Pearl oyster spat collection requires deployment of specialised substrates to the ocean and subsequent harvest of oysters after an appropriate duration of immersion. Pearl oyster spat farms in Fiji utilise specialised commercially available spat collectors purchased from a Chinese supplier (Honor Stand Enterprise Limited, Zhejiang, China), and their importation and supply to spat farms is facilitated by Ministry of Fisheries, Fiji (MFF). This service is provided by MFF in support of the pearl culture sector. Costs of these imported infrastructure items, including relevant taxes and duties, were included in the economic modelling. Commercially available, factory standard, spat collector units consists of a 200 m long-line (16 mm nylon rope) to which 620 individual spat collectors are attached at 300 mm intervals. Each spat collector consists of black perforated ribbon sewn concertina-style (Haws 2002) onto an 8 mm diameter black rope in lengths of 1 m (Kishore et al. 2018, Figure 4.1). Each factory standard spat collector unit (200 m) is cut in half so that the standard unit used for pearl oyster spat collection in Fiji is 100 m long and contains 310 individual spat collectors. Spat collector infrastructure is deployed to the ocean for a period of 12 months when oysters are harvested, and infrastructure is checked and monitored on a monthly basis. Equipment and operational costs associated with the spat collection farming, and used in this economic model, are outlined in Table 4.1. The average price for pearl oysters sold to round pearl farmers was set at USD 1.18 and this price applies to both *P. margaritifera* sold to round pearl farms, and to *Pt. penguin* transferred for use in community-based mabé pearl production (opportunity cost).

Figure 4.1 Commercial spat collectors used for community-based spat collection in Fiji consist of a 100 m longline to which 310 x 1-m long individual plastic spat collectors are attached (Photo courtesy of Dr Pranesh Kishore).

Table 4.1 Equipment and operational costs associated with pearl oyster (*Pinctada margaritifera* and *Pteria penguin*) spat collection in Fiji. Costs based on a minimum wage of USD 1.26 per hour ($ in USD).

Production Parameter			
Total length of spat collection long-lines			4 x 100 m
Number of spat collectors			1,240
Time from deployment to oyster harvest			12 months
Expected number of oysters per collector			2
Expected mortality after collection			1%
Total annual saleable oysters (both species)			2,455
Capital Investment in Collection Infrastructure	**Units**	**Cost per Unit ($)**	**Total Value ($)**
Long-lines	400 metres	0.36	144
Anchor lines	960 metres	0.27	259
Spat collection droppers	1,240 droppers	0.50	620
Anchors	16 anchors	0.70	11
Buoys	32 buoys	6.58	211
Annual Labour Commitment	**Units**	**Cost per Unit ($)**	**Total**
Deployment			8 hours
Monitoring			120 hours
Harvesting			160 hours
Brokering			4 hours
Annual labour cost	292 hours	1.26	368

The scale of the economic model is set by entering a figure for the number of spat collector long-lines used for pearl oyster spat collection. Our modelling is based on standard 100 m spat collection units (with 310 individual spat collectors), with four units representing a standard operating spat collection business or community group. Other physical parameters set in the model include details of farming infrastructure e.g., longlines including rope, anchors, buoys and other collection and culture equipment (Southgate et al. 2008, Johnston et al. 2014). Information entered in this section of the model informs the capital requirements section of the economic model and sets area and density measures for the farm. Labour is broken down into tasks over the 12-month spat collection period, with each task allocated working hours that would be required for completion (Table 4.1).

4.2.3 Mabé pearl production

Mabé pearl production involves fixing commercially available, hemi-spherical, plastic nuclei to the inside shell surfaces of each adult *Pt. penguin* (>175mm dorso-ventral measurement), using cyanoacrylate glue. This activity is conducted by community members following training (Southgate et al. 2019). Once nuclei are applied, oysters are returned to the ocean where they are grown for 12 months before resulting mabé pearls are harvested. Data used here relating to mabé pearl production was based on three nuclei (2 x 14 mm and 1 x 16 mm diameter) being inserted to each pearl oyster, which is standard practice in Fiji, following the suggested optimal nucleus arrangement of Gordon et al. (2019). The location and size of implanted nuclei impacts harvest quality of mabé pearls, and different nucleus sizes are used to maximise quality (Gordon et al. 2019). Mabé pearls are allocated to one of four grades in Fiji according to their quality, A, B, C and D (rejects), and the mabé pearl economic model developed here assumed a distribution of resulting pearls of 40% A-grade, 30% B-grade, 20% C-grade and 10% rejects of no commercial value, reflecting average production data across five community-based mabé pearl farms. Average wholesale values used in the modelling for each of these pearl grades was USD 14.10, USD 9.40, and USD 7.05 for A, B, and C grades, respectively. Rejects, or D grade pearls can be sold to handicraft and jewellery makers but were excluded from this study because of their low value and sporadic nature of such sales.

4.2.3.1 Husbandry and production scale for mabé pearls

Similar to culture methods for round pearls production from *P. margaritifera* in the Pacific region, oysters implanted for mabé pearl production are typically cultured using the 'ear-hanging' method (Haws and Ellis 2000, Haws 2002, Southgate et al. 2008). A small hole of 2–3 mm is drilled through the base of the shell in the dorso-posterior region, and this is used to attach the oyster to a rope using monofilament fishing line or wire (Gervis and Sims 1992, Southgate et al. 2008). A number of oysters are usually attached to a single rope, either singly or in pairs, to form a ‘chaplet’ (Friedman and Southgate 1999), and chaplets are attached directly to a surface longline (Kishore et al. 2014) (Table 4.2).

The scale of the model is set by entering a figure for the number of oysters that will be harvested for pearls per production cycle (nucleus implantation to harvest). The economic model estimates the total number of oysters required on the farm at any point in time. This accounts for the number of oysters at all stages of the production cycle: juveniles, pre-implanted oysters and implanted oysters that will be harvested for mabé pearls, with corrections for expected mortalities. Other physical parameters set in the model include details of farming infrastructure e.g., longlines including rope, anchors, buoys, and chaplets (Kishore et al. 2015). Information entered in this section of the model informs the capital requirements section of the economic model and sets other spatial data for the farm (Table 4.2).

Table 4.2 Farm husbandry and production parameters for mabé pearl production using *Pteria penguin*.

Category	**Quantity**
Longline number/length	2/100 m
Total number of chaplets	306
Chaplets with implanted oysters/oysters per chaplet	200/10
Chaplets with pre-implant oysters/oysters per chaplet	106/20
Production length after implant (months)	12
Nuclei per oyster	3
Annual oyster harvest	2,000
Number of saleable pearls produced annually	5,400

4.2.3.2 Farm labour

Similar to spat collection, farm labour is broken down to the tasks required on an annual basis from nucleus implantation to harvest. Table 4.3 outlines the breakdown of farm labour and the description of the tasks undertaken.

Table 4.3 Farm labour breakdown per mabé pearl (using *Pteria penguin*) production cycle.

Labour Component (based on an 8-hour day)	**Description**
Purchase and deploy oysters (2 days/16 hours)	Purchase juvenile oysters from community spat collection operation. Drill juvenile oysters and ear-hang on chaplets (20 oysters).
Implant oysters (8.8 days/70.4 hours)	Implant oysters with pearl nuclei (120 per technician x 2) and reduce implanted oysters to ten per chaplet.
Implantation support (44 days/352 hours)	Support nucleus implantation technicians (five people: two cleaning; one opening oysters; two gluing nuclei).
Pearl harvest (3 days/24 hours)	Harvest mabé pearls 12 months after nucleus implantation
Oyster cleaning and maintenance (72 days/576 hours)	Remove biofouling from oysters and chaplets (six people per 1,000 oysters - one day every two months)

Biofouling can be a significant issue that increases operational and economic costs associated with pearl production and requires a significant proportion of farm labour to control (Pit and Southgate 2003, de Nys and Ison 2008, Bertucci et al. 2016). Labour allocated for pearl nucleus implanting accounted for 120 oysters implanted per day at a minimum hourly wage rate for Fiji of USD 1.26 per hour.

4.2.3.3 Additional operating costs

Additional operating costs not captured in the wider modelling exercise include fuel and oil, electricity, repairs and maintenance, accounting and legal, office and administration, government fees and charges, phone, travel, vehicle registrations and insurances.

4.2.3.4 Capital expenditure

The capital costs associated with the mabé pearl farm were divided into six main components: (1) land and buildings; (2) boats and vehicles; (3) culture equipment; (4) culture infrastructure and implantation; (5) diving equipment; and (6) miscellaneous (e.g., tools). Capital equipment bought at farm inception is replaced at pre-determined periods over the 20-year life of the farming project. Replacement costs are estimated as the amount of money required to replace capital items, net of its salvage or trade-in value. The initial year of capital purchase is year-0, and the model assumes that all relevant capital is sold, and the proceeds enter the cashflow as a revenue stream in year-20. Capital items purchased for the mabé pearl farm are described in Table 4.4.

Table 4.4 Farm infrastructure and equipment costs for a mabé pearl farm using *Pteria penguin* ($ in USD).

Item	Units	Value / Unit ($)	Total Value ($)	Salvage Value (%)	Year of Purchase / Replacement
Implantation structure	1	14	14	0	0,5,10,15
Long-line rope (16 mm)	200 m	0.36	72	0	0,5,10,15
Anchor rope (12 mm)	180 m	0.27	49	0	0,10
Anchors	4	3.29	13	0	0,10
Anchor mould	1	38	38	0	0,10
Buoys	8	6.58	53	0	0,10
Chaplet rope (12 mm)	459 m	0.27	124	0	0,5,10,15
Chaplet fishing line	918 m	0.10	92	0	0,2,4,6,…,18
Boat	1	3,713	3,713	50	0,-
Outboard	1	2,538	2,538	20	0,10
Mask, snorkel and fins	1	94	94	0	0,3,6,9,12,15,18
Implant rack and openers	2	195	390	50	0,10
Drill	1	35	35	0	0,2,4,6,…,18
Implant table	1	94	94	0	0,10
Total			**7,319**		

4.3 Results

4.3.1 Spat collection

4.3.1.1 Farm cost summary

The spat collection operation in Fiji produced an annual total of 2,332 saleable *P. margaritifera* pearl oysters annually, plus *Pt. penguin* that can be retained for mabé pearl production and value adding. . Annual gross revenue from sale of the *P. margaritifera* juvenile oysters totalled USD 2,648 (USD 1.14 per saleable oyster), while annual production costs totalled USD 1,737 (USD 0.74 per saleable oyster) (Table 4.5). Breakdown of the spat collection cost structure is shown in Table 4.5. Operating expenditure (USD 0.29) made up the largest components of around 39% of costs per oyster (Table 4.5).

Table 4.5 Breakdown of annual production costs for pearl oyster spat collection of both *Pinctada margaritifera* and *Pteria penguin* ($ in USD).

Cost Item	Units	Annual Cost ($)	Cost per Oyster ($)
Farm labour ($1.26 per hour)	292 hours	368	0.16
Fuel and energy		395	0.17
Operating expenditure		670	0.29
Capital purchase and replacement		305	0.13
Total		**1,737**	**0.74**

4.3.1.2 Net Present Value (NPV)

NPV over the 20-year life of the project, using a discount rate of 6%, was USD 10,439. As shown in Figure 4.2, the model indicates that it would take four years to recoup the original investment in the project.

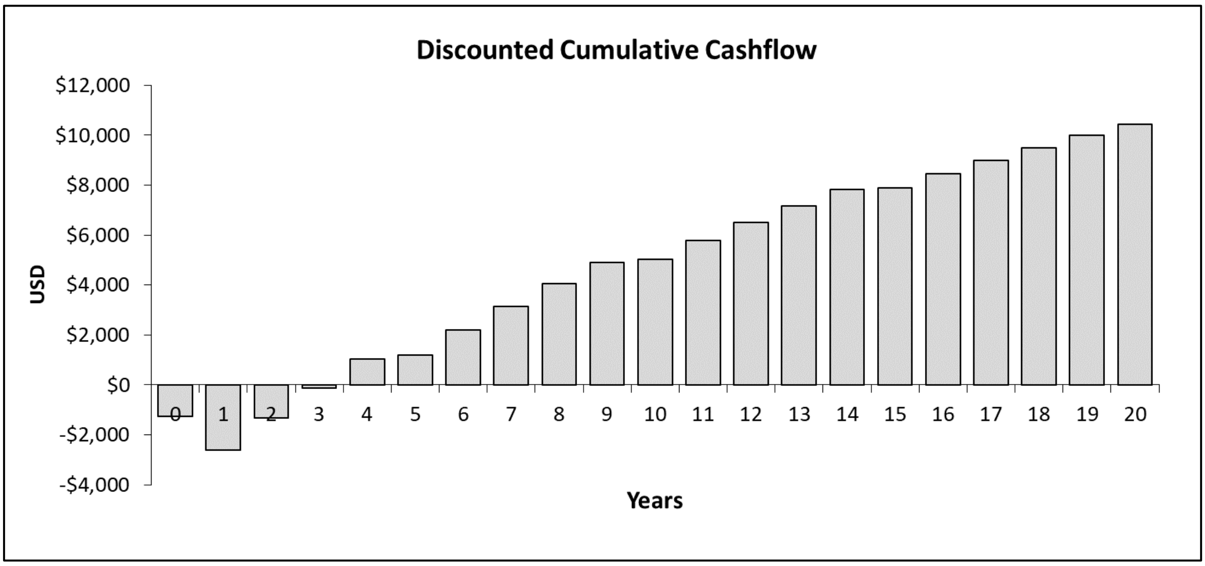

Figure 4.2 Discounted cumulative cashflow for the modelled pearl oyster spat collection farm in Fiji ($ in USD).

4.3.1.3 Other economic indicators

The results of the analysis are shown in Table 4.6 with some additional economic indicators. The MIRR was 12.24%, BCR was 1.52, and a payback period of four years was estimated (Table 4.6).

Table 4.6 Summary of other economic indicators for pearl oyster spat collection in Fiji targeting *Pinctada margaritifera* and *Pteria penguin*.

Measure	Result
MIRR	12.24%
BCR	1.52
Payback period	4 years

4.3.2 Mabé pearl production

4.3.2.1 Farm output summary

The mabé pearl farming operation, utilising juvenile oysters from the spat collection operation purchased for USD 1.18 per oyster (*Pt. penguin*), produced 5,400 saleable pearls annually. Annual gross revenue from the sale of the mabé pearls totalled USD 49,754 (USD 9.21 per saleable pearl), while annual production costs totalled USD 6,870 (USD 1.27 per saleable pearl). Table 4.7 provides a breakdown of the mabé pearl farm cost structure. Purchase of oysters for mabé pearl production (USD 0.48) and farm labour (USD 0.24) made up the largest cost components of around 38% and 19%, respectively (Table 4.7).

Table 4.7 Breakdown of annual production costs for mabé pearl production using *Pteria penguin* ($ in USD).

Cost Item	Average Annual Units	Annual Cost ($)	Cost per Pearl ($)
Oyster purchase	2,217	2,616	0.48
Mabé nuclei	6,002	860	0.16
Farm labour	1,038.4 hours	1,308	0.24
Fuel and energy		447	0.08
Repairs and maintenance		366	0.07
Operating expenditure		462	0.09
Capital purchase and replacement		811	0.15
Total		**6,870**	**1.27**

4.3.2.2 Net Present Value (NPV)

NPV over the 20-year life of the project, using a discount rate of 6%, was USD 491,864. As shown in Figure 4.3, the model indicates that it would take three years to recoup the original investment in the project.

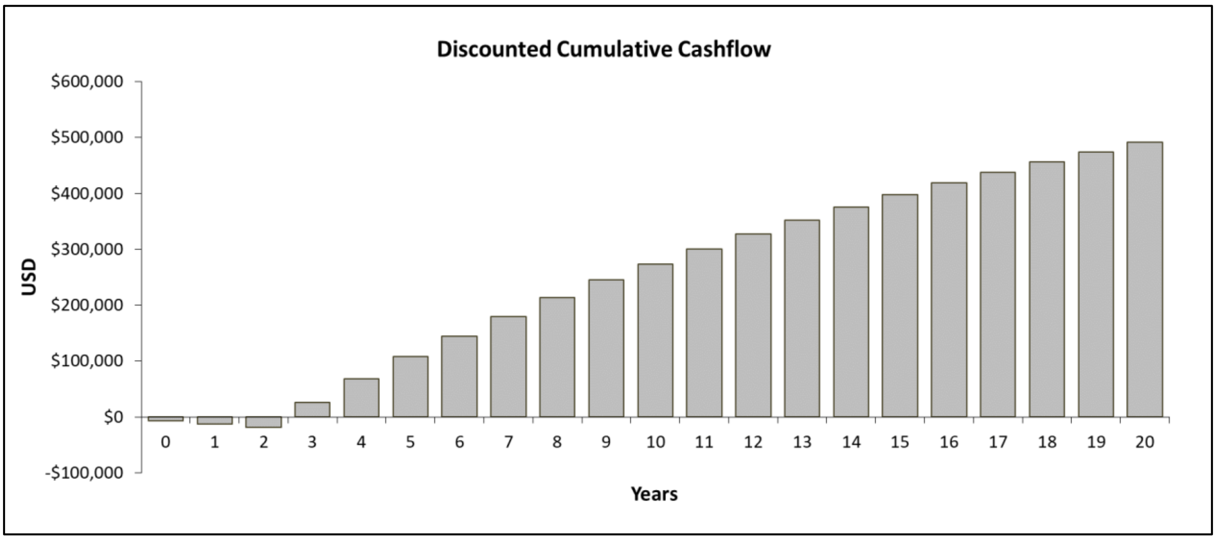

Figure 4.3 Discounted cumulative cashflow for the modelled mabé pearl farm in Fiji ($ in USD).

4.3.3 Other economic indicators

Results of the analysis are shown in Table 4.8 with some additional economic indicators. The MIRR was 22.64%, BCR was 7.24, and a payback period of three years was estimated (Table 4.8).

Table 4.8 Summary of other economic indicators for the mabé pearl farm utilising *Pteria penguin*.

Measure	**Result**
MIRR	22.64%
BCR	7.24
Payback period	3 years

4.3.3.1 Risk analysis

Various methods have been employed to assist estimation of input risk distributions with a degree of confidence to reflect the risky environment of pearl farming in the south Pacific. To improve our understanding of risk, and adoption of the economic model as a business tool, a number of stakeholder workshops were undertaken to enhance risk assessment by pearl farmers (Johnston et al. 2014, section 2.2.2). As an example, production risks that were identified as ‘significant’ during these workshops, delivering ‘poor’ to ‘average’ pearl production, included category 3 to 4 tropical cyclones, flood events that reduced salinity to <25 ppt, and chronic disease of oyster stock. Each was assigned a probability of occurrence and combined to provide the probability in the related distribution.

For the mabé pearl farm modelled here, risk analysis (see section 2.2.2, Equation 3) focused on two key parameters, price, and production, and five-point distributions were used for both variables (Table 4.9). In both distributions, the average point is based on the average revenue per pearl and the estimated maximum production level (upper bound of the production distribution) described in the farm output summary above.

Table 4.9 Production (over the 20-year life of the project) and price distributions for mabé pearl culture with associated cumulative probabilities ($ in USD).

Description	Total Production (No. of Saleable Pearls)	Cumulative Probability (%)
Minimum	10,800	0
Poor	27,000	50
Average	54,000	75
Good	81,000	90
Maximum	108,000	100
Description	**Price per Pearl ($)**	**Cumulative Probability (%)**
Minimum	7.37	0
Poor	8.29	10
Average	9.21	25
Good	10.14	90
Maximum	11.06	100

Minimum production over the life of the farm is set at 10% of potential production due to the likelihood of significant losses from cyclones, disease, theft, and farm mismanagement. A ‘poor’ production result was set at 25% of expected production levels, hence 27,000 saleable pearls. The ‘maximum’ point in the distribution of pearls was set at the estimated production for the farm, representing the number of pearls the farm is expected to produce (108,000). The ‘average’ point in the distribution for production was set at 54,000 (50%) and represents the midpoint of saleable pearl production over the life of the farm. The ‘good’ point in the distribution for production was estimated as the midpoint between the ‘average’ point and the ‘maximum’ point.

The average price for a saleable pearl from the modelled pearl farm was USD 9.21. This was used to set the 'average' point in the price distribution. Remaining distribution points were based on a 10% variance from the 'average', based on stakeholder input. Probabilities were determined following stakeholder input to identify and categorise risks from severe to mild, and their probabilities of occurrence (Johnston et al. 2014). Simulation output is the NPV. The highest NPV was USD 977,125, while the lowest was -USD 1,352 (Figure 4.4). The average NPV produced by the simulation was USD 297,507. Incorporation of production and price risk reduced the expected NPV at steady state from USD 491,864 by USD 194,357 after risk is applied. This represents a 40% correction in the expected NPV.

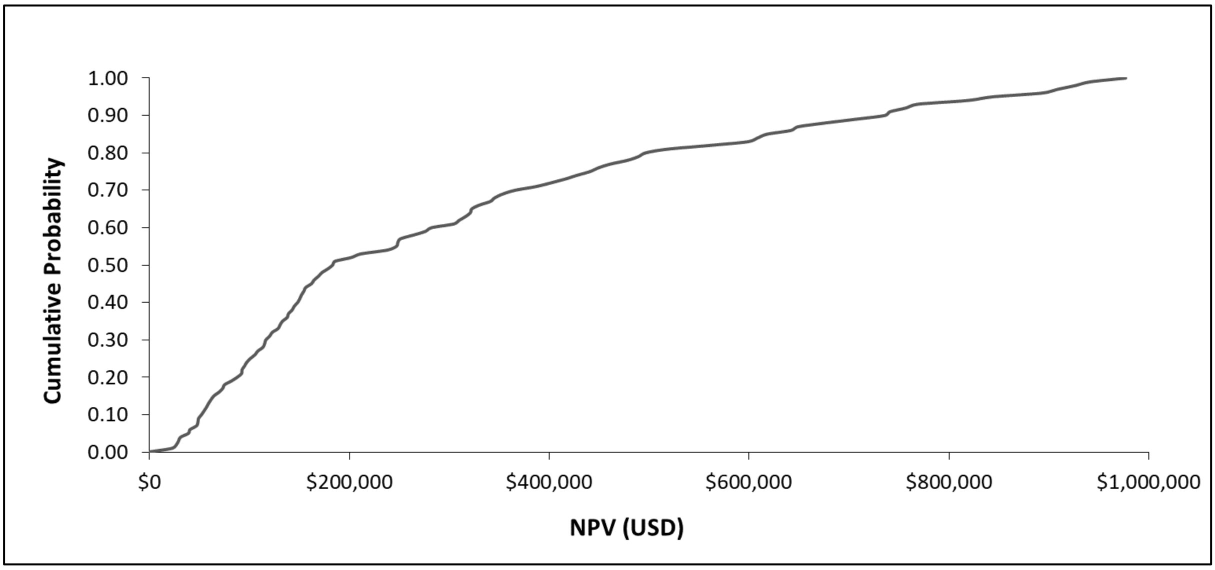

Figure 4.4 Cumulative probability distribution for NPV for mabé pearl culture in Fiji (variables: price and production) ($ in USD).

4.4 Discussion

Economic information relating to pearl farming and associated activities in the south Pacific is sparse, providing little or no insight into the economic opportunity that the pearl sector can provide to remote communities. Using Fiji as an example of this potential, within a broader Indo-Pacific context, this study determined the establishment and operational costs for community-based pearl oyster spat collection and mabé pearl production, and estimated potential profitability of these activities, for the first time.

4.4.1 The role of coastal communities in the Fijian pearl industry

Based on the success of large-scale round pearl culture in French Polynesia, and the broad community benefits associated with it (Arnaud-Haond et al. 2003, Tisdell and Poirine 2008), development of a similar, but smaller pearl sector in Fiji was touted by the Ministry of National Planning in 2009 as a rural enterprise that would generate significant export income and bring prosperity to the more remote regions of Fiji (Johnston et al. 2014). However, the potential financial reward from round pearl farming, based upon the available supply of *P. margaritifera*, is coupled with significant risk. Production of round pearls is commonly characterised by high capital investment, extended cashflow lags following establishment, significant exposure to production risks such as cyclones, disease, and theft, and requires a high level of technical input (Johnston et al. 2014, Chapter 2). For example, the capital or infrastructure cost of a viable scale round pearl farm in Fiji was estimated at more than USD 47,000 with a payback period of five years (Chapter 2). The same research reported that such a farm would be expected to generate annual gross revenue of around USD 347,634, with production costs of USD 191,271 and an estimated 42% probability of making a loss (Chapter 2). On this basis round pearl production is not particularly well suited to resource-poor coastal communities. However, the collection and subsequent sale of pearl oyster juveniles (*P. margaritifera*), and artisanal mabé pearl production using incidentally collected *Pt. penguin*, require much less capital input, are easier to establish, have inherently lower risk, and are less technically demanding than round pearl production. This study has shown that collection and sale of *P. margaritifera* juveniles, as well as mabé pearl production from *Pt. penguin* at a community level, can be profitable at the scale modelled in this study. These activities provide opportunities for appropriately located coastal communities to enter the cultured pearl industry value chain and establish rural enterprises. These activities also provide broader opportunities relating to downstream income-generating activities such as handicrafts and jewellery production using mabé pearls and pearl shell (Southgate et al. 2019), that were not modelled in this study.

4.4.2 Barriers to community pearl enterprise development

One of the key barriers to establishing large-scale rural businesses in Fiji is access to capital (Johnston et al. 2014, Chapter 2). Potential rural business opportunities that require a level of capital investment, premised on borrowed funds, is prohibitive in many Pacific Island countries. High interest rates on business loans (17-25%) and unrealistic assessment criteria exclude many rural Fijians from accessing the capital required to establish high-capital rural enterprises such as round pearl culture.

A recent business skilling workshop for stakeholders in Fiji included a presentation from the Westpac Pacific bank that provided greater clarity around the process and requirements for accessing business capital. The key aspects of the presentation were that applicants were required to have the appropriate insurances for the business, certified business accounts, and some level of collateral appropriate to the size of the loan. The major impediments to meeting these criteria for current and prospective pearl farmers include:

- Insurance is almost impossible to obtain for marine activities in Fiji because of cyclones, disease, theft etc.
- Property rights do not exist – no collateral (no value attributable to the marine area utilised for farming purposes) for loans.

- Certified business accounts are not common amongst rural farmers and community groups.
- Limited alternative income streams to support loan payments in the advent of a failure in the farming enterprise.

It is clear that there are current impediments to obtaining business capital for commercial-scale pearl culture activities in Fiji; the assessment process remains inflexible and is unlikely to change in the near future. It would require some significant shifts in lending practices to open up access to capital for larger-scale pearl culture activities in Fiji. However, small-scale pearl oyster spat collection and mabé pearl production, that are compatible with subsistence-based livelihood activities, offer coastal communities technically appropriate and low-cost entry pathways to the sector that fosters sustainable industry development. Impediments to capital, and the insubstantial opportunity cost for alternative investment of cash inflows, frame these low-capital, low-tech accessible business models.

4.4.3 Opportunities for vertical integration of activities

While spat collection alone was shown to be a profitable activity in this study, there is considerable economic advantage, with minimal extra infrastructure or labour inputs, in communities undertaking both spat collection and mabé pearl production. For farms involved in mabé pearl production only, for example, the cost of each oyster purchased for pearl production was USD 1.18, yet the actual cost of each oyster obtained from spat collection is only USD 0.74. On this basis, the cost of spat supply (per saleable pearl produced) would be reduced from USD 0.48 to USD 0.30 in communities that use self-collected *Pt. penguin* oysters for mabé pearl production, stimulating a 2% increase in annual returns. While these rural enterprises are analysed separately in this study, it is likely that, where possible, Fijian communities will develop farming systems involving both spat collection (*P. margaritifera* and *Pt. penguin*) and mabé production to take advantage of the supply of available *Pt. penguin* oysters at minimal cost to the pearl culture operation. This integrated approach is being encouraged through current extension efforts in Fiji (Southgate et al. 2019).

A further opportunity exists for collaborative enterprise partnerships between neighbouring communities. On the Fijian island of Taveuni for example, a number of neighbouring communities are involved in various pearl-based livelihood activities including spat collection, mabé pearl production, pearl jewellery and pearl shell handicraft production. Together with a local round pearl farm, they collaborate to generate a local 'pearl hub' that improves resource use efficiency and maximises the flow of community benefits (Southgate et al. 2019). This model may provide a basis for expansion of the pearl sector at both national and regional levels.

4.4.4 Value-adding opportunities

Improved availability of both pearl oyster shells (from spat collection) and mabé pearls provides further opportunities for income generation through value-adding and production of handicrafts and jewellery items targeting the domestic tourist markets (Southgate et al. 2019). Although the modelling developed in this study accounted only for spat collection and mabé pearl production, spat collection improves the broad availability of pearl shells, and cutting mabé pearls from *Pt. penguin* oyster shells at harvest, generates mother-of-pearl (MOP) shell pieces as a by-product. Mabé pearls, as well as MOP offcuts, provide a basis for value-adding activities that offer further income generating opportunities for communities and strengthen the viability of farming operations. Fiji is fortunate to be a significant international tourism destination and value-chain analysis has identified that approximately FJD 8.5 million worth of pearl and pearl shell handicraft items are imported into Fiji to each year targeting this market

(Chand et al. 2011). There is strong demand for MOP and mabé pearl items domestically, particularly those with local or traditional design (Naidu et al. 2014, Chand et al. 2015), so locally produced pearl shell and mabé pearl items are likely to find ready markets and offer considerable potential for import replacement (Southgate et al. 2019).

4.5 Conclusions

Round pearl culture in the Pacific relies on community-based spat collection for supply of oysters to pearl farms. This activity generates significant social and economic benefits for coastal communities in French Polynesia. The results of this study have demonstrated the profitability of spat collection activities in Fiji and similar economic benefits to those experienced in French Polynesia. A major advantage of spat collection in Fiji is that, unlike French Polynesia, a second species of pearl oyster, *Pt. penguin*, readily recruits to spat collectors and can be used for community-based mabé pearl production, independent of the round pearl sector. Unlike round pearls, mabé pearls can be made by local people with minimal training and require around half the culture period of round pearls. Perhaps of most importance in rural Pacific communities is the compatibility of pearl oyster spat collection and mabé pearl production with local lifestyles. Spat collection and mabé pearl production require little attention or labour input and both activities appear profitable at relatively small scale. For example, at the profitable scale of operation modelled in this study, spat collection and mabé pearl culture were estimated to require labour inputs of around 6 and 22 hours per week, respectively, and both activities are complementary to existing livelihoods activities such as fishing and subsistence farming. Both pearl oyster spat collection and mabé pearl farming broaden community income generating opportunities, but they must also be compatible with existing food production and collection activities. Expansions of current spat collection and mabé pearl production activities beyond subsistence level is therefore limited by available resources, particularly labour and infrastructure. On this basis, expansion of the sector is more likely to result from uptake of these activities by new communities rather than by increased farming effort in established pearl culture communities which would be resource limited.

The economic models developed in this study will inform prospective industry participants, stakeholders, government departments, research organisations and donors, regional extension agencies and NGOs, describing the inputs required to establish and maintain viable and sustainable pearl industry-based livelihoods and businesses. The models will assist in establishing new businesses, expansion of current spat collection operations and mabé pearl farms and will inform policy development by the Government of Fiji relating to pearl industry expansion and rural development. Although focused on Fiji, the results of this study have broad international relevance. Pearl farming is conducted throughout the Indo-Pacific region. In the Pacific region, pearl farming is the most valuable and highest priority aquaculture activity, supporting associated livelihood activities, including those described here, in countries such as French Polynesia, Cook Islands, Fiji, Tonga and Micronesia (Arnaud-Haond et al. 2003, Teitelbaum and Fale 2008, Cartier et al. 2012, Kishore et al. 2018, Southgate et al. 2019, Gordon et al. 2019).

Chapter 5: Economic feasibility of small-scale mabé pearl production in Tonga using the winged pearl oyster, *Pteria penguin*

Data from this chapter were published as: **Johnston, W**., Gordon, S.E., Wingfield, M., Halafihi, T., Hine, D. and Southgate, P.C. 2020. Economic feasibility of small-scale mabé pearl production in Tonga using the winged pearl oyster, *Pteria penguin*. *Aquaculture Reports*. 17: 100347.

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers' comments, submission, and accepted publication in peer reviewed journal.

5.1 Introduction

There is great interest in many Pacific Island countries to develop cultured pearl production because of the economic and livelihood opportunities it offers (Southgate et al. 2019; Chapter 1). As well as potential export income, coastal communities may, for example, generate income from activities such as spat collection and sale of juvenile oysters to pearl farms, culture and sale of mabé pearls (half-pearls), and production of mabé pearl and pearl shell (MOP) jewellery and handicraft items (Southgate et al. 2019, Simard et al. 2019).

South Pacific nations including French Polynesia, the Fiji Islands (Fiji), the Kingdom of Tonga (Tonga), the Cook Islands, the Republic of the Marshall Islands, the Federated States of Micronesia, Kiribati and the Solomon Islands, have all either developed commercial round pearl culture using the black-lip pearl oyster, *P. margaritifera*, or investigated its potential (Friedman and Bell, 1999, Fong et al. 2005, Tisdell and Poirine 2008, Johnston et al. 2014, Johnston and Hine 2015). Among south Pacific nations, significant cultured round pearl export sectors have been developed in French Polynesia, Cook Islands and Fiji (Chapter 1). Tonga is unique among pearl producing south Pacific nations in focusing on mabé pearl culture using the winged pearl oyster, *Pt. penguin*. Mabé pearls are produced by attaching (gluing) hemispherical nuclei to the inner surfaces of an oyster shell (implantation) where, over a culture period of around 12 months, nuclei are covered with successive layers of nacre or 'mother-of-pearl' (MOP), produced by the mantle tissue of the oyster (Taylor and Strack 2008, Kishore et al. 2015, Gordon et al. 2018). Resulting mabé pearls, commonly three to five per oyster (Gordon et al. 2019), are then harvested by cutting them from the shell then sold (Strack 2006, Taylor and Strack 2008).

Mabé pearl production is much simpler, and requires fewer resources, than round pearl production (Chapter 1) and can be achieved by community members following appropriate training (Southgate et al. 2019). Furthermore, mabé pearl production supports downstream value-adding and product development that broaden community livelihoods opportunities. Mabé pearl production in Tonga is supported by the Ministry of Fisheries (MoF) through hatchery production of spat and provision of oyster juveniles to pearl farmers. Juvenile oysters must be cultured by farmers until they reach an appropriate size for mabé pearl production (>175 mm dorso-ventral measurement). A secure supply of hatchery produced spat (Southgate et al. 2016), and development of more efficient culture methods for oyster juveniles (Gordon et al. 2020), has supported recent expansion of the Tongan mabé pearl sector. Since its inception, the sector has grown from nine initial farms to 24 farms by 2022, with the addition of 15 community based mabé farming operations. These current farms are distributed amongst the three major island groups in Tonga, with collective production of around 4,680 mabé pearls valued at approximately USD 325,000 annually (Southgate et al. 2023).

Few studies have investigated the economics of mabé pearl culture, yet such information is of vital importance in assessing and informing long-term viability. For example, economic modelling recently demonstrated that potential profitability from mabé pearl culture in Tanzania is far greater than that from spat collection and sales of pearl oysters to pearl farmers (Saidi et al. 2017). Recent investigation of the potential profitability of mabé pearl production in Fiji, based on a community-based farm comprising two 100 m longlines supporting 2,000 implanted *Pt. penguin*, reported estimated annual production of 5,400 mabé pearls and very viable economic outputs (Chapter 4). Similar data for mabé pearl production in Tonga are not available but they are likely to differ from those of Fiji because of smaller pearl farm size, and differences in the method used for oyster culture, infrastructure and operations costs, sociocultural and financial aspects. The aim of research reported in this chapter was therefore to determine establishment and operational costs, and potential profitability of a representatively sized mabé pearl farm in Tonga. The models developed in this study provide valuable new information for prospective mabé pearl farmers, funding bodies, policy makers and other stakeholders, and provide a valuable extension tool supporting further development of the Tongan mabé pearl sector with relevance to similar development within the broader Indo-Pacific region.

5.2 Materials and methods

The fundamental basis for the economic modelling utilised here was first applied to assess subsistence level mabé pearl production in Tanzania (Saidi et al. 2017), then round pearl production in Fiji (section 2.2.2) and later extended to mabé pearl production in Tonga. The cost and price data used to inform the modelling in the current study was based on information collected through business skilling workshops, stakeholder interviews and annual surveys of the pearl industry by the Tongan Ministry of Commerce and Labour that began in 2015. Additional data were collected and applied from more recent studies (e.g., Gordon et al. 2019, Gordon et al. 2020) where possible, to improve the modelling and outputs.

5.2.1 Development of the economic model

An economic model for mabé pearl production in Tonga were developed using cost benefit analysis (CBA) methodology incorporating a discounted cashflow framework over a twenty-year period with a standard discount rate (section 2.2.2). The current long-term domestic bond rate in Tonga is 3% (National Reserve Bank of Tonga) and is deemed too low. At 6% the set discount rate provides an acceptable reflection of the 'riskiness' of aquaculture projects in the Pacific while supporting projects that benefit the broader Tongan community.

The economic indicators used in this Chapter include the NPV, EAR, BCR, MIRR and the payback period (section 2.2.2, section 2.3.3.3, section 4.2.1). The MIRR in this Chapter is calculated using loan rates specified for agricultural activities in Tonga at 10% (Tonga Development Bank, www.tdb.to, 2019), and basic savings interest rates that are 1.25%. Estimated annual benefits were developed using revenues generated from the domestic sale of mabé pearls. Average prices for the various grades of mabé pearls were estimated from a number of interviews with existing pearl farmers and wholesalers in Tonga. Sale of value-added pearl products such as jewellery and handicrafts were not included in the analysis. All capital, variable and fixed costs were also estimated based on data collected from business skilling workshops and annual Government surveys with pearl farmers in Tonga between 2015 and 2019.

Finally, the stochasticity of the project was explored using Monte Carlo analysis (section 2.2.2). The critical and uncertain parameters of farm yield and average mabé pearl price had five-point probability distributions applied, utilising data collected from workshops and farmer surveys, informing the assessment of risk for the small-scale mabé pearl farm modelled in this study (Table 5.1). The sampled results for price and yield were then multiplied to generate a revenue sample from which all costs were deducted to produce an estimate of NPV.

Table 5.1 Risk categories for price and production of mabé pearls (from Chapter 2).

Risk Category	Description
Severe	delivers 'zero' to 'poor' production or a minimum to poor price
Significant	delivers 'poor' to 'average' production and price outcomes
Moderate	delivers 'average' to 'good' production and price outcomes
Low	delivers 'good' to 'maximum' production and price outcomes

Modelling, incorporating risk analysis, was developed internally by the authors using the Visual Basic language (section 2.2.2). Incorporation of internal risk analysis programming within the spreadsheet model greatly enhanced the extension capability of the program, avoiding commercial software requirements while improving adoption and application in rural areas of the Pacific.

5.2.2 Mabé pearl production

Mabé pearl production involves fixing commercially available, hemi-spherical, plastic nuclei to the inside shell surfaces of each adult pearl oyster (*Pt. penguin*). This activity is conducted by trained farmers or technicians (Southgate et al. 2019). Once nuclei are applied, oysters are returned to the ocean where they are grown for 12 months before resulting mabé pearls are harvested. Data used here relating to mabé pearl production was based on three nuclei being inserted into each pearl oyster, which is considered best practice in Tonga for pearl quality outcomes as described by Gordon et al. (2019). Studies suggest that an appropriate nucleus height is between 7-9 mm with a base diameter of 15 mm for *Pt. penguin* (Kishore et al. 2015, Gordon et al. 2018). The location and height (profile) of the nucleus within the shell impacts harvest quality of the resulting mabé pearl and, as such, different profiles (high or low) are used to maximise quality (Gordon et al. 2019).

A recognised international grading system for mabé pearls does not exist, and so grading is a subjective exercise. However, as a guide for Tongan mabé pearl farmers, and to support extension activities, mabé pearls are graded using an alphabetical grading system developed by Gordon et al. (2018). Key determinants of mabé pearl quality considered in this grading system are lustre, colour and surface perfection (Table 5.2). Pearl size and shape is not an objective determinant of mabé pearl quality and is instead considered a subjective characteristic.

Table 5.2 The alphabetical grading system and grading characteristics used to classify mabé pearl quality in this study (Ruız-Rubio et al. 2006, Matlins 2008, Kishore et al. 2015, Gordon et al. 2018).

Grade	Mabé pearl characteristics
AAA	Perfect quality. Outstanding lustre and at least 95% of surface free from defects. Regular shape and very good symmetry. The highest quality of mabé pearl.
AA	Very good quality. Very good lustre and at least 75% of surface free from defects. Regular shape and good symmetry.
A	Good quality. Good lustre and at least 50% of surface free from defects. The highest grade possible for irregular shaped mabé pearls.
B	Average quality. Average lustre, considerable surface defects. Irregular shapes with poor symmetry.
C	Minimal commercial value. Poor lustre, major surface defects and highly irregular shape. Includes mabé pearls in which the nucleus is slightly visible through the nacre.
NC	No commercial value. Poorest lustre of all, surface covered in defects and highly irregular shape. Thinnest nacre with highly visible nucleus.

The marketing section of the economic model sets out the breakdown of the harvest in terms of the types (profile) of pearls harvested and their quality based on the grading system outlined in Table 5.2. To reflect industry trends, only round mabé pearls were produced and only grades between AAA and B were assigned a value. Also considered in this section of the model are marketing costs including advertising, auction, brokerage, and commission costs.

5.2.3 Components of the economic model

A conservative establishment phase of two years was factored into the modelling from the time juveniles arrives on farm (April) to allow the initial cohort to reach an appropriate size for nucleus implantation (>170 mm dorso-ventral measurement). The farm will continue to receive juveniles each year and maintain a two-year nursery phase beyond establishment. The first nucleus implantation for mabé pearl production will occur immediately following the initial establishment (nursery) phase. A mabé pearl production period, from implantation to harvest, was set at 12 months (Gordon et al. 2018, Gordon et al. 2019). On this basis it is not until year four that pearls are harvested.

5.2.3.1 Husbandry and production scale

Pteria penguin implanted for mabé pearl production are typically cultured using the "ear-hanging" or chaplet method (Haws and Ellis 2000, Haws 2002, Southgate 2008). A small hole of 1.5 - 2 mm is drilled through the base of the shell in the dorsal-posterior region, which is used to attach the oyster to a rope using monofilament fishing line or wire (Gervis and Sims 1992, Southgate 2008). A number of oysters are usually attached to a single rope, either singly or in pairs, to form a 'chaplet' (Friedman and Southgate 1999), and chaplets are attached directly to a surface longline (Kishore et al. 2014, Chapter 3). In Tonga, the modelled mabé pearl farm is based on one 50 m longline holding 28 chaplets in suspended culture, that are allocated amongst implanted, pre-implant, and juvenile oysters (Table 5.3). Recent introduction of protective wire mesh cylinders to house chaplets holding *Pt. penguin* juveniles has been shown to reduce predation and improve oyster survival to > 90%, compared to around

25% using standard basket culture (Gordon et al. 2020). Cylinder-based culture of *Pt. penguin* juveniles is now being adopted as standard practice within the Tongan pearl sector where, generally, juvenile oysters are held on chaplets within protective mesh cylinders, and larger pre-implanted and implanted oysters held on chaplets without protective cylinders (Figure 5.1).

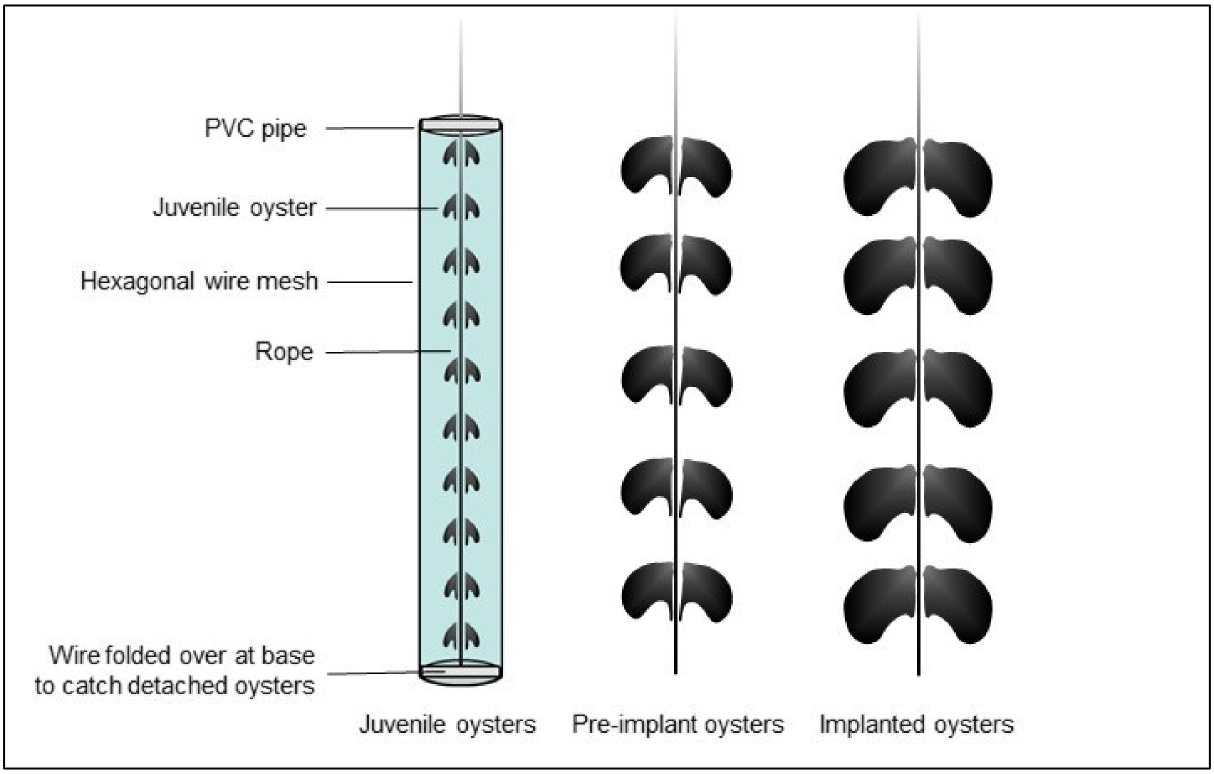

Figure 5.1 Representation of the farming protocol for mabé pearl production using *Pteria penguin* in Tonga. Chaplets containing juvenile oysters are housed in protective wire mesh cylinders (left) and chaplets containing larger pre-implanted and implanted *Pteria penguin* (middle and right) are cultured without protective cylinders (Gordon et al. 2020).

The mabé pearl farm modelled in this study represents subsistence-level production typical of the current Tongan pearl sector. The model targeted annual mabé pearl production from 100 oysters. This required infrastructure comprised of a single 50-m longline to support oyster culture units outlined in Figure 5.1. The scale of the farm model is set by entering a figure for the target number of oysters that will be harvested per production cycle; 100 oysters in this study. By accounting for expected mortality and replacement of harvested oysters, the economic model incorporates the total number of oysters required on the farm at all stages of production, at any point in time, to achieve this target. For example, to achieve 100 mabé pearl producing oysters, the number of oysters required by the farm must account for an estimated 18% oyster mortality between arrival at the farm and nucleus implantation, and further estimated mortality of 2.5% between implanting and mabé pearl harvest. On this basis, 126 juveniles are required at the start of nursey culture on-farm, and 103 oysters must be implanted to assure mabé pearl production from 100 oysters (Table 5.3).

Other physical parameters set in the model include details of farming infrastructure e.g., longlines including rope, anchors, buoys, and chaplets (Kishore et al. 2015). Information entered in this section of the model informs the capital requirements section of the economic model and sets other spatial data for the farm. The modelled farm therefore consisted of a single 50 m longline, 10 chaplets with implanted oysters, 11 chaplets with pre-implanted oysters and 7 chaplets within protective mesh cylinders containing oyster juveniles (Table 5.3) to provide appropriate numbers of oyster for each stage of culture. The model assumed implantation of three nuclei per oyster (Gordon et al. 2019) resulting in annual production of 231 saleable mabé pearls (Table 5.3).

Table 5.3 Farm husbandry and production parameters for the modelled mabé pearl farm in Tonga based on a single 50 m longline.

Category	Number
Longline number / length	1 / 50 m
Total number of chaplets	28
Chaplets with implanted oysters / oysters per chaplet	10 / 10
Chaplets with pre-implant oysters / oysters per chaplet	11 / 10
Cylinder/chaplets with juvenile oysters / oysters per cylinder	7 / 20
Production length after implant (months)	12
Nuclei per oyster	3
Juveniles required for nursery phase	126
Number of oysters implanted (pre-implant)	103
Oysters harvested annually for mabé pearls	100
Number of saleable pearls produced annually	231
Nursery phase mortality – farm arrival to implant	18%
Production mortality – implant to harvest	2.5%

5.2.3.2 Juvenile supply

In support of sector development, hatchery produced *Pt. penguin* juveniles are currently provided to Tongan pearl farmers by the Tongan Government (MoF) hatchery facility free of charge. On this basis, the cost per juvenile oyster was set at zero in this study.

5.2.3.3 Nucleus profile and implantation arrangement

Gordon et al. (2019) recently demonstrated that the number and arrangement of nuclei implanted into *Pt. penguin* may affect the quality of resulting mabé pearls. The study suggested that optimal results are achieved when one ‘high’ profile nucleus (height of 9 mm) was implanted in the posterior-ventral position of the left shell valve, and two low profile nuclei (height of 6 mm) were implanted in both the anterior-ventral position of the left shell valve and the centre of right shell valve if space permits (Figure 5.2).

Our economic modelling is based on the implantation of three nuclei per oyster consisting of one ‘high’ profile nuclei and two ‘low’ profile nuclei as recommended by Gordon et al. (2019). The cost associated with the purchase of nuclei was USD 0.19 per high profile nucleus and USD 0.14 for low profile nuclei. As the modelling is based on a 12-month production cycle, the purchase of nuclei over the 20-year time frame is steady with the first purchase of 309 nuclei required in year three, consisting of 103 high profile nuclei and 206 low profile nuclei.

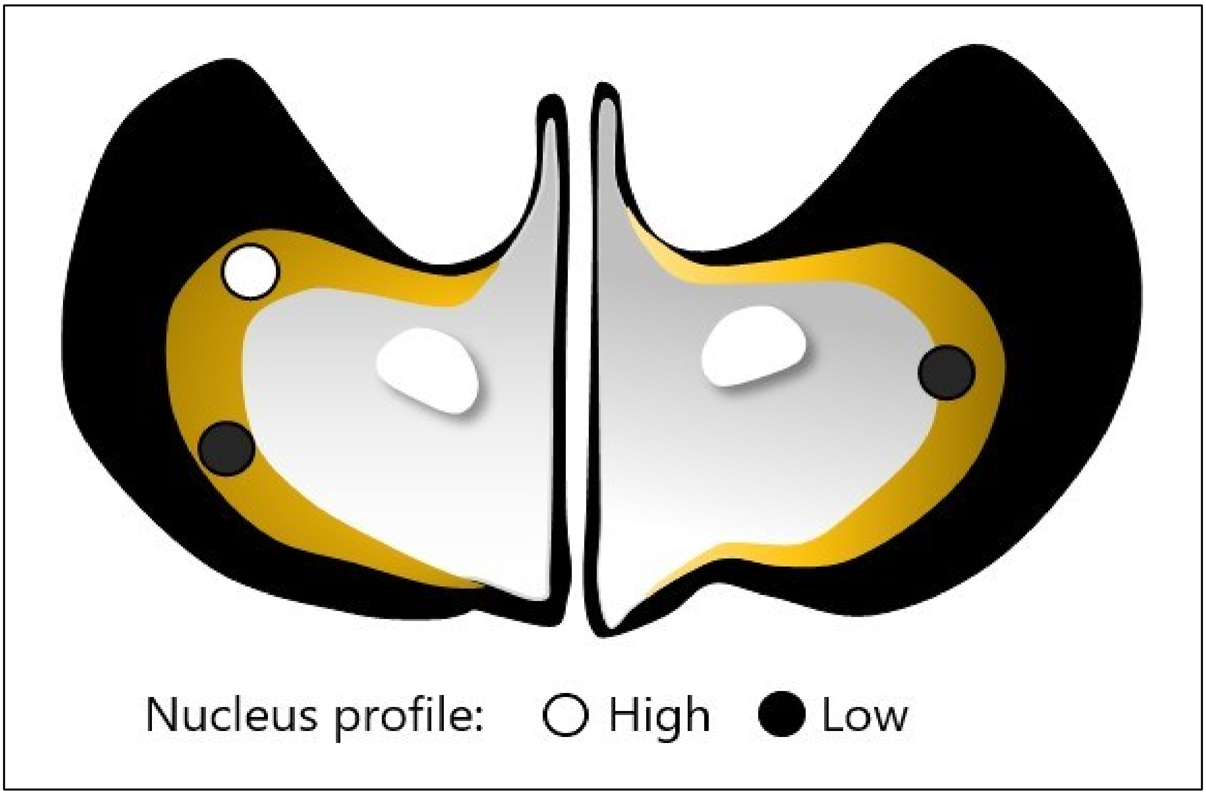

Figure 5.2 Suggested optimal nucleus arrangement to maximise nacre thickness and quality of resulting mabé pearls produced by *Pteria penguin* (Gordon et al. 2019).

5.2.3.4 Pearl grading and marketing

Mabé pearl quality ranges from the highest AAA grade to C grade. Pearls graded NC have 'no commercial' value are given no value. Additionally, low value C grade pearls were also excluded in this study as the majority of their value is derived from value adding (e.g., Teitelbaum and Fale 2008). Only grades AAA through to B were assigned a wholesale price. The average wholesale domestic prices for the sale of mabé pearls in Tonga are shown in Table 5.4.

Table 5.4 Average wholesale domestic prices for Tongan mabé pearls ($ in USD).

Grade	Price per Pearl ($)
AAA	88
AA	66
A	44
B	22

5.2.3.5 Farm labour

The mabé pearl farm modelled in this study comprised a single 50-m longline that could be managed by local communities or individuals on a subsistence basis to enhance rural incomes (e.g., Southgate et al. 2019). A small-scale farming operation, as described, is likely to utilise latent labour resources, rather than external skilled labour. It is worth considering this portion of labour separately, as farm revenue outcomes are tied to it.

A recent FAO report stated that the annual average wage in Tonga is USD 4,020 (FAO 2017). Based on a 40-hour working week (allowing for four weeks leave) a flat hourly wage rate of USD 2.09 is the average (FAO 2017). However, for the farming unit modelled here, a wage rate of USD 1.55 was applied based on the wages of workers (employed by MoF) to support experimental aquaculture farming operations. Farm labour is broken down to the tasks required on an annual basis from purchase and deployment of equipment to pearl harvest. Table 4.5 outlines the breakdown of farming duties and description of farming tasks.

Table 5.5 Breakdown of farm labour required per production cycle to operate the modelled mabé pearl farm in Tonga.

Labour Component	Description	Annual Time Investment (Hours)
Oyster deployment	Purchase juvenile oysters from MoF and ear-hang in oyster cylinders.	16
Density reduction	Relocate every second pair of oysters to a new chaplet.	16
Implant mature oysters	Implant oysters with pearl nuclei at a rate of approximately three oysters per hour.	40
Pearl harvest	Harvest mabé pearls 12 months after nucleus implantation.	24
Oyster cleaning	Remove biofouling from oyster chaplets.	192
Farm maintenance and other requirements	Check longlines for damage and maintenance requirements and oysters for mortality and predation.	202

Biofouling can be a significant issue that increases operational and economic costs associated with pearl production and requires a significant proportion of farm labour to control (Pit and Southgate, 2003; de Nys and Ison, 2008; Bertucci et al. 2016). Labour for pearl nucleus implanting was accounted for on the basis of implanting 20 oysters per day at a minimum hourly wage rate for Tonga of USD 1.55 per hour, but incorporates broader implantation requirements such as area preparation, opening of the oysters ready for implantation, the implantation operation itself, and re-attachment of implanted oysters to chaplets ready for redeployment to the longline.

5.2.3.6 Additional operating costs

This section of the economic model accounts for any additional operating costs not captured in the broader modelling exercise. These include fuel and oil, electricity, repairs and maintenance, accounting and legal, office and administration, government fees and charges, phone, travel, vehicle registrations and insurances as outlined in Table 5.6.

Table 5.6 Additional annual operating expenditure for the modelled mabé pearl farm in Tonga ($ in USD).

Cost Item	Annual Cost ($)
Fuel, oil and electricity	308
Repairs and maintenance	101
Travel	132
Phone	53
Sundries (incl. fees, glue, drill bits, brushes, knives, scissors, buckets)	50
Total	**644**

5.2.3.7 Capital expenditure

Capital costs of mabé pearl farms are divided into five main components: (1) land and buildings; (2) farm infrastructure and production equipment (i.e., chaplets); (3) diving equipment; (4) implantation equipment; and (5) miscellaneous (e.g., tools). Capital equipment bought at farm inception is replaced at pre-determined periods over the 20-year life of the farming project. Replacement costs are estimated as the amount of money required to replace capital items, net of its salvage or trade-in value. The initial year of capital purchase is year-0, and the model assumes that all relevant capital is sold, and proceeds enter the cashflow as a revenue stream in year-20. Farm infrastructure and equipment costs used in this modelling exercise are shown in Table 5.7.

Table 5.7 Farm infrastructure and equipment costs for the modelled mabé pearl farm in Tonga ($ in USD).

Item	Units	Value / Unit ($)	Total Value ($)	Salvage Value (%)	Year of Purchase / Replacement
Implantation structure	1	132	132	40	0,20
Longline rope (16 mm)	50 m	2.13	107	0	0,5,10,15
Anchor rope (12 mm)	120 m	0.97	116	0	0,5,10,15
Anchor blocks	8	8.80	70	0	0,10
Buoys	24	28	672	0	0,10
Chaplet rope (4 mm)	84 m	0.25	21	0	0,5,10,15
Chaplet sundries (fishing line, mesh, shark clips, cable ties)	-	-	90	0	Variable
PVC pipe	4.4 m	2.10	9.24	0	0,10
Wet suits	1	50	50	0	0,3,6,9,12,15,18
Mask, snorkel and fins	1	88	88	0	0,3,6,9,12,15,18
Weight belt	1	50	50	80	0,5,10,15
Implant rack and openers	1 set	395	395	50	0,5,10,15
Drill	1	75	75	0	0,3,6,9,12,15,18
Government licence fee (one-off)	-	-	152	0	0
Total			**2,027**		

5.3 Results

5.3.1 Farm output summary

The mabé pearl farm modelled in this study produced 231 saleable mabé pearls annually. Annual gross revenue from mabé pearl the sales totalled USD 11,757 (USD 50.98 per saleable pearl), while annual production costs totalled USD 2,420 (USD 10.49 per saleable pearl). A breakdown of the mabé pearl farm cost structure is shown in Table 5.8. Farm labour for mabé pearl production (USD 3.05), marketing (USD 2.55), and capital (USD 1.67) made up the largest cost components of around 29%, 24% and 16%, respectively (Table 5.8).

Table 5.8 Breakdown of annual production costs for the modelled mabé pearl farm in Tonga ($ in USD).

Cost Item	Average Annual Units	Annual Cost ($)	Cost per Pearl ($)
Pearl nuclei	278	43	0.19
Implantation labour	40 hours	55	0.24
Farm labour	430 hours	704	3.05
Fuel and energy		308	1.34
Marketing		588	2.55
Repairs and maintenance		101	0.44
Other operating		235	1.02
Capital purchase and replacement		386	1.66
Total		**2,420**	**10.49**

5.3.2 Net Present Value (NPV)

NPV over the 20-year life of the project, using a discount rate of 6%, was USD 107,101. As shown in Figure 5.3, the model indicates that it would take four years to recoup the original investment in the project.

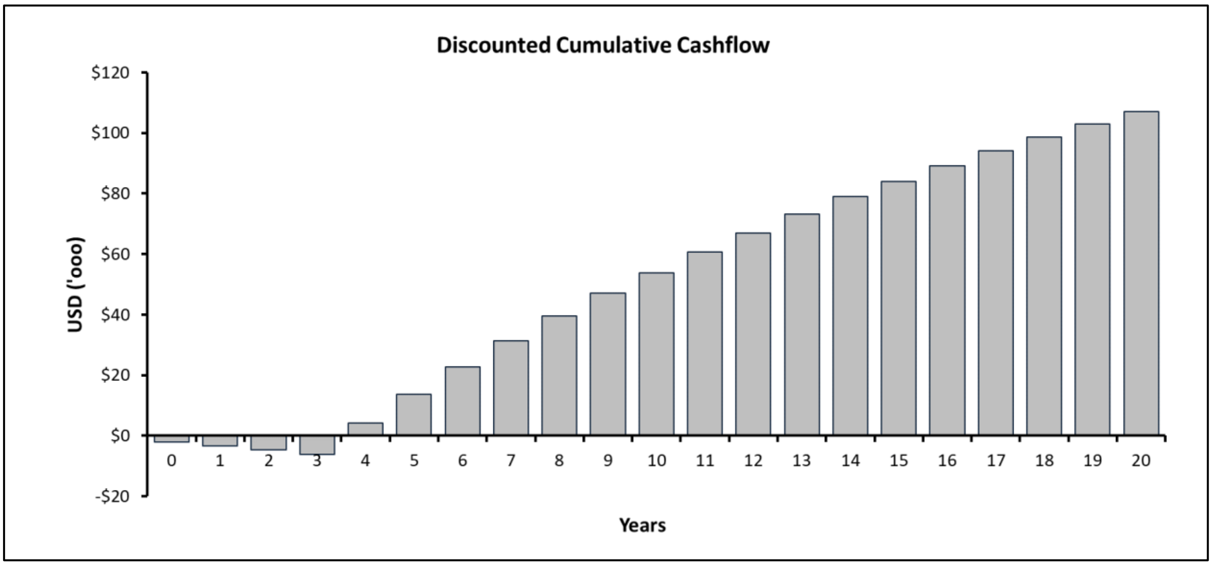

Figure 5.3 Discounted cumulative cashflow for the modelled mabé pearl farm in Tonga ($ in USD).

5.3.3 Other economic indicators

Results of the analysis are shown in Table 5.9 with some additional economic indicators. The MIRR was 20.46%, BCR was 4.86, and a payback period of four years was estimated (Table 5.9).

Table 5.9 Summary of profitability results and other economic indicators for the modelled mabé pearl farm in Tonga.

Measure	Result
Modified Internal Rate of Return (MIRR)	20.46%
BCR	4.86
Payback period	4 years

5.3.4 Risk analysis

Various methods have been employed to assist estimation of input risk distributions with a degree of confidence to reflect the risky environment of pearl farming in the south Pacific. To improve our understanding of risk, and adoption of the economic model as a business tool, a number of stakeholder workshops were undertaken to enhance risk assessment by mabé pearl farmers in Tonga (Johnston et al. 2015). As an example, production risks that were identified as 'significant' during these workshops, delivering 'poor' to 'average' mabé pearl production, included category 3 to 4 tropical cyclones, flood events that reduced salinity to <25 ppt, and chronic disease of oyster stock. Each was assigned a probability of occurrence and combined to provide the probability in the related distribution.

Table 5.10 Production (over the 20-year life of the project) and price distributions for mabé pearl culture with associated cumulative probabilities.

Description	Production (No. of Saleable Pearls)	Cumulative Probability (%)
Minimum	0	0
Poor	461	10
Average	2,306	30
Good	3,459	80
Maximum	4,612	100
Description	**Price per Pearl ($)**	**Cumulative Probability (%)**
Minimum	40.79	0
Poor	45.89	20
Average	50.98	70
Good	56.08	90
Maximum	61.18	100

For the mabé pearl culture farm modelled here, risk analysis (see section 2.2.2, Equation 3) focused on two key parameters, price and production, and five-point distributions were used for both variables (Table 5.10). Minimum production is zero because in Tonga there is potential for cyclones and disease to wipe out annual pearl farm production. A 'poor' production result would set 10% of expected production levels, hence 461 saleable pearls. The 'maximum' point in the distribution of pearls was set at 4,612 and represents the maximum number of pearls that could be sold if all surviving implanted oysters produced saleable mabé pearls between AAA and B grade. The 'average' point in the distribution for production was set at 50% of the modelled pearl production. The 'good' point in the distribution for production was estimated as the midpoint between the 'average' point and the 'maximum' point (75%).

The average price for a saleable pearl from the modelled mabé pearl farm was USD 50.98. This was used to set the 'average' point in the distribution. Remaining distribution points were based on a 10% variance from the 'average', based on stakeholder input. Probabilities were determined following stakeholder input to identify and categorise risks from severe to mild, and their probabilities of occurrence (Johnston et al. 2015). Simulation output is the NPV. The highest NPV was USD 228,597, while the lowest was –USD 27,546 (Figure 5.4). The average NPV produced by the simulation was USD 97,191. Incorporation of production and price risk reduced the expected NPV at steady state by USD 9,910 after risk is applied. This represents a 9.25% correction in the expected NPV. The probability of the small-scale mabé pearl farm making a loss (where the distribution intersects the y-axis; Figure 5.4) is approximately 15%.

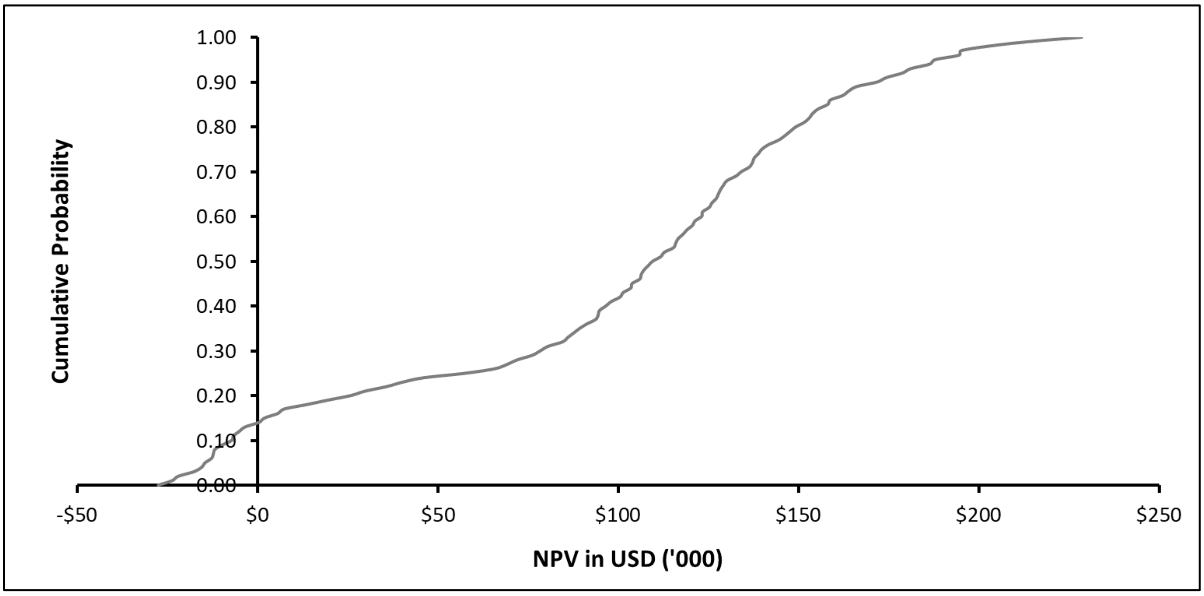

Figure 5.4 Cumulative probability distribution of NPV for the small-scale Tongan mabé pearl farm modelled in this study (variables: price and production) ($ in USD).

5.4 Discussion

This study investigated the economics of small-scale mabé pearl farming in Tonga for the first time. Our modelling indicated an annual profit from the modelled farm of approximately USD 9,338, after all costs, including owner/operator wages. This is more than twice the average annual income in Tonga of USD 4,020 (FAO 2017) and can be achieved with an estimated labour input of 490 h per annum, or 9.4 h per week. On this basis, mabé pearl production is not only profitable, but is also compatible with local lifestyles and allows mabé pearl farmers to maintain viable pearl farms on a subsistence basis and accommodates continuation of other income generating and subsistence activities. It is interesting to note that this level of profitability relates to mabé pearl production only, it does not include potential value-adding activities such as production of mabé pearl and pearl shell jewellery and handicrafts, which may be conducted by the farmer, family and extended family members, or independent artisans. Harvesting mabé pearls involves cutting them from host oyster shells, and so as well as mabé pearls, a considerable volume of MOP shell pieces may be produced as a by-product. Mabé pearls, as well as MOP offcuts, provide a basis for value-adding activities that offer further income generating opportunities for communities and strengthen the viability of farming operations; this aspect is not modelled in the present study. There is strong demand for mabé pearl and MOP items in both the domestic tourist market in Tonga and overseas.

5.4.1 Realising the potential of mabé pearl culture in Tonga

There has been a rapid expansion of the mabé pearl culture sector in Tonga over recent years. There were four operational mabé pearl farms in 2008. More recently, an additional 15 community mabé pearl farms are in operation bringing the number of mabé pearl farms up from nine farms in 2015to 24 farms in 2022 (Southgate et al. 2023). Mabé pearl culture now occurs in all three island groups within the Tongan archipelago (Vava'u, Ha'apai and

Tongatapu; Chapter 1). Given the potential economic benefits reported here, as well as the livelihoods opportunities afforded by mabé pearl farming, it is not surprising that development of the mabé pearl farming sector, and its associated value-adding activities, is a priority of the Tongan government. This expansion has been possible through investment in research to simplify methods for hatchery production of *Pt. penguin* spat (Southgate et al. 2016) on which the sector relies, development of more efficient ocean-based culture methods for juvenile and implanted oysters (Gordon et al. 2020), improved pearl culture and quality control techniques (Gordon et al. 2018, Gordon et al. 2019), and institutional capacity building that have collectively supported a rise in annual mabé pearl production to around 4,680 pieces (Southgate et al. 2023, Chapter 1). There is likely to be continued opportunity for expansion of the Tongan mabé pearl farming sector into the future. In 1997 the Food and Agriculture Organisation of the United Nations (FAO) commissioned a report into the potential for commercial development of mabé pearl farming in the Vava'u island group of Tonga. As outlined in Chapter 1 the report estimated that, in the Vava'u islands alone, up to 850 hectares could be dedicated to mabé pearl culture, with a potential annual harvest of 750,000 mabé pearls that could generate around USD 7,500,000 (Tanaka, 1997).

5.4.2 Impediments and solutions to future development

Previous studies have highlighted potential bottlenecks to development of the mabé pearl sector in Tonga, including availability of basic culture items such as ropes, buoys and culture containers, standardisation of culture methodology across farms, limited access to boats required to service farm infrastructure, reliability of spat supply from the government-run hatchery, and the need for training for value-adding activities to maximise potential economic benefits (Johnston et al. 2015). As mentioned above, reliable hatchery production is now routine, and the cylinder-based culture method recently adopted by farmers has greatly improved survival of cultured juveniles and resulted in an approximate 50% reduction of the culture period required for oysters to reach mabé pearl production size (Gordon et al. 2020). However, pearl oyster juveniles are currently supplied to farmers from the government hatchery free of charge and the government is considering the possibility of charging farmers for juveniles as a means of cost-recovery. Prior economic research has examined hatchery production of *Pt. penguin* in the Tongan Government run hatchery and determined that the production cost of each oyster juvenile provided to mabé pearl farmers is approximately USD 2. The economic model developed here can be used to assess the economic impact to Tongan mabé pearl farmers should charges for oyster juveniles be introduced. It indicates that even if a charge as high as USD 5 per spat/juvenile were charged to farmers, the resulting fall in NPV from USD 107,101 to USD 99,875 (a decrease of approximately 7%) still brings substantial economic benefits. In fact, the small-scale farm modelled here generates sufficient profits to absorb potential costs around USD 74 per juvenile oyster, well above what a commercial hatchery facility might charge. The number of juveniles required annually over the life of the farm modelled in this study is 126. Increases in the number of farmed *Pt. penguin* in the Vava'u island group of Tonga had led to increasing reports of naturally recruited pearl oyster spat associated with pearl culture equipment. Current research is assessing whether collection of wild pearl oyster spat (Kishore et al. 2018; Johnstone et al. 2020) could become a supplemental source of oysters for Tongan mabé pearl farmers.

5.5 Conclusions

This study has shown that a small scale mabé pearl farm can generate in excess of USD 9,000 in annual profits for mabé pearl farmers or communities without the requirement for high capital input or technical skills. Furthermore, the time commitment required to implant oysters and maintain the culture apparatus through to harvest equates to less than ten hours per week, allowing continuation of other income generating and subsistence activities. Our economic analysis was based on a small mabé pearl farming comprising a single 50-m longline supporting 103 implanted oysters; it offers a profitable scale of production for experienced mabé pearl farmers and a good basis for potential entrants to the sector, recognising the possibility for up-scaling. Addition of more culture units or longlines to the farm, as skills develop and profits are re-invested, could move farm operations from small-scale part-time ventures to larger-scale commercial operations. The economic models developed in this study can be used to inform existing and prospective industry participants, government departments, research and extension agencies and donors, policy makers and NGOs, describing the inputs required to establish and maintain viable and sustainable mabé pearl industry-based livelihoods and businesses. Although focused on Tonga, the results of this study have broad regional relevance, particularly in the Pacific region where pearl farming is the most valuable and highest priority aquaculture activity (SPC 2007, Ponia 2010) providing considerable livelihood benefits (Southgate et al. 2019).

Chapter 6: Production cost of farm-ready pearl oysters (*Pteria penguin*) used for mabé pearl production in the Kingdom of Tonga

Data from this chapter were published as: **Johnston, W.**, Wingfield, M., Gordon, S., Halafihi, T. and Southgate, P.C. 2020. Production cost of the farm-ready pearl oyster *Pteria penguin* used for mabé pearl production in the Kingdom of Tonga. Journal of Shellfish Research. 39(3): 671-677.

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers' comments, submission, and accepted publication in peer reviewed journal.

6.1 Introduction

Like many Pacific Island countries, Tonga has developed cultured pearl production to facilitate economic prosperity and enhance livelihood opportunities for coastal communities. (Southgate et al. 2019). French Polynesia, the Cook Islands and Fiji, for example, developed round pearl culture on a commercial scale using the black-lip pearl oyster, *Pinctada margaritifera* (Southgate et al. 2008, Tisdell and Poirine, 2008, Chapter 2, Chapter 3). The Kingdom of Tonga (Tonga) is unique among the south Pacific countries engaged in pearl culture, focussing solely on mabé pearl (half-pearl) production utilising the winged pearl oyster *Pteria penguin*. Mabé pearl production is relatively simple, requiring fewer resources, than round pearl production (Gordon et al. 2018, 2019) and may be achieved solely by community members following appropriate training (Southgate et al. 2019). As outlined in Chapter 5 mabé pearls are produced by gluing hemispherical nuclei to the inner shell surfaces of oysters followed by a culture period of around 12 months that allows successive layers of nacre to cover the nuclei to produce mabé pearls (Taylor and Strack 2008, Kishore et al. 2015, Gordon et al. 2018).

Mabé pearl production offers a range of income generating opportunities for stakeholders including direct sale of resulting pearls, and production of value-added pearl and MOP jewellery and handicraft items (Southgate et al. 2019, Southgate et al. 2023). As reported in Chapter 5 a community-based, subsistence level farm, producing mabé pearls from 100 implanted *Pt. penguin* annually, had an estimated an annual production of 231 saleable pearls, generating a potential profit of USD 9,338 per annum. At this level of profitability, the modelled pearl farm generates more than double the average annual income in Tonga (FAO 2017, Chapter 5).

A major developmental bottleneck for the mabé pearl sector in Tonga was an initial reliance on wild spat collected for culture stock (Southgate et al. 2016). Although spat collectors were deployed to collect wild spat (e.g., Kishore et al. 2018), poor recruitment forced pearl farmers to turn to the collection of adult oysters from the wild (Southgate et al. 2016). This practice resulted in a continued decline in recruitment of spat. The Ministry of Fisheries in Tonga (MoF) attempted to address this issue through the establishment of a part-time pearl oyster hatchery at Sopu on the main island of Tongatapu. A more stable supply of hatchery produced *Pt. penguin* spat (Southgate et al. 2016), and ongoing development of more efficient hatchery and nursery culture methods for juvenile oysters (Gordon et al. 2020), has supported significant expansion of the Tongan mabé pearl sector over recent years. At last count, in 2022, there were 24 mabé pearl farms and communities operating across the three largest island groups in Tonga, producing approximately 4,680 mabé pearls annually (Southgate et al. 2023).

The MoF currently supplies juvenile pearl oysters (post-nursery phase) to pearl farmers at no cost; however, it is likely that this will change to a cost recovery operation as the sector matures and the financial capacity of farms increases. The aim of this study was therefore to determine the operational costs of the MoF pearl oyster hatchery in Tonga, and to provide an estimate of hatchery operation costs and the production cost of individual oysters supplied to mabé pearl farmers. Future cost recovery is seen as a step towards a sustainable long-term future for the Tongan mabé pearl sector that is less reliant on external support. There are few operational mariculture hatcheries in the south Pacific region that support the development of national aquaculture industries. This is due to limiting factors such as access to establishment capital and operational funds in the early stages of development, lack of regular or ongoing technical support or expertise, and site availability or other spatial resources (Sarkis and Lovatelli, 2007). Although predominantly focused on Tonga, the study's results will have broader relevance in the Indo-Pacific region where hatchery production is likely to have a key role in the future development of high-value aquaculture opportunities.

6.2 Materials and methods

Cost and price data used in this modelling exercise were collected through one-on-one interviews with MoF hatchery staff. Further, additional data were applied from relevant recent studies (e.g., Gordon et al. 2019, Gordon et al. 2020) to improve modelling and outputs.

6.2.1 Development of the economic model

The economic model for hatchery production of *Pt. penguin* in Tonga was based upon a discounted cashflow framework with a twenty-year horizon as applied in Chapter 5 to estimate the costs of producing viable *Pt. penguin* juveniles for local mabé pearl farmers.

The economic indicators used in this Chapter include the NPV, EAR, BCR, MIRR and the payback period (section 2.2.2, section 4.2.1). The MIRR in this Chapter is calculated using loan rates as specified in Chapter 5. Estimated annual benefits were developed using revenues generated from the domestic sale of mabé pearls. Average prices for the various grades of mabé pearls were estimated from a number of interviews with existing pearl farmers and wholesalers in Tonga. Sale of value-added pearl products such as jewellery and handicrafts were not included in the analysis. All of the capital, variable and fixed costs were estimated from interviews with the hatchery facility manager and relevant Government staff.

6.2.2 Hatchery and nursery production

The MoF pearl oyster hatchery facility is located at Sopu on the main island of Tongatapu in Tonga (21º07’20’’S 175º13’35’’E). In past years, the hatchery conducted up to three oyster production runs per year using mature wild collected broodstock. But improved hatchery and nursery culture methods (Southgate et al. 2016; Gordon et al. 2020) have greatly improved oyster survival, and currently, only one annual hatchery production run is sufficient to meet annual demand for juvenile oysters. The single hatchery run occurs over a 67-day period with the major breakdown of associated inputs and activities shown in Figure 6.1.

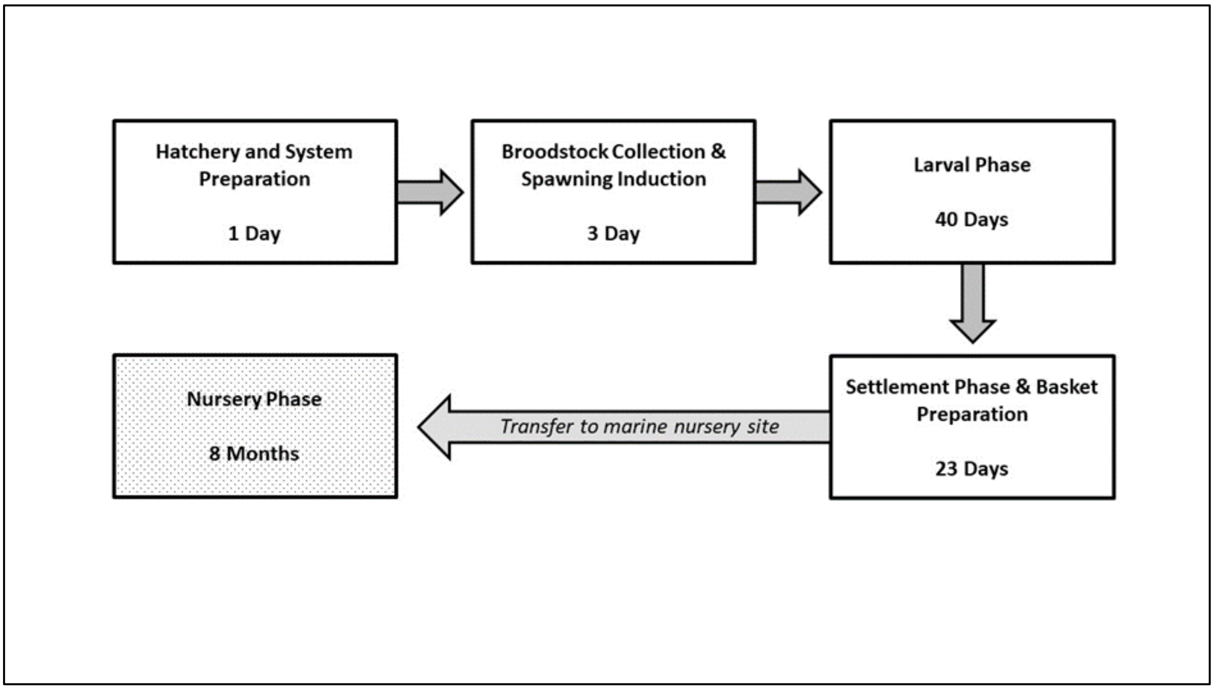

Figure 6.1 Timeline (over 67 days) for a single *Pteria penguin* hatchery production run at the Ministry of Fisheries hatchery at Sopu, Tonga. Nursery phase duration is estimated at ten months.

Allowing for transport mortalities of juvenile oysters from nursery culture systems to pearl farms, approximately 6,600 oysters are required to support annual mabé pearl production in Tonga.

Larval development and hatchery production of *Pt. penguin* are well documented (Wassnig and Southgate 2012, Southgate et al. 2016). The hatchery expects to produce 60 million eggs from the broodstock spawning event. Table 6.1 outlines the expected targets and survival rates for each of the steps from spawning through to settlement, and nursery site to farm. These figures are based on averages deduced from ten years of hatchery production using a standardised hatchery protocol, and they are used as a basis for the modelling reported here.

Table 6.1 Expected hatchery production targets and survival rates per run.

Phase	Number	Survival (%)
Eggs stocked into larval culture tanks	60 million	-
Viable larvae produced	40 million	66.67
Stocked larvae	30 million	75
Settlement ready larvae	6 million	20
Settled spat transferred to ocean-based nursery	200,000	3.33
Number of farm-ready oysters for distribution	12,000	6

Beyond the 67-day hatchery production run, resulting oyster spat are transferred to the MoF ocean-based nursery site, off-shore from the hatchery at Sopu where they are monitored and maintained by MoF staff. Once most oysters have reached a minimum dorso-ventral shell height (DVH - Gordon et al. 2017) of 30 mm (with a range of 30-85 mm), they are distributed to mabé pearl farmers. It is expected that once transported to the farm, oysters will be further grown until they reach a DVH of 100-140 mm when they are implanted with nuclei for mabé pearl production (Gordon et al. 2018, 2019). Up until nucleus implantation, oysters are attached to chaplets that are housed within protective mesh cylinders (Gordon et al. 2020, Figure 6.2) which supports survival rates of >90% (Gordon et al. 2020). From nucleus implantation to pearl harvest the expected mortality of oysters falls significantly to 2.5% (Gordon et al. 2019).

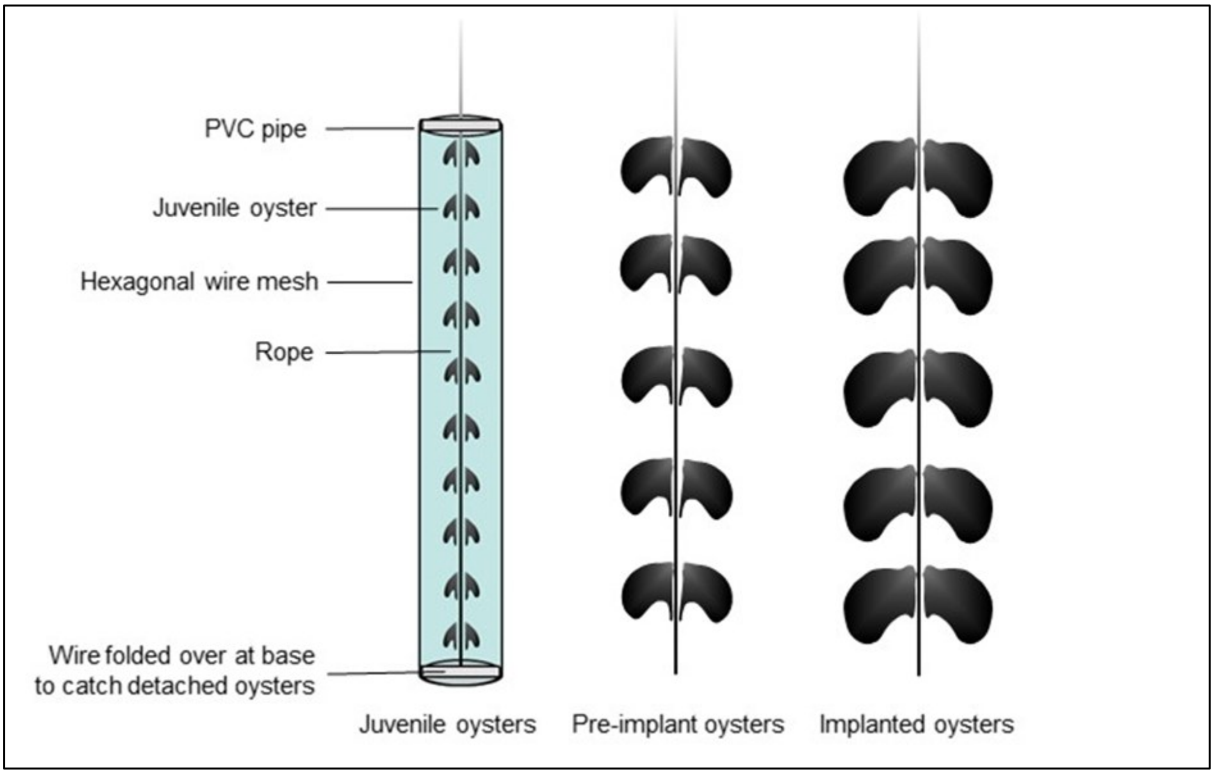

Figure 6.2 Representation of the farming protocol for mabé pearl production using *Pteria penguin* in Tonga. Chaplets containing juvenile oysters are housed in protective mesh cylinders (left) and chaplets containing larger pre-implanted and implanted *Pteria penguin* (middle and right) are cultured without protective cylinders (Gordon et al. 2020).

6.2.3 Cost Components of the economic model

Although the number of hatchery production runs conducted per year may vary according to demand, the economic model developed here assumes a single annual production run, consistent with most years. Hatchery operation occurs from mid-spring and early summer when it is generally more successful.

6.2.3.1 Hatchery labour

Hatchery operation modelled in this study comprises 67 days of continuous operation from hatchery and system preparation through to settlement and nursery culture unit preparation. Total labour resources are described as 'days required' for the hatchery run, rather than based on individuals. All staff are employed by MoF, and the daily wage rate described in Table 6.2 is based on an 8-hour working day.

Table 6.2 Breakdown of labour required per hatchery run ($ in USD).

Labour Component	Days Required	Daily Wage Rate ($)
Lead technician	67	36.00
Technician	67	22.50
Labourer	63	11.25
Maintenance and engineering	12.8	22.50

The total hatchery-based labour resource required to complete a hatchery run in Tonga is 210 days at a total cost of USD 4,916.

6.2.3.2 Nursery labour

Five to ten days after oyster spat have settled, they are transferred to sea (from hatchery to basket culture on a nursery long-line, using locally available plastic mesh baskets). The ocean transfer generally coincides with favourable tides and weather conditions to maximise survival of oysters and minimise stress. The nursery phase of the operation continues for around eight months until the oysters reach a size that they can be moved to commercial farms (30-85 mm DVH). This requires and investment by MoF staff of 45 days annually, based on fortnightly maintenance over an 8-month period. The Tongan Government provides an additional 'sea bonus' to base wages for staff that are regularly required to undertake duties offshore. For example, a hatchery technician receives USD 22.50 per day while a nursery technician with sea bonus receives USD 26.25 per day (16.67% bonus). Maintenance and engineering staff do not receive a sea bonus. Table 6.3 outlines the allocation of labour across different categories of staff.

Table 6.3 Breakdown of nursery labour required to maintain the ocean-based nursery site annually ($ in USD).

Labour Component	**Days Required**	**Daily Wage Rate ($)**
Technician	14	37.50
Labourer	28	26.25
Maintenance and engineering	3.2	22.50

The total nursery-based labour resource required annually in Tonga is 45 days at a total cost of USD 1,332.

6.2.3.3 Additional operating costs

This section collects any additional operating costs not previously captured in the broader modelling exercise. Major costs covered here include electricity for pumping of seawater and powering hatchery, fuel and oil, repairs and maintenance (set at 5% of capital annually), hatchery consumables, and transport and packaging of oysters to commercial farms. All operating costs are outlined in Table 6.4.

Table 6.4 Additional annual operating expenditure ($ in USD).

Cost Item	Annual Cost ($)
Electricity – pumping seawater	1,000
Electricity – hatchery and offices	300
Repairs and maintenance	954
Hatchery consumables:	
* Algal paste	338
* Filter socks	90
* Larval nets	158
* Liquid chlorine	135
* Buckets and tubs	113
* Air hoses and stones	38
* Miscellaneous hardware	75
Fuel and oil	308
Transport and packaging	80
Total	**4,387**

6.2.3.4 Capital expenditure

The capital costs associated with initial hatchery establishment and ongoing operation of the pearl oyster hatchery (including nursery) at the MoF facility in Sopu are divided into four main components: (1) hatchery infrastructure; (2) boats and vehicles; (3) nursery equipment; and (4) diving equipment. Any capital equipment that is purchased to establish the hatchery is replaced at pre-determined intervals over the 20-year life of the hatchery. The replacement cost of capital equipment is calculated as the new purchase price of the item less its trade in value, also known as its salvage value. The initial purchase of capital for the hatchery is denoted as year-0, and at the end of the 20-year project life the model assumes that all capital is sold with the proceeds to enter the cashflow in year-20. Hatchery and nursery infrastructure and equipment costs that are used in the modelling are described in Table 6.5.

Table 6.5 Hatchery and nursery infrastructure and equipment costs for production of *Pteria penguin* pearl oysters ($ in USD).

Item	Units	Value / Unit ($)	Total Value ($)	Salvage Value (%)	Year of Purchase / Replacement
Larval rearing tanks	6	440	2,640	20%	0,10
Boat	1	5,000	5,000	20%	0,10
Outboard motor	1	3,000	3,000	40%	0,5,10,15
Vehicle (utility)	1	5,000	5,000	40%	0,10
Nursery longline (16 mm)	100 m	2.13	213	0%	0,5,10,15
Anchor lines (12 mm)	240 m	0.97	233	0%	0,5,10,15
Anchors	16	8.80	141	0%	0,10
Buoys	48	28	1,344	0%	0,10
Juvenile baskets	120	11	1,320	0%	0,5,10,15
Wetsuits	1	50	50	0%	0,3,6,9,12,15,18
Weight-belts	1	50	50	80%	0,5,10,15
Mask, snorkel, and fins	1	88	88	0%	0,3,6,9,12,15,18
Total			**19,079**		

6.3 Results

6.3.1 Hatchery and nursery output summary

The pearl oyster hatchery analysed in this study produces 6,600 saleable oysters (post-nursery) annually. Annual production costs totalled USD 13,263, equivalent to USD 2.01 per saleable oyster. A breakdown of the hatchery and nursery cost structure is shown in Table 6.6. Hatchery labour for oyster spat production (USD 0.75), capital purchase and replacement (USD 0.40), and electricity (USD 0.20) make up the largest components of cost at around 37%, 20% and 10%, respectively.

Table 6.6 Breakdown of annual costs for hatchery production and nursery culture of *Pteria penguin* oysters in Tonga ($ in USD).

Cost Item	Average Annual Units	Annual Cost ($)	Cost per Oyster ($)
Electricity		1,300	0.20
Repairs and maintenance		954	0.14
Hatchery consumables		945	0.14
Hatchery labour	210 days	4,916	0.75
Nursery labour	45 days	1,332	0.20
Other operating		1,188	0.18
Capital purchase and replacement		2,628	0.40
Total		**13,263**	**2.01**

6.4 Discussion

This chapter investigated the economics of producing *Pt. penguin* to supply the mabé pearl culture sector in Tonga and is the first account of the early production costs for any species of pearl oyster. The modelling indicates that production of *Pt. penguin* juveniles to supply pearl farmers (including nursery phase) costs USD 13,263 annually which, accounting for expected mortality, is equivalent to USD 2.01 per juvenile oyster to the point of shipping to mabé pearl farmers. The pearl oyster hatchery in Tonga currently operates on a part-time basis because it is a multi-purpose facility that undertakes a range of fisheries and aquaculture research projects for the Tongan Government.

The Tongan mabé pearl sector relies on hatchery production of spat. Research to develop improved and simplified hatchery production methods (Southgate et al. 2016) and to standardise culture methods for both non-implanted and implanted oysters that improve survival (Gordon et al. 2020) has overcome major production bottlenecks supporting sector development. Juvenile pearl oysters are currently provided to mabé pearl farmers at no charge.

However, as the Tongan pearl sector matures and the financial capacity of farms increases, some level of cost recovery is likely to be considered. At present the pearl oyster hatchery is also supported by external donor funding that provides a portion of hatchery operational funds as well as technical expertise. A hatchery independent of international support would require the ability to attract skilled labour to the facility while covering all operational costs. The multi-use facility operated by MoF provides significant support for hatchery production of pearl oysters through special resources, access to pumped and filtered seawater, and the necessary labour to support the day-to-day operations of the hatchery and the ocean-based nursery site; however, investment in skilled hatchery technicians, for example, may require funds generated by the sale of oysters to mabé pearl farmers.

Improved production protocols supported a rise in annual mabé pearl production in Tonga from 2,700 to 4,680 saleable mabé pearls between 2015 and 2018 (Southgate et al. 2023). The whole-farm economic model developed in Chapter 5 described a representative, subsistence level, small-scale Tongan mabé pearl farm, based on annual pearl production from 100 oysters. Annual profits from the 231 mabé pearls produced annually were estimated at USD 9,338. This level of profit is more than double the average annual income for workers in Tonga which is USD 4,020 (FAO 2017). This level of production and profitability can be achieved with a labour input of approximately 490 h per annum, or 9.4 h per week (Chapter 5). These estimates indicate that if charges for pearl oyster juveniles supplied to pearl farmers are considered in the future, the economic impact to farmers is manageable. For example, a 'cost-recovery' charge of USD 2 per juvenile would result in an annual cost to the farming operation of USD 254 and would generate a 2.7% reduction in annual profits. In terms of the production cost per saleable pearl produced by the farm, the above cost-recovery charge would represent USD 1.10 of a total production cost per pearl of USD 11.59; currently USD 10.49 per pearl under the no-charge scenario. In context, the average revenue per mabé pearl in Tonga is estimated to be USD 51 (Chapter 5). Using the whole farm economic model (Chapter 5) a charge of USD 2 per juvenile would represent 9.5% of the total production cost for the average farm, compared to farm labour (26%), marketing (21%), and capital depreciation and replacement (14.4%). Introduction of a cost-recovery charge of USD 2 per juvenile would therefore have minimal impact on the profitability of small-scale mabé pearl farms in Tonga that would continue to deliver substantial economic benefits well above the average annual income of most Tongans. In fact, the small-scale pearl farm modelled in Chapter 5 generates profits that could potentially absorb a charge of USD 74 per juvenile oyster, bringing the economic model to the breakeven point (NPV=0), noting that this price is well above what a commercial hatchery facility might charge.

Tonga is unique amongst most Pacific pearl-producing nations in that wild pearl oyster stocks are insufficient to support the industry through wild spat collection (e.g., Kishore et al. 2018), as occurs in other pearl producing nations, such as French Polynesia and Fiji. This remained a constraint to industry development until the hatchery reached an output level that addressed this bottleneck (Chapter 5). Economic assessments of pearl culture in a broader Pacific context are scarce, but production costs for other countries, where available, are summarised in Table 6.7.

Table 6.7 Summary of reported costs for pearl oyster juvenile and pearl production in Pacific pearl producing nations including Tonga ($ in USD). Round (black) pearls are produced using *Pinctada margaritifera* and mabé pearls are produced from *Pteria penguin*.

Country	Pearl Type	Production Cost per Pearl ($)	Supply Method	Cost per Juvenile Oyster ($)	Source
Marshall Islands	round (black)	19.15	Wild spat	-	Fong et al. (2005)
French Polynesia	round (black)	9.93	Wild spat	-	Poirine & Kugelmann (2003)
Fiji	round (black)	21.93	Wild spat	3.91	Chapter 2
Kiribati	round (black)	31.69	Wild spat	1.36	Tisdell & Poirine (2008)
Kiribati	round (black)	39.24	Wild spat	-	Tisdell & Poirine (2008)
Kiribati	round (black)	69.90	Wild spat	-	Tisdell & Poirine (2008)
Cook Islands	round (black)	25.43	Wild spat	0.27	Johnston (2006)
Fiji	mabé	9.21	Wild spat	1.27	Chapter 4
Tonga	mabé	10.49	Hatchery	0	Chapter 5
Tonga	mabé	-	Hatchery	2.01	This chapter

Information in Table 6.7 illustrates that the introduction of an arbitrary USD 2 cost-recovery charge for hatchery produced pearl oyster juveniles in Tonga, would not be excessive compared to similar costs to pearl farmers in other countries. However, introduction of a charge that generates revenue above cost recovery, such as USD 5 per juvenile oyster, could generate sufficient funds to cover hatchery and nursery operational costs as well as provide additional funds for reinvestment into maintenance and upgrading of culture facilities, provision of more advanced hatchery and nursery culture equipment, upgrading of vehicles and boats (improving reliability), and facility expansion supporting increased production in line with expansion of the Tonga mabé pearl sector. At present the hatchery supplies 6,600 juvenile oysters to mabé pearl farmers that, on the basis of a USD 5 charge per juvenile, could generate an annual profit of USD 19,737 above total hatchery production cost of USD 13,263. Modifying the whole-farm model developed in Chapter 5 to include a USD 5 charge per juvenile oyster, shows that the impact of this to the profitability of mabé pearl farmers is not considerable, with estimated annual profits of USD 8,708 and relative cost of USD 2.73 per saleable pearl, representing 20.6% of total production costs of USD 13.22 after the USD 5 is applied. This increase in production cost does reduce profits, but the production system is extremely robust economically, generating USD 3.86 per dollar invested at this proposed price point.

The Pacific pearl sector provides considerable livelihood opportunities for coastal communities (Southgate et al. 2019, 2023) and development of these opportunities is a priority in many south Pacific countries including Tonga (Tonga Ministry of Fisheries 2018). The outputs of the economic model developed in this study are valuable to pearl industry stakeholders including fisheries agencies, government departments, research and extension agencies and donors, policy makers and NGOs. The model outlines in detail the inputs required to establish and maintain a productive pearl oyster hatchery and nursery in the Pacific, utilising existing amenities. Although this study is based on the Tongan hatchery facility, the results have broad relevance in the Pacific region, where pearl farming generates the highest gross value of production (GVP) and is considered the highest priority aquaculture activity (SPC 2007, Ponia 2010). Mabé pearl production has proven to be highly profitable and complements the lifestyles of coastal communities. It allows mabé pearl farmers to operate profitable pearl farms at a subsistence level (part-time) with a relatively low labour input that allows continuation of additional income generating and subsistence activities for coastal community households.

Chapter 7: Influence of production method on the profitability of mabé pearl farming using traditional and research-informed nucleus implanting practices with the winged pearl oyster, *Pteria penguin*

Data from this chapter were published as: **Johnston, W.**, Gordon, S.E., Wingfield, M., Halafihi, T. and Southgate, P.C. 2022. Influence of production method on the profitability of mabé pearl farming using traditional and research-informed nucleus implanting practices with the winged pearl oyster, *Pteria penguin*. Aquaculture. 546: 737280.

Author Contribution: conceptualisation, methodology, data collection and curation, economic and statistical analysis, visualisation, writing original draft, managing publication process, addressing reviewers' comments, submission, and accepted publication in peer reviewed journal.

7.1 Introduction

Development of mabé pearl culture in Tonga using *Pteria penguin* has accelerated in recent years due to proven economic viability (Chapter 5) and the livelihood opportunities it offers through direct pearl sales, and through value adding activities such as jewellery and handicraft production (Southgate et al. 2019). Tonga is unique among south Pacific pearl producing countries in focusing on mabé pearl culture (Chapter 1), which requires reduced infrastructure, lower levels of investment and technical input, and reduced financial and production risks compared to round pearl culture (Chapter 2, Chapter 5).

As demonstrated in Chapters 4 and 5, mabé pearl production is a profitable rural livelihood activity for coastal communities in the south Pacific that is achievable by community members following appropriate training (Southgate et al. 2019). Mabé pearl production in Tonga has developed rapidly over recent years on the basis of rountine hatchery production of spat (Southgate et al. 2016), more efficient culture methods for oyster juveniles during the nursery phase (Gordon et al. 2020), and provision of oyster juveniles to pearl farmers at no cost. In 2022 there were 24 farms and communities collectively producing mabé pearls, an increase of approximately 300% (Southgate et al. 2023).

As reported in Chapter 5 of this thesis, mabé pearl production in Tonga, based on a community pearl farm harvesting 100 *Pt. penguin* annually, was shown to generate an annual profit of USD 9,338, which is significant considering the average annual income in Tonga is USD 4,020 per capita (FAO 2017). On this basis, mabé pearl farming offers significant economic opportunity and supports additional socio-economic benefits for rural communities involved in downstream activities relating to handicraft and jewellery production, and tourism (Mikhailovich et al. 2019).

Mabé pearls are produced by attaching (gluing) hemispherical nuclei to the inner surfaces of an oyster shell (implantation) where, over a culture period of around 12 months, nuclei are covered with successive layers of nacre or MOP, produced by the mantle tissue of the oyster (Taylor and Strack 2008, Kishore et al. 2015, Gordon et al. 2018, Chapter 5). Resulting mabé pearls, are then harvested by cutting them from the shell (Strack 2006, Taylor and Strack 2008). Tonga mabé pearl farmers may implant up to five or six nuclei per oyster (> 170 mm dorso-ventral measurement) to maximise yield. Most commonly, farmers implant four high-profile nuclei with a height of 9 mm, and this is considered the 'traditional' method of implantation. However, recent research reported improved mabé pearl quality when only three nuclei were implanted, as a combination of one high-profile (9 mm height) and two low-profile (6 mm height) nuclei (Gordon et al. 2019; Fig 5.2). This three-nucleus arrangement has since become best practice within the Tongan mabé pearl sector. Although this has provided the basis for extension activities (Wingfield et al. 2020), validation of the economic impact of this shift in production practice has not been investigated. The aim research in this chapter was therefore to compare these two pearl production protocols as suggested by Gordon et al. (2019). The results of this study will help define the most profitable option for mabé pearl production in Tonga, supporting further development of the sector with broader regional significance.

7.2 Materials and methods

The economic modelling method utilised in this study was previously used to assess subsistence level mabé pearl production in Tanzania (Saidi et al. 2017) and mabé pearl production in Tonga (Chapter 5). The economic data used to inform the modelling was based on information collected through business skilling workshops, stakeholder interviews and annual surveys of the mabé pearl sector by the Tongan Ministry of Commerce and Labour that began in 2015 (Chapter 2). Additional data were collected and applied from more recent studies (e.g., Gordon et al. 2019; Gordon et al. 2020) where possible, to improve the modelling and outputs. All costs reported here relate to US dollars (USD).

7.2.1 Development of the economic model

The economic model for hatchery production of *Pt. penguin* in Tonga was based upon a discounted cashflow framework with a twenty-year horizon as applied in Chapter 5 to estimate the costs of producing viable *Pt. penguin* juveniles for local mabé pearl farmers.

The economic indicators used in this Chapter include the NPV, EAR, MIRR and the payback period (section 2.2.2, section 4.2.1). The MIRR in this Chapter is calculated using loan rates as specified in Chapter 5.

7.2.2 Nucleus arrangements and mabé pearl production

- four high-profile nuclei, three on the inner surface of the rounded side (left) of the oyster and one on the flat (right) side (Figure 7.1);
- one 'high' profile nucleus implanted in the posterior-ventral position of the left shell valve, and two low profile nuclei implanted in both the anterior-ventral position of the left shell valve and the centre of right shell valve (Figure 7.2).

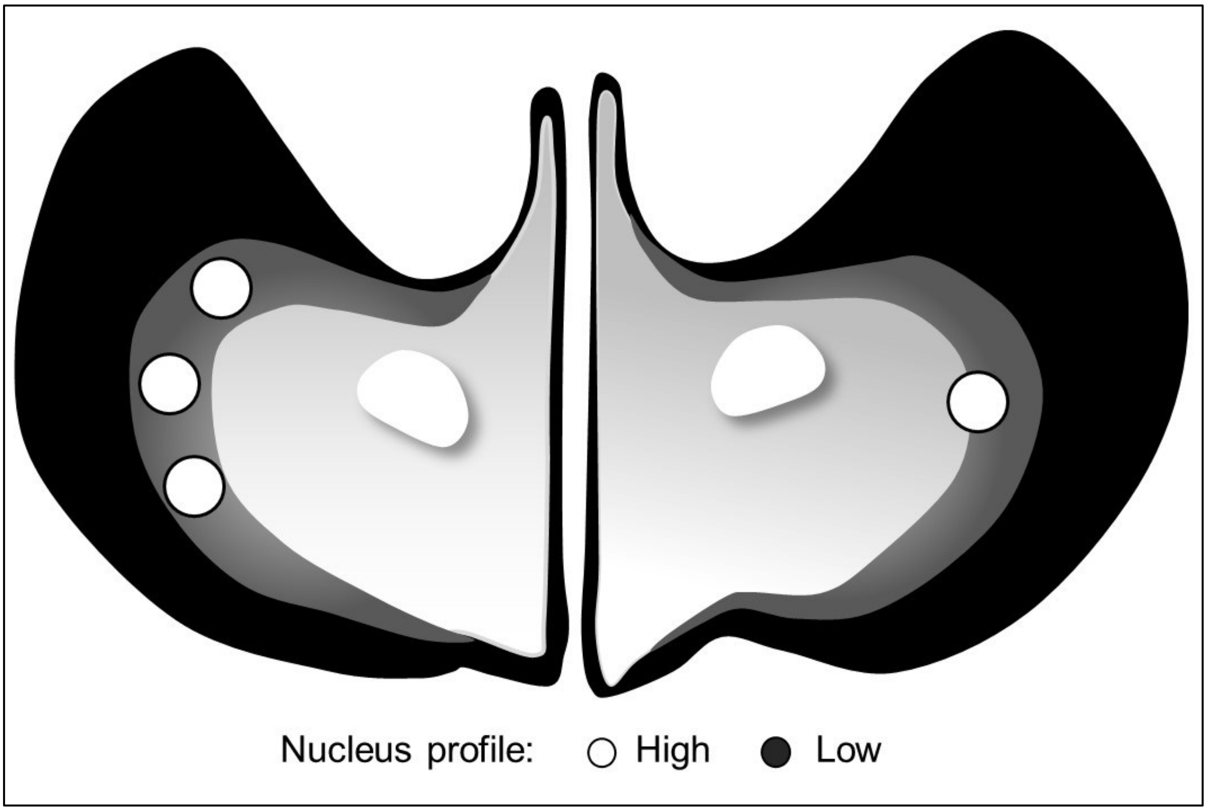

Figure 7.1 Diagrammatic representation of the traditional arrangement of four high profile nuclei, with three on the left (concave) shell valve and one on the right (flat).

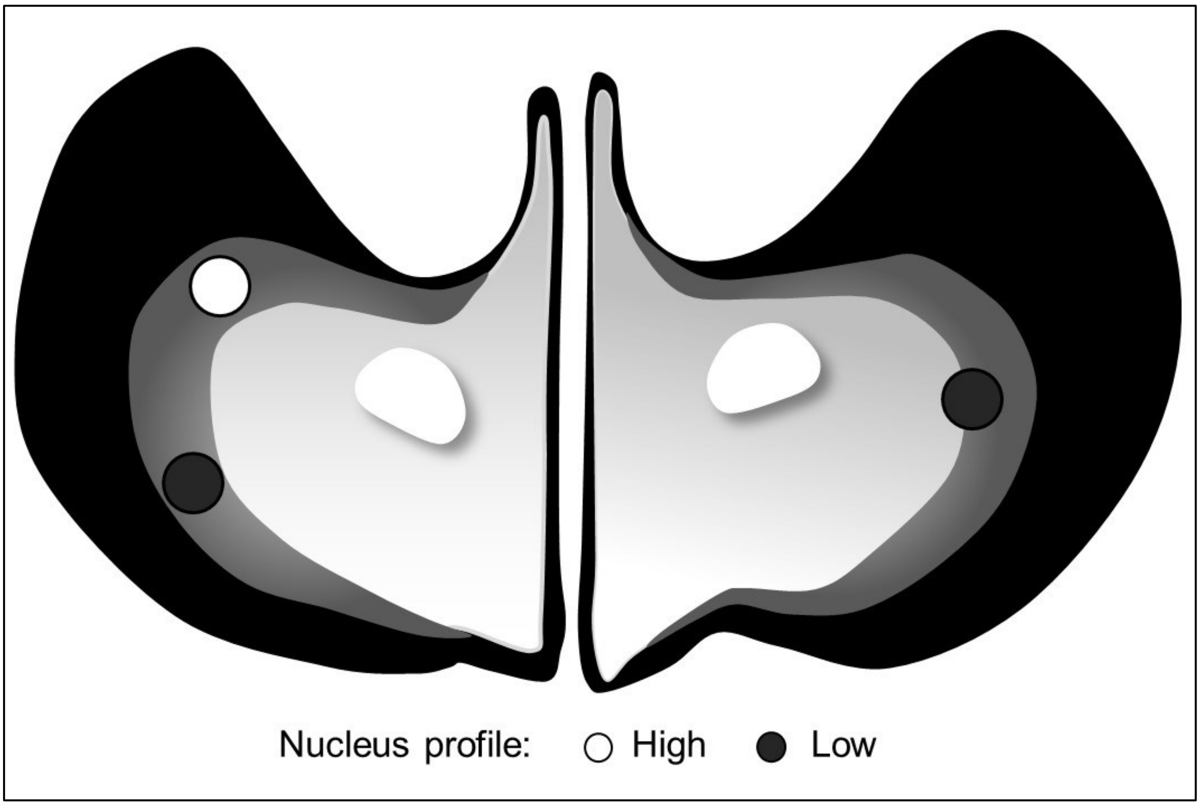

Figure 7.2 Suggested optimal nucleus arrangement (best-practice) to maximise nacre thickness and quality of resulting mabé pearls produced by *Pteria penguin* based on the findings of Gordon et al. (2019).

The cost associated with the purchase of nuclei was USD 0.19 per high profile nucleus and USD 0.14 for low profile nuclei.

7.2.3 Components of the economic model

7.2.3.1 Juvenile supply

In support of sector development, hatchery produced *Pt. penguin* juveniles are currently provided to Tongan pearl farmers free of charge by the Tongan Government hatchery facility. On this basis, the cost per juvenile oyster was set at zero in this study.

7.2.3.2 Husbandry and production scale

Juvenile and implanted *Pt. penguin* are held in suspension using the "ear-hanging" or chaplet method (Southgate, 2008). Recent introduction of protective mesh cylinders to house chaplets holding *Pt. penguin* juveniles for a period of 12 months before implantation has been shown to reduce predation and improve oyster survival (Gordon et al. 2020). Cylinder-based culture of *Pt. penguin* juveniles has now been adopted as standard practice within the Tongan pearl sector, while larger pre-implanted and implanted oysters are held on chaplets without protective cylinders.

The mabé pearl farm model used in this study targeted annual mabé pearl production from 100 viable oysters that were housed on a single 50-m longline, supporting oyster culture units (see section 5.2.3.1). To account for expected oyster mortality following arrival at the farm (18% mortality from nursery to implantation), 126 juveniles are acquired for the start of nursey culture, and 103 oysters (2.5% mortality between implantation and harvest) must be implanted to assure mabé pearl production from 100 oysters.

The first nucleus implantation for mabé pearl production will occur immediately following a two-year nursery phase. The pearl production period, from implantation to harvest, was set at 12 months (Gordon et al. 2018, Gordon et al. 2019). On this basis it is not until the start of year four that the first mabé pearls are harvested.

Other physical parameters set in the model include details of farming infrastructure e.g., longlines including rope, anchors, buoys, and chaplets (Kishore et al. 2015). The modelled farm consists of one 50-m longline, 11 chaplets with implanted oysters, 11 chaplets with pre-implanted oysters and 7 chaplets within protective mesh cylinders containing oyster juveniles (Table 7.1).

Table 7.1 Farm husbandry and production parameters for the modelled mabé pearl farm in Tonga based on a single 50 m longline.

Category	**Number**
Longline number / length	1 / 50 m
Total number of chaplets	28
Chaplets with implanted oysters / oysters per chaplet	11 / 10
Chaplets with pre-implant oysters / oysters per chaplet	11 / 10
Cylinder/chaplets with juvenile oysters / oysters per cylinder	7 / 20
Production length after implant (months)	12
Juveniles required for nursery phase	126
Number of oysters implanted (pre-implant)	103
Oysters harvested annually for mabé pearls	100
Nursery phase mortality – farm arrival to implant	18%
Production mortality – implant to harvest	2.5%

7.2.3.3 Pearl grading and marketing

Mabé pearl quality (Table 7.2) ranges from the highest AAA grade to B grade and considers size, shape, colour, lustre, and surface quality (Gordon et al. 2019). Specific criteria used to grade mabé pearls as described in section 5.2.3.4. Pearls graded C and 'not commercial' have no value are not considered in this study. Only grades AAA through to B were assigned a wholesale domestic price, and the average wholesale domestic prices for the sale of mabé pearls in Tonga are shown in Table 7.2.

Table 7.2 Average wholesale domestic prices for raw Tongan mabé pearls (Chapter 5) ($ in USD).

Grade	Price per Pearl ($)
AAA	88
AA	66
A	44
B	22

Gordon et al. (2019) reported that the application of a lower density nucleus implanting arrangement (three nuclei; Figure 7.2) produced higher-grade mabé pearls, with a higher incidence of regular shape (round) and a greater nacre thickness. Table 7.3 describes the percentages of each pearl grade applied from the Gordon et al. (2019) study.

Table 7.3 The percentage (%) of resulting mabé pearls (high and low-profile) for each saleable grade comparing the 'traditional' (four high profile nuclei) and 'best-practice' (one high and two low profile nuclei) nucleus arrangements (Gordon et al. 2019).

Grade of Pearls	**Traditional**	**Best-Practice**	
	High-Profile	**High-Profile**	**Low-Profile**
AAA	5.8	35.9	7.9
AA	20.2	38.5	18.4
A	26.9	10.3	29.0
B	29.8	12.8	21.1
Not Saleable	17.0	2.6	23.7

7.2.3.4 Farm labour

A small-scale farming operation is likely to utilise latent labour resources, rather than employ additional skilled labour external to the community. However, it is worth considering this portion of labour separately, as farm revenue outcomes are tied to it.

Based on a 40-hour working week, an hourly wage rate of USD 2.09 was expected in Tonga (FAO 2017); however, for this study, a wage rate of USD 1.55 was applied based on the wages of workers that are employed by Ministry of Fisheries, Tonga, that tend the research-based aquaculture farming operations.

Labour required for pearl nucleus implantation assumed an implantation rate of 20 oysters per day as outlined in section 5.2.3.5. This incorporates implantation activities such as area preparation, opening of the oysters ready for implantation, the implantation operation itself, and re-attachment of implanted oysters to chaplets ready for redeployment to the longline.

7.2.3.5 Additional operating costs

This section of the economic model accounts for any additional operating costs such as fuel and oil, electricity, repairs and maintenance, accounting and legal, office and administration, government fees and charges, phone, travel, vehicle registrations and insurances. The annual additional operating costs for both farming scenarios account for USD 644 of the total annual production costs.

7.2.3.6 Capital expenditure

As outlined in Chapter 5 the main components of mabé farm capital costs include: (1) land and buildings; (2) farm infrastructure and production equipment (i.e., chaplets); (3) diving equipment; (4) implantation equipment; and (5) miscellaneous (e.g., tools). Capital equipment bought at farm inception is replaced at pre-determined periods over the 20-year life of the farming project. Replacement costs were estimated as the amount of money required to replace capital items, net of its salvage or trade-in value. The initial year of capital purchase is year-0, and the model assumes that all relevant capital is sold, and proceeds enter the cashflow as a revenue stream in year-20. The model uses an estimated capital expenditure of USD 2,027 to establish the farms based on the results of this study.

7.3 Results

7.3.1 Farm output summary – traditional nucleus arrangement

Modelling of production from the mabé farm based on the traditional nucleus implanting practice of four, large nuclei, produced 281 saleable mabé pearls and generated an AGR of USD 9,338 (USD 33.21 per saleable pearl). Annual production costs totalled USD 2,360, or USD 8.40 per saleable pearl. This generated an annual return for the traditional farm of USD

6,977. Like the best-practice farm, the major costs were farm labour (30%), marketing (20%) and capital (16%) (Table 7.4).

Table 7.4 Breakdown of annual production costs for a mabé pearl farm using traditional nucleus implanting practice (four large nuclei) ($ in USD).

Cost Item	Average Annual Units	Annual Cost ($)	Cost per Pearl ($)
Pearl nuclei (saleable pearls)	400 (281)	72	0.26
Implantation labour	40 hours	95	0.34
Farm labour	450 hours	697	2.48
Fuel and energy		308	1.09
Marketing		467	1.66
Repairs and maintenance		101	0.36
Other operating		235	0.84
Capital purchase and replacement		385	1.37
Total		**2,360**	**8.40**

7.3.2 Farm output summary – best-practice nucleus arrangement

The mabé pearl farm modelled in this study, utilising the best-practice nucleus arrangement (two low profile and one high profile nucleus) produced 213 saleable mabé pearls annually. Annual gross revenue (AGR) from mabé pearl sales totalled USD 9,075 (USD 42.70 per saleable pearl), while annual production costs totalled USD 2,280 (USD 10.73 per saleable pearl). This generated an annual return of USD 6,795. A breakdown of the mabé pearl farm cost structure is shown in Table 7.4. Farm labour for mabé pearl production (31%), marketing (20%), and capital (17%) made up the largest cost components (Table 7.5).

Table 7.5 Breakdown of annual production costs for a mabé pearl farm using the best-practice nucleus implanting practice (two low profile and one high profile nuclei) ($ in USD).

Cost Item	Average Annual Units	Annual Cost ($)	Cost per Pearl ($)
Pearl nuclei (saleable pearls)	300 (213)	43	0.20
Implantation labour	40 hours	57	0.27
Farm labour	450 hours	697	3.28
Fuel and energy		308	1.45
Marketing		454	2.14
Repairs and maintenance		101	0.48
Other operating		235	1.10
Capital purchase and replacement		385	1.81
Total		**2,280**	**10.73**

7.3.3 Net Present Value (NPV)

NPV over the 20-year life of the traditional and best-practice mabé pearl farming projects, using a discount rate of 6%, was USD 80,030 and USD 77,937 respectively. As shown in Figure 7.3, the cumulative cash-flow for the traditional model indicates that it would take four years to recoup the original investment in the project. The cumulative cash-flow for the best-practice mabé pearl farm (Figure 7.4) shows that it would have an initial payback period of four years.

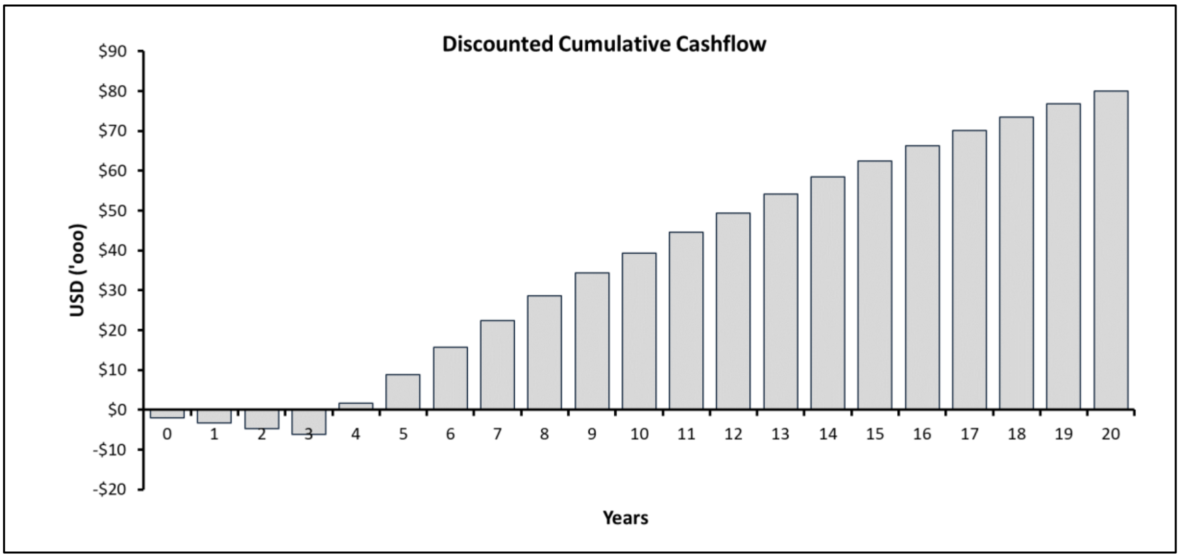

Figure 7.3 Discounted cumulative cashflow for the traditional mabé pearl farm in Tonga ($ in USD).

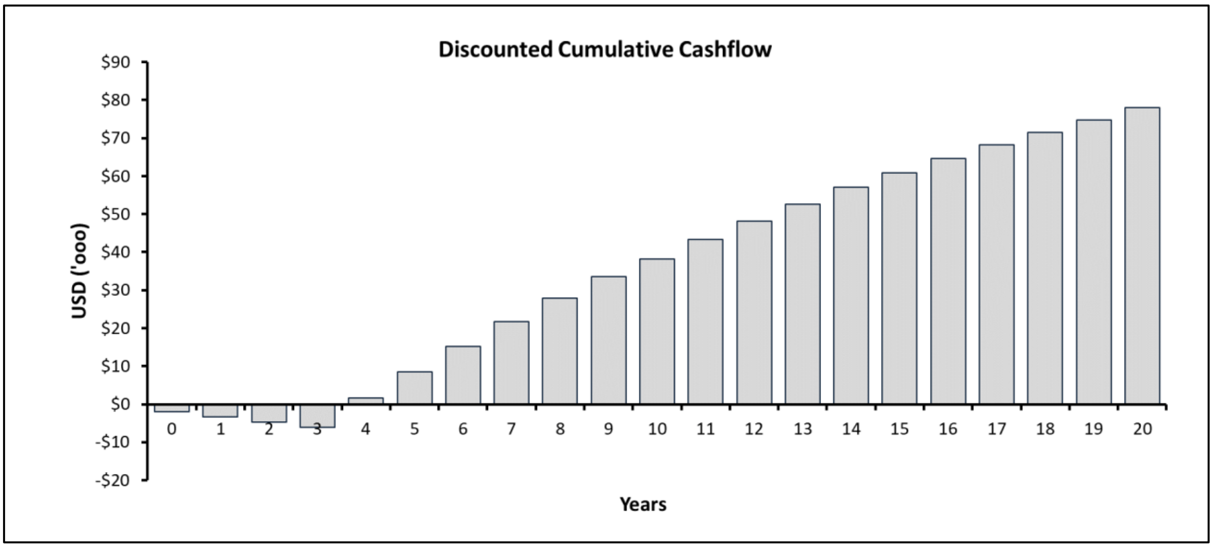

Figure 7.4 Discounted cumulative cashflow for the best-practice mabé pearl farm in Tonga ($ in USD).

7.3.4 Modified Internal Rate of Return (MIRR)

The farm based on the traditional method of nucleus implantation generated an MIRR of 18.78%, while the MIRR for the best-practice method mabé farm was 18.74%.

7.3.5 Economic summary

A summary of results and key economic indicators of the economic analysis comparing the two nucleus implantation methods are shown in Table 7.6.

Table 7.6 Summary of profitability and other economic indicators for the traditional and best-practice nucleus implantation methods for mabé pearl production ($ in USD).

Measure	Traditional	Best-Practice
NPV ($)	80,030	77,937
EAR ($)	6,977	6,795
Annual Return (AR) per saleable pearl ($)	24.82	31.97
MIRR	18.78%	18.74%
Payback period	4 years	4 years

7.4 Discussion

Prior economic analysis of mabé pearl production in Tonga outlined in Chapter 5 estimated a total production of 231 pearls using the same best-practice method applied in the current study. It should be noted that in the current study a reduced number of 213 saleable mabé pearls was estimated for the best-practice method. This discrepancy between studies results from refined mabé pearl grading standards such that some of the mabé pearls included and valued in Chapter 5, were not considered to have commercial value in the current model because of the improved pearl quality criteria now used.

While Gordon et al. (2019), and others (Ruiz-Rubio et al. 2006, Kishore et al. 2015) have suggested that a low-density nucleus arrangement is more suitable for mabé pearl production based on pearl quality outcomes, the results of the present study, which assessed outcomes from an economic perspective, show that there is little differentiation between the traditional and best-practice nucleation protocols tested.

The key differences in the two modelled nucleation protocols resulted from differences in the cost of nuclei, implantation labour, marketing costs (tied to revenue), and the number of mabé pearls harvested annually. Both the cost of nuclei and implantation labour are higher in the traditional nucleation method because more nuclei are implanted, and the implantation process takes longer to complete. The traditional nucleation scenario requires 412 nuclei annually and 67 hours for nucleus implantation, while the best-practice method requires 309 nuclei and 40 hours of labour. Clearly, the traditional nucleation method generates more saleable pearls (281) than the recommended best-practice nucleation method (213) simply by virtue of the number of nuclei implanted. However, is there sufficient improvement in mabé pearl quality, when using the best-practice nucleation method, to overcome the reduced number of saleable pearls?

Given the current pricing structure in Tonga for raw mabé pearls (Table 7.2), both nucleation methods tested in this study generated similar annual returns, with a marginal difference of USD 182 in favour of the traditional nucleation method. With annual returns being similar, it is worth noting the comparison of pearl quality output from each of the two nucleus implanting methods. While the traditional practice achieves a marginally greater return by implanting four nuclei (i.e., achieves a similar revenue through increased number of pearls), the production of higher quality pearls is of importance for the sector more broadly. Dismissing the height of the nuclei (high or low), Table 7.7 shows the grades of pearls generated by the two nucleation methods tested.

Table 7.7 The percentage of resulting mabé pearls for each saleable grade comparing the 'traditional' and best-practice nucleus implanting arrangements (Gordon et al. 2019).

Grade of Pearl	Traditional	Best-Practice
AAA	5.8%	17.2%
AA	20.2%	25.1%
A	26.9%	22.7%
B	29.8%	18.3%
Not Saleable	17.3%	16.6%

Of the mabé pearls produced by the traditional method, 52.9% were within the top grades of AAA through A, while the best-practice method generated 65.0% within these grades, supporting the assumption that lower density nucleus arrangements generate higher quality mabé pearls (Gordon et al. 2019, Kishore et al. 2015, Ruiz-Rubio et al. 2006). Total annual production costs for mabé pearl production using the traditional nucleating method are marginally (USD 80 per annum) greater than for the best-practice nucleation method because of the increased cost of nuclei and implantation labour, and a higher marketing cost due to the greater revenues it generates; but these differences are marginal. Mabé pearl production costs are marginally higher in the best-practice nucleation method (USD 10.73) compared to the traditional nucleation method (USD 8.39) due to costs being distributed over a smaller number of pearls. However, in terms of profit margin per pearl, the traditional method generates a profit margin per pearl of USD 24.82, compared to the best-practice method with a higher margin of USD 31.97 per pearl. This difference in margin is expressed due to the significantly higher average prices received per pearl (USD 42.70) compared to the pearls produced using the traditional nucleation method (USD 33.21).

In context, annual returns generated for both nucleation methods compared in this study are not dissimilar and it should be noted that both methods are highly profitable compared to the average annual income in Tonga of USD 4,020 per capita (FAO 2017). The traditional and best-practice nucleating methods produced annual returns of USD 6,977 and USD 6,795, respectively.

Pearls are a luxury item, and their value and demand are driven by quality (Southgate 2021). The value of pearls, underpinned by perceived quality, is the main determinant of production methods. Lower grade mabé pearls were excluded from analysis in this study as outlined above and in the study by Gordon et al. (2019). However, although oysters implanted with nuclei at higher densities can yield mabé pearls that are deformed (Figure 7.5) and potentially unsaleable, skilled jewellers and handicraft artisans can utilise mabé pearls with imperfections and irregularities and potentially transform them into higher value items by showcasing the high-quality portions of the pearl and disguising imperfections or irregularities that initially decreased the grade of the pearl. While the outputs of this study did not include such pearls because of their overall poor-quality grading, those with good nacre thickness, lustre and colour, could be utilised to add more value to mabé pearl farming operations, if turned in to bespoke items with higher values in the marketplace. Relatively small changes in the grading of raw pearls, up or down, or changes in price following value adding, can have significant impact on pearl farm profits.

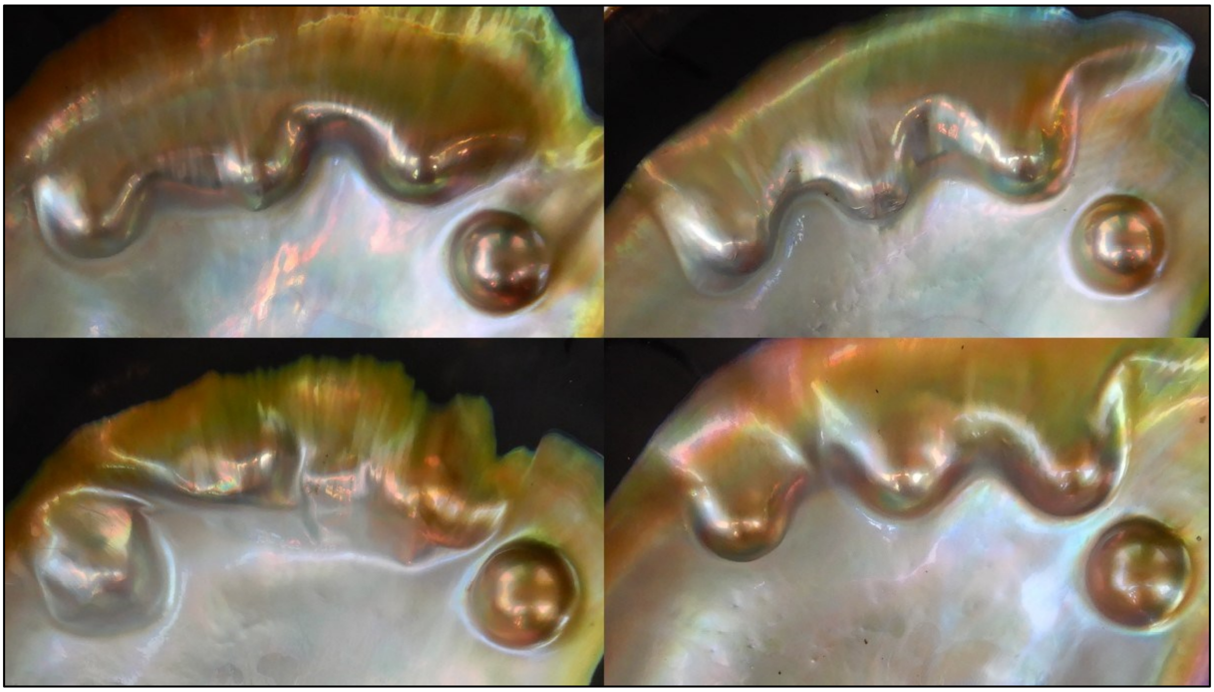

Figure 7.5 Examples of highly deformed mabé pearls produced by oysters nucleated with a high-density nucleus arrangement to the extent that resulting mabé pearls merged into the margin of neighbouring pearls generating a low grade and making them unsaleable (Gordon et al. 2019). Note that in each oyster, saleable mabé pearls with high grading (A-AAA) showing good shape, colour, minimal surface defects and high lustre were also produced in these oysters (bottom right of photos).

7.5 Conclusions

Use of two low-profile and one high-profile nuclei for mabé pearl production in Tonga was recommended by Gordon et al. (2019) based on resulting pearl quality. However, our reassessment of this method from an economic perspective has shown it to be less profitable than the traditional nucleation method, based on four high-profile nuclei. Both methods have similar annual costs and annual returns, and so the overall economic argument in favour of the recommended best-practice nucleation method is based primarily on labour efficiency and the quality of pearls produced annually. One of the key differences between the nucleation methods tested in this study relates to the investment of time. Mabé pearl farms in Tonga operate at subsistence level with farmers engaged in many other subsistence and livelihood activities, such as fishing and food production. The best-practice nucleation method reduces the annual implantation labour requirement by approximately 27 hours (3.3 days); time that could be invested into other livelihood activities that support the household or broader community benefits. While the opportunity cost of labour is relatively low, given the wage rate in Tonga is around USD 1.55 per hour, the benefits that this labour could deliver in terms of food security and other livelihood essentials, could be much significant. It is reasonable to consider that the benefits of reduced labour input of the best-practice nucleation method may outweigh the marginal revenue gain of the traditional nucleation method.

Additionally, the farm-level economic argument to apply the best-practice nucleation method is based on the greater number of higher quality pearls produced (Table 7.7). Continued development of the mabé pearl sector in Tonga will include a greater focus on export markets that will rely on a reputation for producing high quality mabé pearls. Export product will be derived from the higher-grade pearls in AAA to A grading bands, with the remaining grades likely to be sold domestically after local value-adding. Export markets are likely to deliver higher returns than domestic sales through local retailers to the tourist market. Adoption of the best-practice nucleation method recommended by Gordon et al. (2019) will therefore benefit individuals and communities, as outlined above, and support development of new markets.

Chapter 8: General discussion

8.1 Introduction

Pearl culture in the Pacific region is dominated, in scale and value, by production in countries such as China, Japan and French Polynesia. More relevant to this study is the success of pearl culture in French Polynesia, which has developed to become a significant contributor to the country's economy (second only to tourism), while maintaining compatibility with traditional indigenous lifestyles (Tisdell and Poirine 2008; Institut Statistique de Polynésie Française). Pearl culture offers direct employment (Tisdell and Poirine 2008; Southgate et al. 2019) and income generation to local communities offering both upstream and downstream opportunities that maximise economic benefits from the pearl culture value chain. The value chain aims to increase the value of a product as it moves through the supply chain (production and logistics). Upstream income generation may be derived from the supply of juvenile pearl oysters (based on wild spat collection) or benefit local purveyors of infrastructure and equipment. Downstream, beyond the harvest and sale of raw pearls, there is opportunity to value add through jewellery and handicraft production that further expands income generating opportunities for commercial farms and local communities alike (Southgate et al. 2019). Another significant benefit of pearl culture is that the products are generally of potentially high-value (depending on grade – see Chapters 2 and 7) and non-perishable. Being small and non-perishable, pearls, and pearl products (jewellery and handicrafts) are an ideal commodity for both domestic and export markets. This characteristic provides the opportunity for producers to manage the temporal flow of pearls and pearl products into markets to maximise prices as market demand fluctuates i.e., targeting the tourist season within a domestic setting.

This study focused on improving economic understanding of various aspects of pearl culture in the Pacific countries of Fiji and Tonga. Pearl culture in Fiji is traditionally based on wild spat collection of the black-lip pearl oyster *Pinctada margaritifera* used to culture round pearls. Tonga however has developed a pearl culture sector founded on hatchery culture of the winged pearl oyster, *Pteria penguin*, used predominantly for culture of mabé, or blister pearls.

There is a paucity of information on the economics of pearl culture internationally, and particularly within the developing pearl sectors of Fiji and Tonga. Improved understanding of the economics of pearl culture in these countries supports improved decision making for entrants and stakeholders, access to technical and financial services, provides a basis for assessment and adoption of research and development opportunities, informs government processes underpinning strategic industry development, and is vital for the long-term viability of pearl culture activities that ultimately provide livelihood benefits to coastal communities (Hambrey Consulting 2011).

The overall objective of this study was to deliver robust economic analyses aligning with the priorities of industry and key stakeholders within the developing pearl culture sectors in Fiji and Tonga, as a basis for informed, sustainable, sector development. The major outputs and applications of this study are summarised in Table 8.1.

Table 8.1 Major outputs and applications from this study

Prior Knowledge / Practice
• Limited knowledge of farm establishment and operational costs and other inputs for regional pearl culture (Fiji and Tonga). • No prior economic analyses of components of cultured pearl production value chains (hatchery, wild spat collection, pearl production). • No prior examination of production scales required to sustain viable pearl farming systems (commercial or artisanal). • Lack of economic analyses assessing contemporary developments in pearl culture practice. • Limited knowledge of impediments, bottlenecks, and risk factors associated with entry to, and operation of, cultured pearl production systems.
Outputs of this Study
• Tailored whole-farm economic models for round and mabé pearl production systems (Fiji and Tonga). **Chapter 2 and 5** • Establishment of baseline farm scales, for both round and mabé pearl culture, supporting viable farm production (Fiji and Tonga). **Chapter 2 and 5** • Confirmation of profitability of wild-caught spat operations generating downstream economic opportunity (Fiji). **Chapter 4** • Demonstration of significant profitability from small-scale community-based mabé pearl culture operations (Fiji and Tonga). **Chapter 4 and 5** • Evidence of the cost effectiveness of hatchery culture (Tonga). **Chapter 6** • Proof of economic viability of new or modified production methods (Fiji and Tonga). **Chapter 3 and 7**
Applications of this Study
• Whole farm economic models adopted as extension / training tools to improved decision making and underpin long-term sustainability. • Viable production scales for both pearl culture systems set as industry benchmark. • Economically viable community-based spat collection in Fiji supporting development of mabé pearl farming and broader participation in the pearl culture value chain. • Economic assessment of hatchery-based spat supply supporting cost recovery policy for Tongan Government. • Advancements in production technologies for pearl culture systems via adoption of robust economic evaluation. • Economic knowledge and awareness of industry challenges guiding future investment, planning, and policy for key industry stakeholders.

8.2 Economic research – decisions of adoption and impact

The word 'economics' conjures thoughts of dollars and cents, revenue and costs, profit and loss, but the application of an economic lens over commercial activities can deliver a much greater benefit than revelations of prosperity or poor investment. The development of aquaculture in any setting, as with other competing activities, is premised on the ability to either generate profits commercially or contribute to semi-subsistence or subsistence lifestyles. Economics can provide context to the potential impacts or adoption of husbandry improvements, new technologies, nutrition, environmental factors, pathology, government policy and institutional frameworks, amongst others. This study is premised on the ability to demonstrate the importance of applying robust economic analysis, where there was none, to improve the foundation on which sector growth relies, ensuring adoption of industry best practice, and providing guidance for key stakeholders for the benefit of individuals, communities, and industry alike.

Underpinning this study was the development of whole-farm economic models for pearl culture activities detailing physical production systems, capital requirements and annual farm production costs, and market structures and pricing, weighed against the risks taken in pearl culture activities. The models developed for this study considered investments over a 20-year time horizon to ensure temporal robustness and applied risk analysis (five-point Monte Carlo simulation) to production and price, where appropriate. The resulting whole-farm models provide a comprehensive economic assessment platform that has been, and still is applied in ongoing research, development, and extension activities in Fiji and Tonga. Variants of this model have been and continue to be applied to other aquaculture activities in the Pacific such as culture of sea cucumbers, seaweed, giant clams, marine prawns, tilapia, and *Macrobrachium*

(Johnston and Pickering 2003, Sauni 2006, Johnston et al. 2014, Johnston et al. 2015, Gordon 2020, Dobson et al. 2022).

The economic models developed in this study (for round pearl, mabé pearl, wild spat collection, and hatchery culture) provide a basis for informed decisions regarding the selection of activities that best serves the interests of potential participants (individual, community, commercial or government entity). Robust economic evaluation provides investor confidence when selecting amongst competing activities. Significant effort was expended throughout this study to ensure that the economic models and relevant risk factors of pearl sector activities in Fiji and Tonga accurately reflected the outputs expected through partnerships with researchers, government, and industry participants or potential entrants (in country workshops). Economic research not only provides a strong basis for decision processes but supports a broader scope including the identification of future research priorities, planning for industry development and formulation of government policy.

This study has taken significant steps towards ensuring the longevity of the investment in economic modelling. Each of the economic models developed and tested for the study were prepared in a recognised format (Microsoft Excel) and presented as a professional software package (tamper proof and password protected) for distribution to industry participants and key stakeholders. In addition, the risk analysis component of the economic software for pearl culture activities is bespoke. As part of this study, development of stand-alone visual basic code was incorporated into the Excel models so that the models developed during this study could be used by all stakeholders and extension agents widely and for perpetuity.

8.3 Artisanal pearl culture sector development

This section outlines changes to the pearl sectors in Fiji and Tonga over the duration of this study using information in Chapter 1 as a baseline and points which have been highlighted during this study. One significant advantage of aquaculture (more broadly) is its suitability to small-scale, community-based settings where it can integrate with existing artisanal agriculture and small-scale fishing activities; however, at the other end of the spectrum, it offers commercial scale opportunities to sate demand for marine and freshwater products, in the face of the declining outputs of capture fisheries. In the case of Fiji and Tonga, the development of pearl culture activities progresses in competition with embedded subsistence and semi-subsistence activities such as fishing and farming.

8.3.1 Pearl sector development in Fiji

At the start of this study in 2016, the Fijian cultured pearl industry was predominantly centred around the development of commercial scale round pearl culture and its associated activities, due in most part to the availability of *P. margaritifera* in the wild (Kishore et al. 2018).

The Fijian pearl sector has undergone a transformation since then. As discussed in Chapter 2, round pearl culture requires significant capital and time investment, a high level of technical skills, and is inherently riskier than mabé pearl culture in numerous aspects (Chapter 2). The barriers to entry ultimately inhibited the continued growth of round pearl culture in Fiji with the number of round pearl farms declining from eight in 2011, to six by 2016, and further to two in 2023 (Dr Pranesh Kishore, University of the Sunshine Coast, Fiji, *pers. comm.* 2023). It should be noted that they are still significant contributors to the local economy. Commercial round pearl farms began to divest from internally operated spat collection activities of *P. margaritifera* in favour of a community-based spat collection model as it grew throughout Fiji

(Kishore et al. 2018, Chapter 4). Spat collection has now grown to include 18 local communities managing 28 spat collection sites (Dr Pranesh Kishore, University of the Sunshine Coast, Fiji, *pers. comm.* 2023, Southgate et al. 2023). It has allowed round pearl farmers to focus primarily on pearl production while the community-based spat collection initiative provided regular and improved supply to round pearl farms, expanding spatial diversity and community benefits, while mitigating supply risks from natural disasters such as tropical cyclones (e.g., cyclone Thomas in March 2010). The establishment of a community-based wild spat collection program now provides an alternative income stream for remote, coastal communities. Growth of the wild spat sector in Fiji also provided further economic opportunity because spat collectors targeting *P. margaritifera* to supply round pearl farms incidentally collected *Pt. penguin*. Incidental capture of *Pt. penguin* has supported transition of some spat collection communities toward mabé pearl production, a vertical movement in the pearl culture value chain for coastal communities in Fiji.

Research reported in Chapter 4 was initially based upon an assessment of how wild spat collection activities contributed economically to the local communities through the sale of juveniles to commercial round pearl farms. At the time, trials in mabé pearl culture had begun in Fiji and as a result the economic study expanded its scope to include mabé pearl culture based on wild-caught spat. Unlike the Tongan industry which relies on hatchery produced oysters, the opportunity in Fiji was different. The commercial sale of *P. margaritifera* resulting from wild spat collection was proven to be economically viable in isolation. Incidental collection of *Pt. penguin* spat could be used for mabé pearl culture. The economic analysis showed that communities in Fiji could develop economically viable mabé pearl farms in combination with spat collection, integrating broader components of the pearl value chain.

As an indication of the success of wild spat collection as a community-based activity in Fiji, approximately 16,300 *P. margaritifera* and 11,500 *Pt. penguin* juveniles have been collected since 2016 from spat collection activities. Sales to commercial farms of juvenile *P. margaritifera* has generated an estimated USD 13,800, while sales of raw mabé pearls (in shell) from local communities has generated more than USD 20,000 across seven mabé pearl producing communities in Fiji with an additional farm to be operational by the end of 2023. While significant, these figures are underreported due to an inability to monitor and regulate the pearl trade, it is estimated that additional value-adding for the jewellery and handicraft markets (Southgate et al. 2019, Naidu et al. 2014) could increase the value of the current harvest to date to USD 115,000 (Dr Pranesh Kishore, University of the Sunshine Coast, Fiji, *pers. comm.* 2023).

Further income generating activities are yet to be investigated, but as an indicator of the broadening value chain, two communities in Fiji are engaged in production of jewellery and handicrafts using the oyster shells and value-adding to raw mabé pearls. As an indicator of growth in the community-based pearl culture value chain, a handicraft workshop and centre is being established in Savusavu (Vanua Levu, Fiji) to further encourage growth in the community-based value adding component; this is additional to the mabé pearl / pearl shell handicraft training and production workshop in Somosomo, Taveuni, established in 2018. Such handicraft centres allow jewellery and handicraft artisans from local communities to access powered equipment such as grinders, cutters, and drills. In addition to workshops equipped with power tools, handicraft training using basic hand tools has been provided at Raviravi and Ravita (Vanua Levu), with resulting products sold at local markets and resorts.

8.3.2 Pearl sector development in Tonga

The Tongan pearl sector, based on hatchery production of *Pt. penguin* (Southgate et al. 2016) has focused on developing mabé pearl culture which integrates well with other community subsistence activities (Chapter 5). *Pt. penguin* is utilised for pearl culture based on its environmental suitability and minimal technical and labour requirements. Mabé pearl culture in Tonga provides a range of benefits beyond the sale of raw pearls, generating income through value adding of raw pearls and shell into jewellery and handicrafts for domestic sale, but also providing a food source for communities through the pearl tissue which consists of viscera (composed of mantle, gill, gonad and other tissues) and the valuable adductor muscle (referred to as 'pearl meat' below). Development of the mabé pearl sector in Tonga has seen growth to 24 mabé pearl farms and farming communities, producing approximately 4,680 pearls valued at USD 325,000 (Southgate et al. 2023). However, pearl culture development in Tonga is characterised by its ongoing reliance on hatchery produced spat given insufficient wild stocks of *Pt. penguin* to support sector expansion through spat collection (Kishore et al. 2018), in contrast to the situation in Fiji. While the hatchery manages sufficient output to address current demand (Chapter 5) there are several issues that potentially restrict hatchery production and could impact potential for sector expansion. Hatchery supply, throughout the recent sector growth period, was supported operationally and technically by international funding and expertise. For continued development of the industry over the long term, the hatchery will need to operate, and maintain or increase production, independent of international support (Chapter 6). More so, the Ministry of Fisheries (MoF) requires an industry development plan that incorporates the strategies to attract skilled labour and operational funding. While the multi-use fisheries facility provides an operational site and access to resources for hatchery production of pearl oysters, investment in skilled labour to operate the hatchery and nursery phases has been difficult to obtain, given limited availability of skilled staff, and remains an issue for continued development and longer-term future of the pearl sector in Tonga. A future industry development plan is likely to consider a cost recovery strategy to underpin hatchery and nursery operations (Chapter 6). Further, funds could be generated through industry fees (aquaculture licence) or a levy on sale of pearl products.

8.3.3 Pearl culture value chain in Fiji and Tonga

The current value chain profile for community-based pearl industry activities in Fiji and Tonga is outlined in Figure 8.1.

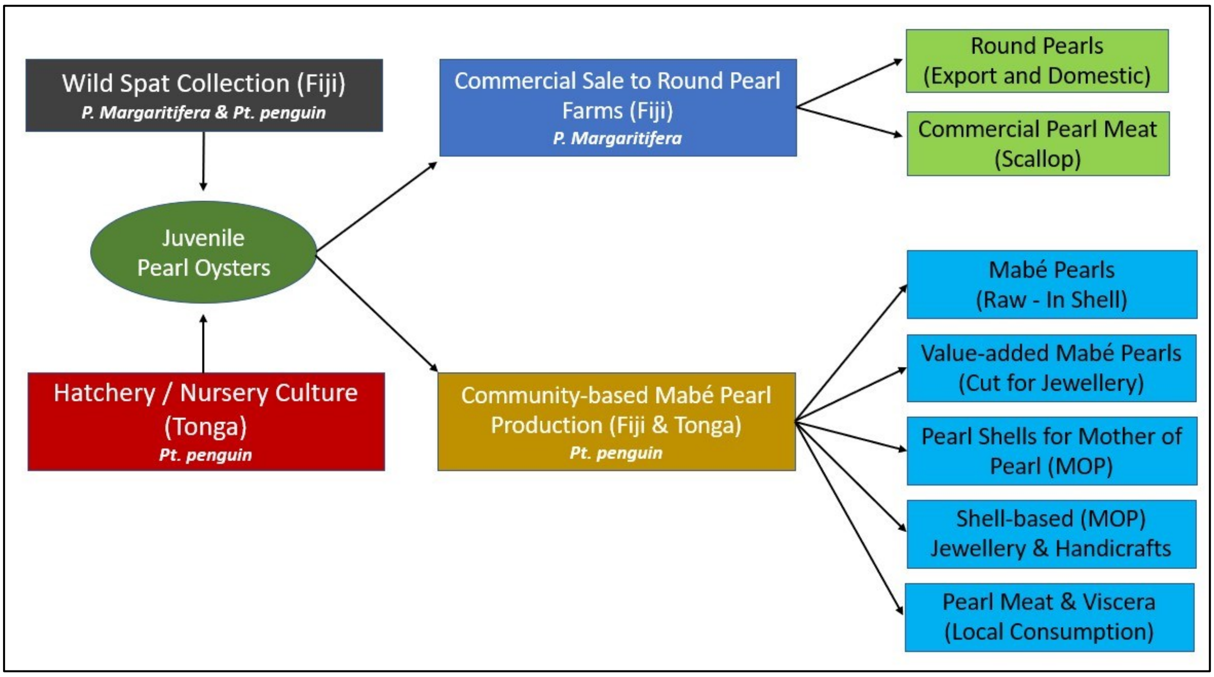

Figure 8.1 Components of the value chain for community-based pearl culture in Fiji and Tonga.

8.4 Round pearl culture sector insights

Examining the two harmonised system (HS) codes for pearls (HS 71.01 – natural pearls, unworked cultured pearls and worked cultured pearls) and pearl products (HS 71.16 – articles of natural or cultured pearls) the following section takes a broad view of global trade in pearls and pearl products. The value of pearl (HS 71.01) exports worldwide was approximately USD

450 million in 2021 which is a significant contraction from 2019 where export trade in pearls was estimated at USD 910 million (-50.5%). For further context, the global export trade in pearls in 2017 was estimated at over USD 4.5 billion. The largest exporters in 2020 were Japan (USD 75.2 million), Australia (USD 69.9 million) and Indonesia (USD 66 million). In terms of pearl products (HS 71.16) the global export value in 2020 was approximately USD 1.07 billion which had remained steady since 2016. Prior to 2016, pearl products for 2014-15 were valued at USD 2.0-2.5 billion, predominantly buoyed by exports from China and India which has now contracted and stabilised (www.oec.world). Looking at both pearl and pearl products there have been significant contractions since 2015.

The global decline in the trade of pearls is most likely due to the negative effects of recent international economic shocks, such as the COVID-19 pandemic and the war in Ukraine, impacting international tourism and business travel, trade logistics, and increasing costs of production inputs. Given trade has declined significantly, a closer examination of pearl exports from French Polynesia is a litmus test to understand the impacts on other regional round pearl producers like Fiji and the Cook Islands. Globally, French Polynesia ranks fifth in terms of pearl exports (HS 71.01). Figure 8.2 describes the export trend for pearl exports from French Polynesia measured in kilograms and value in USD.

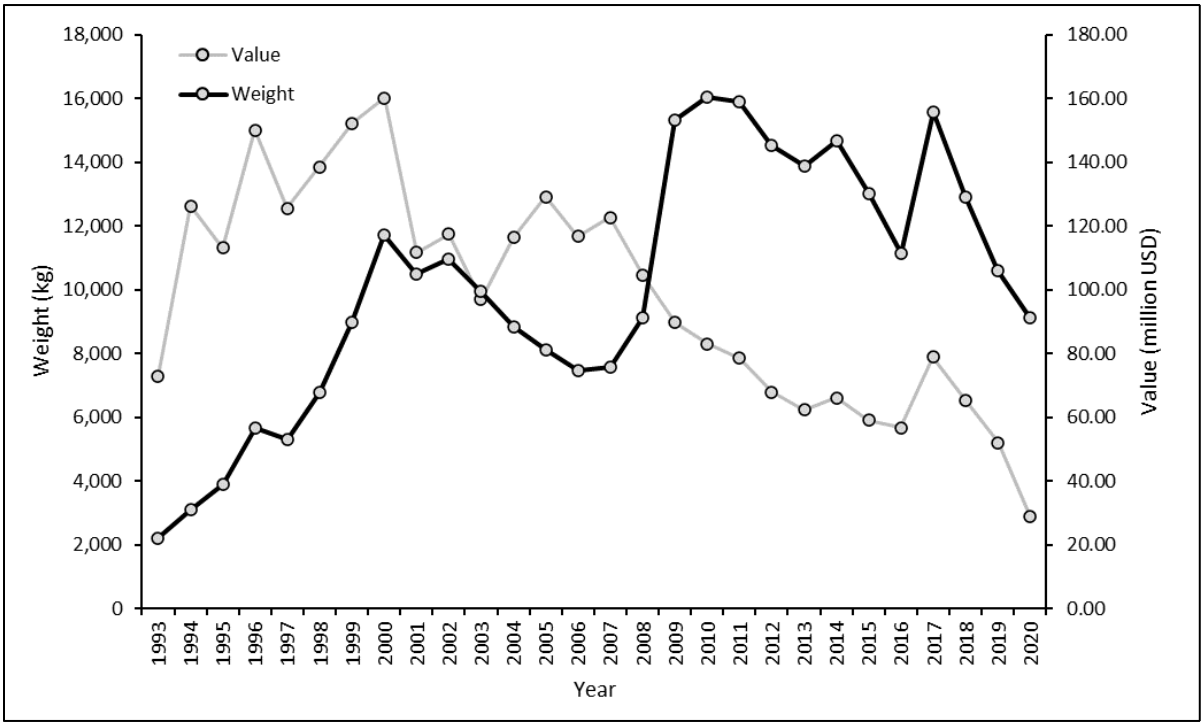

Figure 8.2 Export of raw cultured pearls from French Polynesia (HS 71012190) and their value (million USD) from 1993 to 2020 (source: Institute of Statistics of French Polynesia www.ispf.pf – excludes unreported pearls and domestic sales).

According to the Institute of Statistics of French Polynesia (ISPF) the area under production and the number of pearl farmers has declined consecutively since 2018. Pearl exports are the second largest contributor to GVP but have also declined to represent only 44% (50% of GVP in 2019). The ISPF declared that COVID-19 was the major contributor to the decline in pearl exports however Figure 8.2, updated from the previous overview presented in Chapter 1, shows a sharp decline in both weight and value from 2017 onward, symptomatic of falling global demand for gem quality pearls. Comparing 2017 to the most recent figures available for 2020, the value of pearl exports has declined from USD 78.99 million to USD28.81, and weight exported has declined from 15.6 tonnes to 9.1 tonnes While the weight of pearls exported has fluctuated over time the value of pearls has declined steadily since 2004. The decline in the pearl industry in French Polynesia underlines the difficulty in establishing and developing black pearl culture for Pacific nations such as Fiji in this economic climate. One factor that has aided the establishment and maintenance of round pearl culture in Fiji, albeit at a much smaller scale than in French Polynesia, is product differentiation through quality and colour. The *P. margaritifera* endemic to Fijian waters produces a wide array of nacre colours, many unique to Fiji. Some of the colour descriptions include shades of champagne, gold, copper, pistachio, cranberry, rose, taupe and chocolate (Source: fijipearls.com). This differentiation provides a market niche for the cultured pearls produced in Fiji on the international market, as well as a draw for tourists. Despite this, the Fijian round pearl sector has contracted to only two farms in 2023. Another indicator of the overall health of the Pacific round black pearl industry is demonstrated in Figure 8.3, which updates Figure 1.4 (Chapter 1), outlines the trends in the price of pearls per gram exported from French Polynesia over the past 30 years.

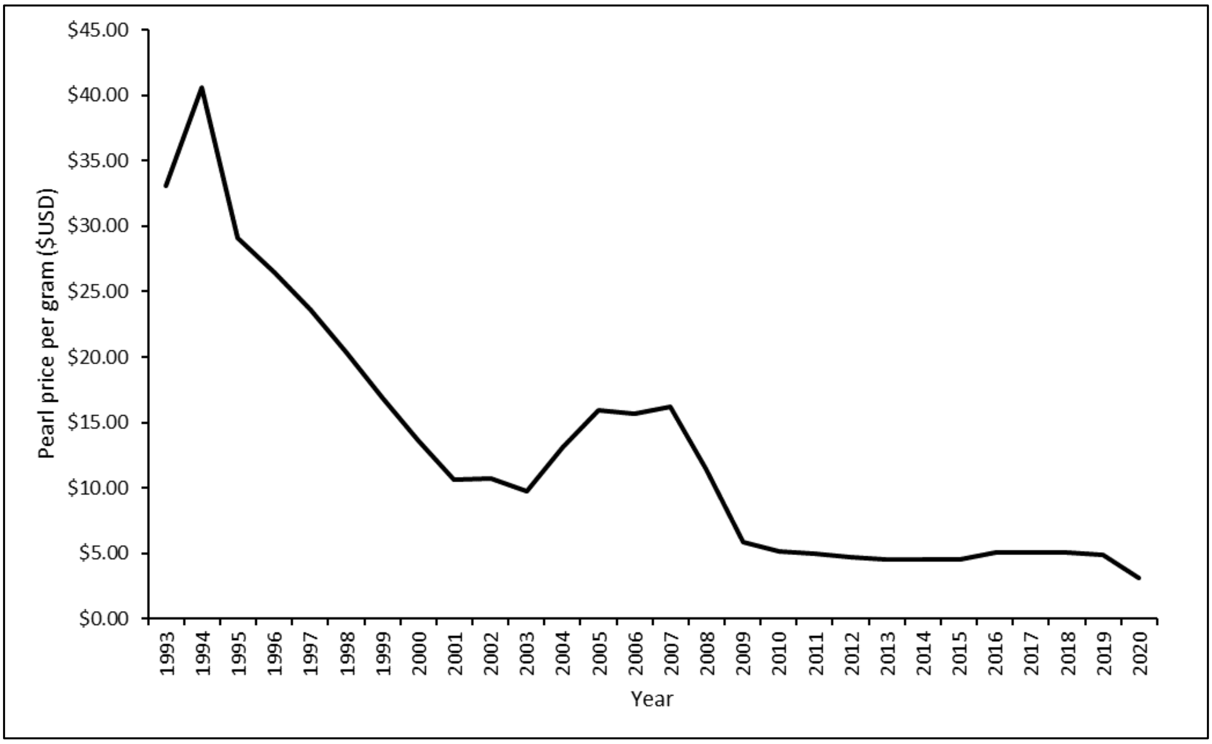

Figure 8.3 Price per gram (USD) of exported pearls from French Polynesia from 1993 to 2020 (*source*: ISPF).

According to ISPF (www.ispf.pf) the price per gram for exported round pearls from French Polynesia reached a record low of USD 3.15 per gram in 2020. The average from 2009 to 2020 is only USD 4.79 while the average from 1993 to 2008 was USD 19.20 with a maximum price per gram of over USD 40 in 1994. The economic outlook for the round pearl industry in the Pacific is likely to continue its downward trend but investment in product diversification (e.g., to produce pearl meat, and accessing previously unexploited areas of the pearl value chain) could assist in improving the sustainability of round pearl farming operations in Fiji and encourage the uptake of other opportunities across the value chain. While French Polynesia provides some context for Fiji, its scale of production dwarfs that of Fiji and, given the data presented, is likely to continue to decrease in size and require structural adjustments to ensure long-term sustainability.

8.5 Opportunities for pearl sector development

Modern differentiation of traditional activities that move to utilise agricultural and fisheries products in a growing commercial context follow a path from value creation, through value delivery to value capture (Brea 2017). Value is created at the community level when the raw product enters the supply chain (farm output) but where the value is captured by other stakeholders, creating an environment that drives innovation. However, the ability to monetise the created value tends to be lacking in rural communities dealing with perishable primary agricultural and fishery products with temporal constraints and limited market channels (Brea 2017). Many coastal communities throughout the Pacific struggle to translate value creation (potential income) into value capture (income generation) and tend to be characterised by low 'local' value capture stemming primarily from a lack of infrastructure and market power. Pearl culture in the Pacific is an example of where community-based participants have been able to capture much of the created value to improve livelihood outcomes.

Inherently, any business model will go through changes, supported by experimentation, and knowledge and skills development (McDonald and Eisenhardt 2019). Innovation in traditional coastal community fishing activities generally involves the shift to more organised farming of marine resources (aquaculture) that provides improved food security and an increased and more sustainable income generating capacity. The shift to aquaculture (marine and freshwater) in the Pacific, more generally, has had mixed success, but community-based pearl culture, nurtured with ongoing support and the goal of sustainable development, can exist as a long-term livelihood option for coastal communities in Fiji and Tonga (SPC 2007, Ponia 2010).

The current value chain (Figure 8.1) operates within the boundaries of what is possible given resources, infrastructure, and training and skills development. Understanding that community-based pearl culture and its related activities are still in a development phase, the opportunities to extend are potentially significant and yet to be explored in full. In Fiji, there are currently 28 spat collecting sites supported by 18 communities, seven community-based mabé pearl farms, two communities specialising in jewellery and handicrafts production, and two commercial round pearl farms (Dr Pranesh Kishore, University of the Sunshine Coast, Fiji, *pers. comm.* 2023). In Tonga mabé pearl production has increased by 73% to nearly 5,000 pearls annually at last count in 2018, compared to 2015 production of 2,700 (Southgate et al. 2023). The successful establishment of mabé pearl culture, and both its upstream and downstream components, has been a catalyst for many communities to seek involvement in the sector as it has added demonstrable diversity and economic opportunity to community livelihoods. However, given its challenges (see section 8.3.2) the future of the industry in Tonga will require investment by the Government to restructure the sector, at a minimum, to stabilise the sector and provide a platform for further growth.

The potential value chain for pearl culture could become more extensive in scope as the pearl industry matures at a community level in Fiji extending the viability of the two remaining commercial round pearl farms (Civa Pearls and J Hunter Pearls). For example, an opportunity that is not currently exploited is the commercial sale of pearl meat. The pearl meat identified previously in Figure 8.1 relates purely to a food source for the communities undertaking pearl culture, but it has potential for both domestic and international markets. As described in Figure 8.1 there are two components to harvestable pearl oyster tissue, the viscera (composed of mantle, gill, gonad and other tissues), and pearl meat. While both components are considered a food source for communities and workers, and are readily consumed at a local level, further opportunities exist for both. Viscera for example, can be turned into an organic fertiliser because shellfish waste is nutrient rich, containing elements such as nitrogen (van der Schatte et al. 2020, Pal et al. 2023). The fertiliser could be used to enhance crop yields thereby improving agricultural production output in community-based terrestrial farming systems. Commercial scale production of pearl oyster-based fertilisers may be possible but is more likely to occur in Fiji where commercial round pearl farms with significant numbers of oysters could catalyse a broader Fijian industry. The other significant component of the pearl tissue is the pearl meat. While pearl oysters are traditionally associated with the production of pearls and MOP, the pearl meat has become of significant commercial value in the food services sector, not only in Fiji and Tonga, but internationally. The pearl meat can command wholesale prices of up to USD 135 per kilogram (wet weight) and even more when dried, the majority of which (~60%) is destined for SE Asian markets (Broadfield 2010, Brearley 2021). However, exploration of this component of the value chain would require significant investment in cold chain logistics, something that is limited in capacity in both Fiji and Tonga. Additionally, as a food destined for human consumption, domestically or internationally, there would need to be adherence to government legislated food safety standards, both of which Fiji and Tonga have in place (MOH 2009, KTCL 2020).

Apart from their capacity to produce pearls and provide a food source, pearl oysters, and marine bivalves more broadly, generate ecosystem services and other incidental benefits (Smaal et al. 2019). One of the direct benefits to livelihoods of coastal communities is that the hanging structures in the water column (spat collectors, panels, ropes, buoys, oysters etc) provide structure for a diverse range of marine life (Shumway et al. 2003). Apart from the benefits to marine biodiversity, they function as fish attracting devices (FADs) that can enhance catches of fish, improving food security for local communities in proximity to them (Cartier 2014). Other additional benefits of spat collection and pearl culture include improvement in water quality, through the filter feeding mechanism of pearl oysters that can remediate nutrients in the water and improve water quality (O'Connor and Gifford 2008). They are also important contributors to coastal ecosystems through biodeposition (Ferreira and Bricker 2016). Additionally, oysters can sequester carbon which is then removed through use of the harvested oyster shell from the pearl culture production system (Smaal et al. 2019). Research also suggests that marine bivalves could be carbon sinks or a net contributor to CO2 levels (Jansen and van den Bogaart 2020). However, there is international debate on the potential of pearl oysters to sequester carbon (act as sink), and this is yet to be fully assessed.

8.6 Impediments to pearl sector development in Fiji and Tonga

There are impediments to the development of pearl culture that are common to both countries and to both pearl culture production systems (round pearls in Fiji and mabé pearls in Tonga). There are also impediments that are unique to each country.

8.6.1 Fiji

The round pearl sector in Fiji, currently with two active businesses, continues to produce high quality round pearls for domestic and international markets. However, there is movement away from the primary core business of trading raw pearls, towards other parts of the value chain. Diversification is based primarily on value adding to raw pearls to access the jewellery and handicraft markets, targeting both domestic tourism market and the international jewellery trade. More recently one of the round pearl farms (J Hunter Pearls) has diversified into the pearl meat market using hatchery produced *P. margaritifera* (Vitukawalu et al. 2021). As discussed in Chapter 2, production of round pearls is high risk and characterised by high levels of capital investment and technical input as well as cashflow lags at inception. Utilising the same round pearl culture infrastructure with some modification, pearl meat production negates many of the issues posed by round pearl production. The production system for pearl meat is similar to that for round pearl production temporally, with time from spat collection to farm-ready juveniles (~12 months), to harvest (~18 months). Diversion to targeting pearl meat, without pearl production will have its own challenges, particularly in accessing suitable cold chains in the domestic setting to access the food service sector (hotels and restaurants).

Some of the broad issues facing the pearl sector in the Pacific include access to, or lack of (1) policy development and development planning; (2) technical expertise, appropriate training and extension support; (3) appropriate technology and infrastructure; and (4) market and branding development. In 2017 the Ministry of Economy in the Fiji National Development Plan recognised that there were several sectoral development issues of which slow development in aquaculture (pearls, seaweed and other aquaculture activities) was one. Following up from this document is the release of the National Fisheries Policy in 2020. While policy development and planning for the aquaculture industry in Fiji are fundamental in addressing sectoral issues and outlining research and extension priorities in support of sectoral growth, pearl culture (round or mabé) is not identified as key species but would likely benefit from the broader application of the policy. Given the success of wild spat collection activities and the establishment of community-based mabé pearl culture, which is underpinned by Ministry of Fisheries support, its lack of specific recognition in the policy may reduce the ability of pearl aquaculture to attract or compete adequately for technical and other support for ongoing development in relation to the key aquaculture species identified in the National Fisheries Policy document (tilapia, shrimp, prawns, sandfish, seaweed, carp, and local species of coral reef fish and invertebrates).

8.6.1.1 Targeted policy development

While recognition and input at the policy level is important, it requires engagement at the individual farm level to develop an understanding of underlying issues and barriers to development. For example, the success of the spat collection initiative saw a significant increase in the number of spat collectors deployed to communities across Fiji. However, issues began to arise with many spat collectors mismanaged or neglected to livelihood commitments or lack of access to basic needs to manage and maintain spat collectors, such as a boat and motor. These issues are addressed based on the experiences at the activity level. For example, communities that wish to undertake mabé pearl culture, following demonstration of time investment and capability at the spat collection level, are limited to a maximum of 700 seeded oysters per production cycle (Dr Pranesh Kishore, University of the Sunshine Coast, Fiji, *pers. comm.* 2023), and have an operational boat and motor to ensure they can manage and care for the oysters through to harvest while maintaining other livelihood activities.

8.6.2 Tonga

In Tonga, the mabé pearl sector relies on supply of hatchery produced *Pt. penguin* spat because wild caught spat collection is not an option. Spat produced in the hatchery are then managed through a nursery phase to improve survival rates on farm, beyond which they are supplied to pearl farming operations. Hatchery supply is identified as a major bottleneck for the ongoing development of the mabé industry in Tonga as it relies on a high level of technical training and external support to maintain consistent supply to farmers. Improved hatchery and nursery culture methods have supported supply of larger, more robust, oysters to farmers on a more regular basis. As the supply side (hatchery/nursery) of the sector transitioned from external intervention and support to self-reliance, hatchery supply issues are again retarding the development of the sector. Further intervention from key stakeholders, and further potential external interventions may be required to stabilise the hatchery pearl oyster program to support industry sustainability and future growth. Despite the issues faced by the sector in Tonga it continues to survive and expand and has a reputation for high quality mabé pearls. There is a small but thriving domestic niche market based on trading half pearls to tourists in Vava'u and Tongatapu, and a small export market (to Hawaii) for 500 mabé pearls per month established during the COVID pandemic.

8.6.3 Pearl Grading

Discussed in Chapter 2, pearls are the only gem not to have a recognised grading system. However, the Tahitian system for the grading of round black pearls is commonly used across the Pacific region and is well recognised internationally by wholesalers and other traders in the round pearl supply chain. It grades pearls for shape, size, lustre, colour and surface perfection and rates them for quality from A to D. The established grading system provides a foundation for market recognition based on pearl quality and consistency. This in turn allows individual businesses or cooperatives to establish value in a brand within the marketplace. In the example of mabé culture in Fiji and Tonga a standardised grading system is lacking, posing an issue as assessment of quality becomes broadly subjective in the market. For *Pt. penguin* mabé pearl culture in Tonga and Fiji it is common to insert 4-5 nuclei. However, Gordon et al. 2019, based on the development and application of a robust grading system, concluded that three nuclei, while reducing overall pearl yield, improves the quality of the final product. This is now adopted as best practice. Grading for mabé pearls considers the important characteristics of nacre thickness, colour and lustre, while regularity of shape is less important than in round pearls and provides a potentially unique characteristic for individual pearls. An economic assessment was undertaken in Chapter 7 to examine traditional versus research-driven nucleation scenarios, concluding that both implantation scenarios produced similar annual profits. However, the lower nuclei density is considered best-practice based on the higher proportion of quality pearls. One key element here is the development of the grading system for mabé pearls developed in the study by Gordon et al. (2019) as it provides a basis for the broader mabé industry to establish quality parameters upon which all mabé pearls can be compared. While sales are predominantly domestically focused in Fiji and Tonga, with local demand greater than supply, it is critical that there is industry wide adoption of a standardised grading system in the Pacific for mabé pearls. This requires investment in the creation of skills in quality and value assessment of mabé pearls because future industry growth including movement into the international marketplace, will require a high level of consistency in exported pearls. For example, mabé pearls of AAA, AA and A may be prioritised for export while lesser grades of B, C and NC could be committed to value-adding for sale in the domestic market. As discussed for round pearls, it allows for brand establishment based on a reputation for quality. This is particularly important for countries like Fiji and Tonga where small-scale community-based farming will predominantly rely on the reputation of the country.

8.6.4 Market access in a domestic environment

Following on from the previous points, growth of sales of pearl products within domestic markets is often limited because retail space in major towns is often cost prohibitive for most participants in mabé pearl culture. Some examples exist in Tonga where dedicated retail space is allocated, with Government support, for the sale of indigenous products that includes pearl jewellery and MOP handicrafts. Temporary sales areas (market stalls) are often established adjacent to berthed cruise liners that regularly visit Tonga and Fiji generating jewellery and handicraft sales targeting tourists. One potential avenue is the establishment of an online sales platform to market pearl products internationally. While seemingly a simple solution it requires appropriate information technology skills and hardware and would need to be underpinned by resources in marketing and branding. Another factor for consideration is competition between locally produced products and imported jewellery and handicrafts from countries such as Indonesia, Philippines and China. Investment in skilling labour and providing access to advanced technology and equipment, such as the handicraft centre in Savusavu, will support import replacement. Again, forward thinking and development planning are key to understanding impediments and creating solutions to overcome them.

8.7 Further research

There are many pathways that future research in this area could take given the role economics could play in the assessment of research and development activities. The scope of future research related to pearl culture seed supply, production methods, food security, health and nutrition, value-adding and product quality etc. will continue to require economic context to ensure that recommendation and adoption of research is of benefit to the continued growth and development of pearl farming in the Pacific.

One key element of future research lies in mapping the pearl culture value chain and exploring the economic opportunities within it. As an example, pearl oysters farmed exclusively for high-value 'pearl meat' is only in its infancy in Fiji and the economics of this development opportunity is yet to be explored. This activity, if profitable, could provide greater options for pearl oyster collecting communities where oysters, not used for mabé pearl production, could be cultured for pearl meat production. Such a development could also promote the entry of new businesses to grow the aquaculture sector in the Pacific and expand its contribution to regional economies and employment. Mapping the pearl culture value chain and exploring such opportunities in the context of economic, social, and environmental parameters, should be evaluated more closely.

All economic modelling is limited in this study to the revenue streams for raw pearls because estimations of pearl value, once transformed into a partially value-added product or its end-product as jewellery are difficult to capture. The profitability of pearl farms discussed in Chapters 2 and 5 that integrate value adding practices, could be an underestimate given potential price differences compared to the raw product. Additionally, lower grade pearls that may have significant defects or character flaws can be elevated by skilled artisans to fetch higher value than if they were sold as a raw product. For example, a survey of mabé pearl jewellery prices in Tonga was conducted by ACIAR in 2018 and pearl quality graded by the system developed by Gordon et al. (2019). For example, of the highest product prices (TOP 1,200, USD 516) within a survey of 126 jewellery pieces at retail outlets in Tonga one was deemed AAA (highest grade), two were AA, one was A, and two were C grade. Value adding is the fundamental enhancement and improvement of the raw product, with the level of transformation contributing to retail value and marketability. Certainly, the skill of the artisan is critical to the quality of the product, the degree of product differentiation and design uniqueness from competitors, the cultural uniqueness of the product, and the continued development of new or innovative products for the market (Naidu et al. 2014). While it is understood that value adding activities create retail ready jewellery and handicraft products for the market, further investigation is required to assess this segment of the value chain in terms of capital investment, variable and fixed input costs, and labour requirements. More difficult will be understanding the market and revenue streams that ultimately determine the profitability of such businesses. Economic assessment of the value-adding component of the pearl livelihoods value chain was beyond the scope of the present study but will be a key avenue for future investigation.

Another impact of mabé pearl culture in Fiji and Tonga, setting aside direct income generation and skills development, is how the integration of the pearl farming has shifted, or altered, the social dynamic within villages undertaking the activity and within the broader community. Gender roles within communities have always been traditionally well defined for both men and women. The introduction of mabé pearl culture has seen a shift to a collaborative approach between genders where each has a role to play in achieving success, but additionally, has significantly improved the supplementary income for women engaged in mabé pearl culture and associated production of handicrafts and jewellery (Mikhailovich et al. 2022). For many women the engagement in the pearl culture value chain brought new skills, confidence, income earning capacity and contributed to their status in their community and family. However, income distribution and application still vary widely. Typically, many communities engage in resource sharing to provide for the community. Differences can include some models where a proportion of income will go the individual and the rest to the community (Mikhailovich et al. 2022). Further research is required to assess and map income flows from mabé pearl culture to gauge levels of reinvestment in pearl culture to ensure long-term profitability (Chapter 2 and 5), diversion to other activities (subsistence and commercial), and the broader regional and economy wide impacts to Fiji and Tonga.

As previously discussed, the domestic tourism market in both Fiji and Tonga are the largest income generating segment for mabé pearls and MOP handicrafts (Chapters 4 and 5). Currently, the development of handicrafts for the tourism market is disconnected from the consumer preferences of the domestic tourism cohort. While many tourists express demand for locally crafted products over imported items, it is more complex. It is likely that opportunities to take full advantage of tourist demand for handicrafts is not maximised. To improve the economic benefits to locals, given the same demand conditions, consideration needs to be given to tailoring future handicraft design and form to align with consumer preferences more closely to improve sales and income generation (Miltz et al. 2021). From a tourism perspective there are a number of factors that enhance saleability. These can include the level of value adding, the design and uniqueness of the product, its cultural significance, and the quality of raw materials (Naidu et al. 2014). Given that mabé pearl and MOP handicraft production is becoming more organised, such as the recent establishment of dedicated handicraft centre in Savusavu (Fiji) and established workshops in Somosomo (Taveuni, Fiji) and Vava'u (Tonga), there is an opportunity to undertake consumer surveys of tourists in both countries that will inform handicraft product development, provide a platform for focused training programs, improve sales of locally made products, and maximise economic benefits to communities, farmers and artisans.

8.8 Concluding comments

Pearl culture offers significant livelihood opportunities for communities in Fiji and Tonga and creates the potential for broader economic benefits across the Pacific region at an artisanal level. To ensure sustainable expansion of the pearl sector research and development activities to improve livelihoods require robust economic analyses, both ex-ante and ex-post, to ensure that investments are sound, and community adoption and benefits are maximised. As an example, the French Polynesian pearl sector has, since 1993, continued an upward trend in production of round pearls that has delivered a commensurate devaluation of the product in the international marketplace, falling from a high of USD 40 per gram to less than USD 5 per gram. This increase in pearl supply demonstrates a need to establish development plans that consider the sectors ability to match demand both internationally and domestically. Understanding the markets capacity to absorb supply, developing new market segments and accessing broader value chain opportunities, while maintaining quality, requires significant investment in development planning that provides a basis for sustainable, not maximal development. In the context of Fiji and Tonga the focus of pearl sector development has centred around the core value of improving community livelihoods, particularly for women, and encouraging participation within the wider value chain (pearl production, jewellery and handicrafts, subsistence food supply etc.). There are significant opportunities to develop country specific products that satisfy market niches and can negate some of the market competition that may occur. Finally, this research has demonstrated beyond doubt the need for applied economic studies of potential or existing activities, and any interventions for the purpose of industry development, to ensure benefits accrue to the pearl sector. Such an approach is recommended for all future regional aquaculture-based interventions.

References

Adams, T., Bell, J., and Labrosse, P. 2001. Current status of aquaculture in the Pacific Islands. The International Center for Living Aquatic Resources Management (ICLARM). Contribution 1574, pp. 13.

Andréfouët, S., Charpy, L., Lo-yat, A., and Lo, C. 2012. Recent research for pearl oyster aquaculture management in French Polynesia. *Marine Pollution Bulletin*, 65**:** 407-414.

Andréfouët, S., Thomas, Y., and Lo, C. 2014. Amount and type of derelict gear from the declining black pearl oyster aquaculture in Ahe atoll lagoon, French Polynesia. *Marine Pollution Bulletin*, 83**:** 224-230.

Andréfouët, S., Thomas, Y., Dumas, F., and Lo, C. 2016. Revisiting wild stocks of black lip oyster *Pinctada margaritifera* in the Tuamotu Archipelago: The case of Ahe and Takaroa atolls and implications for the cultured pearl industry. *Estuarine, Coastal and Shelf Science*, 182: 243-253.

Anon. (1956, April 1). Extending MOP Beds in Cook Islands. Pacific Islands Monthly. Volume XXVI (No.9), pp.50. Available at: nla.gov.au

Anon. (1957, December 1). Cook Island pearling: Manihiki may be closed again. Pacific Islands Monthly. Volume XXVIII (No.5), pp.67. Available at: https://nla.gov.au

Anon. 2007. Justin Hunter and Pearls Fiji. *Pearl World: International Pearling Journal*,16:10–15.

Anon. 2012. Fiji's Unique Pearls. Available at: www.seafiji.com

Anon. 2014. Heart of Darkness - The Black Pearl. Available at: www.ck

Anon. 2016. The Cook Islands - What is our past?. Available at: www.ck

Anon. 2018. Cook Islands Pearl Authority. Available at: www.pearlauthority.com

Arnaud-Haond S., Vonau, V., Bonhomme, F., Boudry, P., Prou, J., Seaman, T., Veyret, M., and Goyard, E. 2003. Spat collection of the pearl oyster (*Pinctada margaritifera cumingii*) in French Polynesia: an evaluation of the potential impact on genetic variability of wild and farmed populations after 20 years of commercial exploitation. *Aquaculture*, 219(1-4): 181-192.

Arnaud-Haond S., Vonau, V., Bonhomme, F., Boudry, P., Blanc, F., Prou, J., Seaman, T., and Goyard, E. 2004. Spatio-temporal variation in the genetic composition of wild populations of pearl oyster (*Pinctada margaritifera cumingii*) in French Polynesia following 10 years of juvenile translocation. *Molecular Ecology*, 13(7): 2001–2007.

Beechey, F.W. 1831. Narrative of a voyage to the Pacific and Bering's Strait (1825–28). 2 Volumes. London.

Benzie, J. and Ballment, E. 1994. Genetic differences among black-lipped pearl oyster (*Pinctada margaritifera*) populations in the western Pacific. *Aquaculture*, 127(2-3)**:** 145-156.

Bertucci, F., Legraverant, Y., Berthe, C., Brooker, R.M., Lo, C., and Lecchini, D. 2016. Natural cleaning of the black-lip pearl oyster *Pinctada margaritifera* by butterflyfishes (Chaetodon) in French Polynesia. *Estuarine, Coastal and Shelf Science*, 182: 270–273.

Blay, C., Sham-Koua, M., Vonau, V., Tetumu, R., Cabral, P., and Ky, C.L. 2014. Influence of nacre deposition rate on cultured pearl grade and colour in the black-lipped pearl oyster *Pinctada margaritifera* using farmed donor families. *Aquaculture International*, 22(2): 937–953.

Bolatagici, L. 2016 (April 22). $240k for pearl industry. The Fiji Times [online]. Available at: www.fijitimes.com/240k-for-pearl-industry

Bouchon-Brandeley, G. 1885. Les pêcheries des îles Tuamotu. *Journal des Etablissements Français d'Océanie*, pp. 206-226.

Brea, E., 2017. A developmental perspective on business model innovation: exploring sequences of change in high-performing IT firms. PhD Thesis. University of Queensland.

Brearley, M. 2021. Eating pearl: a staple for millennia becomes a modern luxury. The Guardian, 19 December. Available at: www.theguardian.com/food

Broadfield R. 2010. Pearl meat the new gem on menus. The West Australian, 26 April. Available at: thewest.com.au/lifestyle/food

Byron, J., Wallis, S., Carteret, P., Cook, J., Banks, J., and Mulgrave, C.J.P.B. 1775. An Account of the Voyages Undertaken by the Order of His Present Majesty, for Making Discoveries in the Southern Hemisphere: And Successively Performed by Commodore Byron, Captain Wallis, Captain Carteret, and Captain Cook, in the Dolphin, the Swallow, and the Endeavour: Drawn Up from the Journals which Were Kept by the Several Commanders, and from the Papers of Joseph Banks. Volume 2, James Williams.

Cabral, P. 1989. Problems and perspectives of the pearl oyster aquaculture in French Polynesia. Actes de colloques Ifremer (February 20 – March 4). Tahiti, French Polynesia, 9(7): 57-66. Available at: archimer.ifremer.fr

Cariño, M. and Monteforte, M. 2009. An Environmental History of Nacre and Pearls: Fisheries, Cultivation and Commerce. *Global Environment*, 2(3)**:** 48-71.

Cartier, L.E., Krzemnicki, M.S., and Ito, M. 2012. Cultured pearl farming and production in the Federated States of Micronesia. *Gems & Gemology*, 48(2): 108-122.

Cartier, L.E. and Carpenter, K.E. 2014. The influence of peal oyster farming on reef fish abundance and diversity in Ahe, French Polynesia. *Marine Pollution Bulletin*, 78(1-2): 43-50.

Chand, A., Naidu, S., Southgate, P.C., and Simos, T. 2011. Pearl Industry Value Chain Review 2011: Fiji Islands. Report for Pacific Agribusiness Research for Development Initiative (PARDI). Australian Centre for International Agriculture (ACIAR), Canberra, pp. 15.

Chand, A., Naidu, S., Southgate, P.C., Simos, T. 2015. The relationship between tourism and the pearl and mother of pearl shell jewellery industries in Fiji. In: Harrison, D. and Pratt, S. (Eds.) Tourism in Pacific Islands: Current Issues and Future Challenges. Routledge, Oxford, pp. 148-164.

Chen, J. Q., Haws, M.C., Fong, Q.S., and Leung, P. 2017. Economic feasibility of producing oysters using a small-scale Hawaiian fishpond model. *Aquaculture Reports*, 5: 41–51.

Cochennec-Laureau, N., Montagnani, C., Saulnier, D., Fougerouse, A., Levy, P., and Lo, C. 2010. A histological examination of grafting success in pearl oyster *Pinctada margaritifera* in French Polynesia. *Aquatic Living Resources*, 23(1)**:** 131-140.

Coppell, W.G. 1973. About the Cook Islands. Their nomenclature and a systematic statement of early European Contacts. *Journal de la Société des Océanistes*, 29(38)**:** 23-56.

Corney, B.G. 2016. The Quest and Occupation of Tahiti by Emissaries of Spain During the Years 1772-1776: told in despatches and other contemporary documents (Vol. 1). The Hakluyt Society. New York. Routledge (Taylor and Francis).

de Nys, R. and Ison, O. 2008. Biofouling. In: Southgate, P.C. and Lucas, J.S. (Eds) The Pearl Oyster. Elsevier, Oxford, pp. 527–553.

Demmer, J., Cabral, P., and Ky, C.L. 2016. Comparison of harvested rate and nacre deposition parameters between cultured pearls issued from initial graft and second nucleus insertion in *P. margaritifera*. *Aquaculture Research*, 47(10): 3297–3306.

Diggles, B. and Hine, P. 2001. Mortality of blacklip pearl oysters in Manihiki Lagoon. Government of the Cook Islands, Ministry of Marine Resources. Wellington, pp. 36.

Dobson, G.T., Johnston, W.L., Duy, N.D.Q. and Southgate, P.C., 2022. Assessing Productivity and Economic Potential of Pond-Based Culture of Sandfish (*Holothuria scabra*) and Babylon Snail (*Babylonia areolata*) in Monoculture and Four Different Coculture Arrangements. *Journal of Shellfish Research*, 41(3): 361-367.

FAO. 2017. Effects of Food Taxation in Tonga: A Snapshot. Food and Agriculture Organisation of the United Nations and the Fiji National University Pacific Research Centre for the Prevention of Obesity and Non-communicable Diseases (C-POND). FAO, Rome, pp. 56.

Farn, A.E. 1986. Pearls: natural, cultured and imitation. Butterworth and Co. Ltd., London.

Ferreira JG, Bricker SB (2016) Goods and services of extensive aquaculture: shellfish culture and nutrient trading. *Aquaculture International*, 24(3): 803–825

Fiji Government. 2013. Government Turns Focus to Pearl Farming. Ministry of Communications. Available at: www.fiji.gov.fj

Fiji Ministry of Health (MOH), 2009. Food Safety Regulations – Fiji Islands. Fiji Government, Suva. pp.201. Available at: www.health.gov.fj

Fong, Q.S., Ellis, S., and Haws, M. 2005. Economic feasibility of small-scale black-lipped pearl oyster (*Pinctada margaritifera*) pearl farming in the Central Pacific. *Aquaculture Economics & Management*, 9(3): 347-368.

Friedman, K.J. and Bell, J.D. 1999. Variation in abundance of blacklip pearl oyster (*Pinctada Margaritifera* Linne.) spat from inshore and offshore reefs in Solomon Islands. *Aquaculture*, 178(3-4): 273-291.

Friedman, K.J., and Southgate, P.C. 1999. Growout of blacklip pearl oysters, *Pinctada margaritifera*, on chaplets in suspended culture in Solomon Islands. *Journal of Shellfish Research*, 18: 451–458.

George, C. D. 1968. Pearl cultivation in the South Seas. South Pacific Bulletin (4th Quarter), pp. 49-54.

Gervis, M. and Sims, N.A. 1992. The biology and culture of pearl oysters (*Bivalvia: pteriidae*). International Center for Living Aquatic Resources Management (ICLARM) Studies and Reviews (Volume 21). Overseas Development Administration (ODA), London, pp. 49.

Gillett, R. 2009. Fisheries in the economies of the Pacific island countries and territories. Pacific Studies Series. Asian Development Bank, Mandaluyong City, Philippines, pp. 480.

Gillett, R. 2016. Fisheries in the economies of the Pacific Island countries and territories. Pacific Studies Series (Second Edition). Australian Department of Foreign Affairs and Trade and the Secretariat of the Pacific Community. Noumea, New Caledonia, pp. 684.

Gillett, R. and Tauati, M.I. 2018. Fisheries of the Pacific Islands: regional and national information. FAO fisheries and aquaculture technical paper #625. FAO, Apia, pp.400.

Goebel, M. and Dirlam, D.M. 1989. Polynesian Black Pearls. *Gems & Gemology*, 25**:** 130-148.

Gordon, S.E., Ngaluafe, P., Wingfield, M., and Southgate, P.C. 2017. Morphometric relationships and shell form of cultured winged pearl oysters (*Pteria penguin*) in Tonga. *Journal of Shellfish Research*, 36(3)**:** 677-682.

Gordon, S.E., Wingfield, M., Kishore, P., and Southgate, P.C. 2018. Using microradiography to assess nacre thickness of mabé pearls: Technique suitability and insights. *Aquaculture*, 492: 195-200.

Gordon, S.E., Malimali, S., Wingfield, M., Kurtböke, D.I., and Southgate, P.C. 2019. Effects of nucleus position, profile and arrangement on the quality of mabé pearls produced by the winged pearl oyster, *Pteria penguin*. *Aquaculture*, 498: 109-115.

Gordon, S.E., Wingfield, M., Malimali, S., Halafihi, T., and Southgate, P.C. 2020. Assessing protective mesh cylinders for chaplet-based culture of the winged pearl oyster, *Pteria penguin*. *Journal of Shellfish Research*, 39(1): 59-66.

Gordon, S. 2020. Optimizing mabé pearl culture with the winged pearl oyster, *Pteria penguin*, in the Kingdom of Tonga [Chapter 8: Maximizing profitability and value of mabé pearl production through adoption of improved culture practises]. PhD Thesis, University of the Sunshine Coast, Queensland, pp. 111-122.

Government of Cook Islands. 2018. Pre-election Economic and Fiscal Update 2017/18. Ministry of Finance, Rarotonga, pp. 164. Available at: www.mfem.gov.ck

Hales, S. 2015. Vava'u Pearl Farmers Survey - Report of Survey Results. Ministry of Commerce and Labour, Tonga, pp. 8.

Hambrey Consulting. 2011. Opportunities for the development of the Pacific Islands' mariculture sector. Secretariat of the Pacific Community, Noumea. pp. 123.

Hardaker, J.B., Huirne, R.B.M., and Anderson, J.R. 1997. Coping with Risk in Agriculture. CAB International, New York, USA, pp. 269.

Haws, M. and Ellis, S. 2000. Collecting black-lip pearl oyster spat. Aquafarmer Information Sheet #144, Center for Tropical and Subtropical Aquaculture, Honolulu, pp. 8.

Haws, M. 2002. The Basic Methods of Pearl Farming: A Layman's Manual. Center for Tropical and Subtropical Aquaculture Publication #127, Hilo, pp. 84.

Haws, M., Ellis, S., and Ellis, E.P. 2006. Producing Half-Pearls (Mabé). Western Indian Ocean Marine Science Association, University of Dar es Salaam, University of Hawaii, Hilo and the Coastal Resources Center, University of Rhode Island, pp. 17. Available at: https://www.crc.uri.edu

Haws, M., Crawford, B., Portella, M.C., Ellis, S., Jiddawi, N., Mmochi, A., Gaxiola-Camacho, E., Rodriguez-Dominguez, G., Rodriguez, G., and Francis, J. 2010. Aquaculture research and development as an entry-point and contributor to natural resources and coastal management. *Coastal Management*, 38(3)**:** 238-261.

Heffernan, O. 2006. Pearls of wisdom. *The Marine Scientist*, 16**:** 20-23.

Hisada, Y. and Fukuhara, T. 1999. Pearl marketing trends with emphasis on black pearl market. South Pacific Aquaculture Development Project (Phase II), Field Document 13, FAO, Rome, Italy. Available at: www.fao.org

Humphrey, J. D. 2008. Disease and Predation. In: Southgate, P.C. and Lucas, J.S. (Eds.) The Pearl Oyster. Elsevier, Oxford, pp. 367–435.

Intes, A. and Coeroli, M. 1985. Evolution and condition of natural stocks of pearl oysters (*Pinctada margaritifera* Linne) in French Polynesia. In: Delenalle, B., Galzin, R., Salvat, B., La Croix, C., Wolf, A.E., Theibaut, N., and Poli, G. (Eds.) Vth International Coral Reef Congress, 5:545-550.

Ito, M. 2009. Improving pearl quality by grafting and husbandry methods. Center for Tropical and Subtropical Aquaculture (AquaTips #20). College of Micronesia Land Grant Program, Pohnpei, pp. 8.

Jansen, H. and van den Bogaart, L. 2020. Blue carbon by marine bivalves: Perspective of Carbon sequestration by cultured and wild bivalve stocks in the Dutch coastal areas. Research Report No. C116/20 Wageningen University, Netherlands, pp.52.

Johnston, W. and Pickering, T.D. 2003. The economics of aquaculture in comparison with other rural development opportunities in Pacific island countries. Marine Studies Technical Report 2003/07. University of the South Pacific, Suva, pp. 24.

Johnston, W. and Ponia, B. 2006. Pacific Black Pearl Culture [Microsoft Excel Spreadsheet]. Cook Islands Marine Resources Institution Strengthening Project (CIMRIS) Project. Developed by: Queensland Department of Agriculture and Fisheries and Cook Islands Ministry of Marine Resources. Available at: www.business.qld.gov.au/industries

Johnston, W., Hine, D., Limpus, S., and Voronina, M. 2014. Building Business Skills and Community Based Industry Development in the Pacific, Fiji Workshop Series 2013 (Rakiraki and Savusavu). Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 52.

Johnston, W. and Hine, D. 2015. Building Business Skills and Community Based Industry Development in the Pacific. Tongan Workshop Series 2014/15 (Vava'u and Nuku'alofa). Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 33.

Kaeppler, A.L. 1971. Eighteenth Century Tonga: New Interpretations of Tongan Society and Material Culture at the Time of Captain Cook. *Man*, 6(2): 204-220. Available at: doi.org.

Kay, R.D., Edwards, W.M., and Duffy, P.A. 2023. Farm Management (10th Edition). McGraw-Hill Education, London, pp. 512.

KTCL. 2020. Tonga Food Act 2020. Kingdom of Tonga Crown Law, pp.59. Available at: https://ago.gov.to

Kishore, P., Hunter, J., Zeng, C., and Southgate, P.C. 2014. The effects of different culture apparatuses and current velocities on byssus production by the black-lip pearl oyster, *Pinctada margaritifera*. *Aquaculture*, 434: 74–77.

Kishore, P., Southgate, P.C., Seeto, J., and Hunter, J. 2015. Factors influencing the quality of half-pearls (mabé) produced by the winged pearl oyster, *Pteria penguin* (Röding, 1758). *Aquaculture Research*, 46(4)**:** 769-776.

Kishore, P. and Southgate, P.C. 2015. Does the quality of cultured pearls from the black-lip pearl oyster, *Pinctada margaritifera*, improve after the second graft? *Aquaculture*, 446**:** 97-102.

Kishore, P. and Southgate, P.C. 2016a. A detailed description of pearl-sac development in the black-lip pearl oyster, *Pinctada margaritifera* (Linnaeus, 1758). *Aquaculture Research*, 47(7): 2215-2226

Kishore, P. and Southgate, P.C. 2016b. The effect of different culture methods on the quality of round pearls produced by the black-lip pearl oyster *Pinctada margaritifera* (Linnaeus, 1758). *Aquaculture*, 451: 65–71.

Kishore, P., Vuibeqa, G.B., and Southgate, P.C. 2018. Developing a national spat collection program for pearl oysters in the Fiji Islands supporting pearl industry development and livelihoods. *Aquaculture Reports*, 9**:** 46-52.

Kripa, V., Abraham, K., Libini, C., Velayudhan, T., Radhakrishnan, R., Mohamed, K., and Mohan. J.M. 2008. Production of designer mabé pearls in the black-lipped pearl oyster, *Pinctada margaritifera*, and the winged pearl oyster, *Pteria penguin*, from Andaman and Nicobar Islands, India. *Journal of the World Aquaculture Society*, 39(1)**:** 131-137.

Kunz, G.F. and Stevenson, C.H. 1908. The Book of the Pearl: Its History, Art, Science and Industry. The Century Co., New York, pp. 548.

Ky, C.-L., Molinari, N., Moe, E., and Pommier, S. 2014. Impact of season and grafter skill on nucleus retention and pearl oyster mortality rate in *Pinctada margaritifera* aquaculture. *Aquaculture International*, 22: 1689–1701.

Ky, C.L., Blay, C., Aiho, V., Cabral, P., Le Moullac, G., and Lo, C. 2015a. Macro-geographical differences influenced by family-based expression on cultured pearl grade, shape and colour in the black-lip 'pearl oyster' *Pinctada margaritifera*: a preliminary bi-local case study in French Polynesia. *Aquaculture Research*, 48(1): 270-282.

Ky, C.L., Demmer, J., Sham-Koua, M., and Cabral, P. 2015b. Development of cultured pearl circles and shape after initial graft and second nucleus insertion in the black-lipped pearl oyster *Pinctada margaritifera*. *Journal of Shellfish Research*, 34(2): 319–328.

Ky, C.L., Blay, C., and Lo, C. 2016. Half-sib family effects on cultured pearl quality traits in the black-lipped pearl oyster *Pinctada margaritifera*: testing for indirect benefits of polyandry and polygyny. *Aquaculture International*, 24(1): 171-182.

Lacoste, E., Gueguen, Y., Le Moullac, G., Koua, M.S., and Gaertner-Mazouni, M.S. 2014a. Influence of farmed pearl oysters and associated biofouling communities on nutrient regeneration in lagoons of French Polynesia. *Aquaculture Environment Interactions*, 5(3): 209-219.

Lacoste, E., Le Moullac, G., Levy, P., Gueguen, Y., and Gaertner-Mazouni, N. 2014b. Biofouling development and its effect on growth and reproduction of the farmed pearl oyster *Pinctada margaritifera*. *Aquaculture*, 434: 18–26.

Lintilhac, J.P. 1987. Black Pearls of Tahiti. Royal Tahitian Pearl Book, Papeete, pp. 109.

Loret, P., Pastoureaud, A., Bacher, C., and DeLesalle, B. 2000. Phytoplankton composition and selective feeding of the pearl oyster *Pinctada margaritifera* in the Takapoto lagoon (Tuamotu Archipelago, French Polynesia): in situ study using optical microscopy and HPLC pigment analysis. *Marine Ecology Progress Series*, 199**:** 55-67.

Loesdau, M., Chabrier, S., Gabillon, A. 2015. Automatic Nacre Thickness Measurement of Tahitian Pearls. In: Kamel, M., Campilho, A. (Eds) Image Analysis and Recognition. ICIAR 2015. Springer International Publishing, Switzerland, pp. 446-455. Available at: link.springer.com

MacPherson, C. 2000. Oasis or mirage: the farming of black pearl in the northern Cook Islands. *Pacific Studies*, 23**:** 23-23.

Mamangkey, N. G. F., Agatonovic, S., and Southgate, P.C. 2010. Assessing pearl quality using reflectance UV-Vis spectroscopy: does the same donor produce consistent pearl quality? *Marine Drugs*, 8: 2517–2525.

Matlins, A. L. 2008. The Pearl Book - The Definitive Buying Guide: How to Select, Buy, Care for & Enjoy Pearls (Fourth Edition). Gemstone Press, Woodstock, pp. 229.

McDonald, R. and Eisenhardt, K. 2019. Parallel Play: Startups, Nascent Markets, and the Effective Design of a Business Model. *Administrative Science Quarterly*, 65(2): 483-523.

McKenzie, E. 2004. A cost-benefit analysis of projects implemented to assist the black pearl industry in Manihiki Lagoon, Cook Islands. SPC and Pacific Islands Applied Geoscience Commission (SOPAC) Technical Report 371, pp.74.

Metropolis, N. and Ulam, S. 1949. The Monte Carlo method. *Journal of the American Statistical Association*, 44(247): 335-341.

Mikhailovich, K., Smith, D., and Sloan, T. 2019. Monitoring and Evaluation of Socio-Economic Impacts of Pearl-based Livelihood Development - Final Report. Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 16.

Mikhailovich, K., Mackenzie, E. and Smith, D. 2022. Enhancing coastal livelihoods through half-pearl aquaculture and handicrafts in Tonga and Fiji. *Development in Practice*, 33(1): 110-121.

Moorhead, A. 2015. Pearls are the business. *Partners in Research for Development*, Issue 2, pp. 10-11. Available at: search.informit.org/doi

Nagai, K. 2013. A history of the cultured pearl industry. *Zoological Science*, 30(10)**:** 783-793.

Naidu, S., Chand, A. and Southgate, P.C. 2014. Determinants of Innovation in Handicraft Industry of Fiji and Tonga: An Empirical Analysis from Tourism Perspective. *Journal of Enterprising Communities: People and Places in the Global Economy*, 8(4): 318-330.

Nas, T.F. 2016. Cost-benefit analysis: theory and application. Lexington Books, London, pp. 231.

Newnham, R.B.T. 1989. Pearls and politics: the impact of the development of the cultured-pearl industry on Manihiki. PhD Thesis, University of Canterbury, New Zealand, pp. 119.

Niquil, N., Pouvreau, S., Sakka, A., Legendre, L., Addessi, L., Le Borgn, E.R., Charpy, L., and DeLesalle, B. 2001. Trophic web and carrying capacity in a pearl oyster farming lagoon (Takapoto, French Polynesia). *Aquatic Living Resources*, 14(3)**:** 165-174.

O’Connor, W. 2002. Abstracts, Reviews and Current Contents: World Aquaculture Society’s WAS 2002, Beijing. SPC Pearl Oyster Information Bulletin #15. Secretariat of the Pacific Community, Noumea, pp. 23–26.

O'Connor, W.A. and Gifford, S.P. 2008. Environmental Impacts of Pearl Farming. In: Southgate, P.C. and Lucas, J.S. (Eds) The Pearl Oyster. Elsevier, Oxford, pp. 497-525.

Pal, S.W., Southgate, P.C., Iji, P.E., and Ram, R. 2023. Potential bioconversion of black lip and mabé pearl oyster waste into an organic fertiliser. Book of abstracts from the World Aquaculture Society conference, Darwin (May 29 – June 1). World Aquaculture Society, USA.

Pass, D., Dybdahl, R., and Mannion, M. 1987. Investigations into the causes of mortality of the pearl oyster, *Pinctada maxima* (Jamson), in Western Australia. *Aquaculture*, 65(2)**:** 149-169.

Pit, J. H. and Southgate, P.C. 2003. Fouling and predation: how do they affect growth and survival of the blacklip pearl oyster, *Pinctada margaritifera*, during nursery culture? *Aquaculture International*, 11: 545–555.

Poirine, B. and Kugelmann, S. 2003. Etude economique des determinants de la rentabilité des fermes perlières en Polynésie Française. IRIDIP report. University of French Polynesia, Tahiti.

Ponia, B. 2010. A review of aquaculture in the Pacific Islands 1998-2007: tracking a decade of progress through official and provisional statistics. Secretariat of the Pacific Community (SPC) Aquaculture Technical Papers, Noumea. pp. 32.

Pouvreau, S., Bacher, C., and Héral, M. 2000a. Ecophysiological model of growth and reproduction of the black pearl oyster, *Pinctada margaritifera*: potential applications for pearl farming in French Polynesia. *Aquaculture*, 186(1-2)**:** 117-144.

Pouvreau, S., Gangnery, A., Tiapari, J., LaGarde, F., Garnier, M., and Bodoy, A. 2000b. Gametogenic cycle and reproductive effort of the tropical blacklip pearl oyster, *Pinctada margaritifera* (Bivalvia: *Pteriidae*), cultivated in Takapoto atoll (French Polynesia). *Aquatic Living Resources*, 13(1)**:** 37-48.

Preston, G.L. 2008. Stimulating investment in pearl farming in the Solomon Islands: pearl farming policy and management guidelines. The WorldFish Center and the Ministry of Fisheries and Marine Resources, Solomon Islands, Honiara, pp. 31.

Quanchi, M. and Robson, J. 2005. Historical dictionary of the Discovery and Exploration of the Pacific Islands. Historical Dictionaries of Discovery and Exploration, No.2, Scarecrow Press, Oxford, pp. 299.

Queensland Department of Agriculture and Fisheries. 2023. Finance and budgeting tools for agribusiness (Agbiz). Available at: www.business.qld.gov.au/industries/farms-fishing-forestry/agriculture/business/finance/tools

Ranson, G. 1962. Missions dans le Pacifique: récifs coralliens. Huîtres Perlières, Lechevalier, pp. 57.

Rapaport, M. 1994. Defending the lagoons: Insider/outsider struggles over the Tuamotuan pearl industry. PhD Thesis, University of Hawaii at Manoa, United States of America, pp. 558.

Rapaport, M. 1995a. Oysterlust: Islanders, entrepreneurs, and colonial policy over Tuamotu lagoons. *The Journal of Pacific History*, 30(1)**:** 39-52.

Rapaport, M. 1995b. Pearl farming in the Tuamotus: atoll development and its consequences. *Pacific Studies*, 18**:** 1-25.

Reeves, R. 2012. Cook Islands Pearl Industry Shortfalls Buffered By Fishery Revenues. Pacific Islands Report, Pacific Islands Development Program, Hawaii. Available at: pireport.org

Rhodes, F.C. 1937. Pageant of the Pacific: Being the Maritime History of Australasia (Volume 1). FJ Thwaites Pty Ltd, Sydney.

Ruiz-Rubio, H., Acosta-Salmón, H., Olivera, A., Southgate, P.C., and Rangel-Dávalos. C. 2006. The influence of culture method and culture period on quality of half-pearls ('mabé') from the winged pearl oyster *Pteria sterna*, Gould, 1851. *Aquaculture*, 254(1-4)**:** 269-274.

Saidi, I., Johnston, B., and Southgate, P.C. 2017. Potential profitability of pearl culture in coastal communities in Tanzania. *Aquaculture Reports*, 5: 10–17.

Salomon, P. and Roudnitska, M. 1986. Tahiti: la magie de la perle noire. Tahiti Perles (R. Wan et Cie.). Time Editions, Singapore, pp. 220.

Sarkis, S., Lovatelli, A. 2007. Installation and operation of a modular bivalve hatchery. FAO Fisheries Technical Paper No.492. FAO, Rome, pp.173.

Sauni, S. 2006. Cook Islands National Pearl Economics Workshop and Industry Seminar. Fisheries Newsletter #118. Secretariat of the Pacific Community, Noumea, pp.13-15.

Saville-Kent, W. 1893. The Great Barrier Reef of Australia: Its Products and Potentialities. W.H. Allen and Co Ltd, London, pp. 467.

Scoones, R. J. S. 1996. The development of the pearl sac in *Pinctada maxima* (Jameson, 1901) (Lamellibranchia: Pteriidae) and the implications for the quality of cultured pearls. MSc Thesis, University of Western Australia.

Scott, M. 1991. In Search of the Cook Islands - The Pearls of Manihiki. New Zealand Geographic. Available at: http://www.nzgeo.com/stories/in-search-of-the-cook-islands

Shang, Y.C. 1990. Aquaculture Economic Analysis: An Introduction. World Aquaculture Society, Baton Rouge, pp. 211.

Shumway, S.E., Davis C., Downey, R., Karney, R., Kraeuter, J., and Parsons J. 2003. Shellfish aquaculture - in praise of sustainable economies and environments. *World Aquaculture*, 34(4): 8–10.

Silas, E. 2003. Pearl Culture-A New Hope for Aquaculture in the 21st Century. In: *First Indian Pearl Congress and Exposition* (Keynote Address), Central Marine Fisheries Research Institute, India, pp. 5-9.

Simard, N.S., Militz, T.A., Kinch, J., and Southgate, P.C. 2018. Artisanal, shell-based handicraft in Papua New Guinea: Challenges and opportunities for livelihoods development. *Ambio*, 48(4): 374–384.

Sims, N.A. 1992. Abundance and distribution of the black-lip pearl oyster, *Pinctada margaritifera* (L.), in the Cook Islands, South Pacific. *Marine and Freshwater Research*, 43(6)**:** 1409-1421.

Sims, N.A. 1993. Pearl Oysters. In: Wright, A. and Hill, L. (Eds.) Nearshore Marine Resources of the South Pacific – Information for Fisheries Development and Management. Institute of Pacific Studies (Suva) and Forum Fisheries Agency (Honiara), Singapore, pp. 409-430.

Skinner, H.D. 1934. Maori amulets in stone, bone, and shell. *The Journal of the Polynesian Society*, 43(2(170))**:** 106-117.

Smaal, A.C., Ferreira, J.G., Grant, J., Petersen, J.K. and Strand, Ø., 2019. Goods and Services of Marine Bivalves. Springer Nature, Cham, pp. 591.

Southgate, P.C. 1997. Pacific Island pearl oyster resource development. SPC Pearl Oyster Information Bulletin #10. Secretariat of the Pacific Community (SPC), Noumea, pp. 14-16.

Southgate, P.C., Rubens, J., Kipanga, M., and Msumi, G. 2006. Pearls from Africa. SPC Pearl Oyster Information Bulletin #17. Secretariat of the Pacific Community (SPC), Noumea, pp. 16-17.

Southgate, P. C. 2008. Pearl Oyster Culture. In: Southgate, P.C. and Lucas J.S. (Eds) The Pearl Oyster. Elsevier, Oxford, pp. 231–272.

Southgate P.C., Strack, E., Hart, A., Wada, K.T., Monteforte, M., Carino, M., Langy, S., Lo, C., Acosta-Salmon, H., and Wang, A. 2008. Exploitation and Culture of Major Commercial Species. In: Southgate, P.C. and Lucas, J.S. (Eds) The Pearl Oyster. Elsevier, Oxford, pp. 303-355.

Southgate, P.C., Beer, A.C., and Ngaluafe, P. 2016. Hatchery culture of the winged pearl oyster, *Pteria penguin*, without living micro-algae. *Aquaculture*, 451**:** 121-124.

Southgate, P. C. 2018. Half-pearl industry development in Tonga and Vietnam: ACIAR Project FIS/2016/126. Australian Centre for International Agricultural Research (ACIAR), Canberra.

Southgate, P.C. 2019. Pearl industry development in the western Pacific: ACIAR Final Report FR2019/108. Australian Centre for International Agricultural Research (ACIAR), Canberra, pp.40.

Southgate, P.C., Kishore, P., Sharma, S., and Simos, T. 2019. Empowering women through pearl industry-based livelihoods in Fiji. SPC Women in Fisheries Information Bulletin #29. Secretariat of the Pacific Community, Noumea, pp. 24-29.

Southgate, P.C. 2021. Pearl Oyster Culture and Pearl Production. In: Shumway, S. (Editor), Molluscan Shellfish Aquaculture: A Practical Guide. 5m Publishing, Sheffield, pp. 205-231.

Southgate, P.C., Kishore, P., Militz, T., and Wingfield, M. 2023. Developing pearl industry-based livelihoods in the Western Pacific: ACIAR Final Report FR/2014/060. Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 65.

SPC 2007. SPC Aquaculture Action Plan: 2007. SPC Aquaculture Portal [online], pp. 31. Available at: aquaculture.spc.int

SPC 2012. Cook Islands Aquaculture Development Plan 2012-2016. Pacific Agricultural and Forestry Policy Network [online], pp. 48. Available at: pafpnet.spc.int

Stanley, D. 2000. South Pacific Handbook. Avalon Travel Publishing, California, pp. 976.

Strack, E. 2006. Pearls. Rühle-Diebener-Verlag, Germany, pp. 707.

Strack, E. 2008. Introduction. In: Southgate, P.C. and Lucas, J.S. (Eds.) The Pearl Oyster. Elsevier, Oxford, pp. 1-36.

Talvard, C. 2011. La perliculture en 2010. Points Forts de la Polynésie Française [online]. Institut Statistique de la Polynésie Française, Service de la Perliculture, Papeete, pp. 8. Available at: data.ispf.pf

Tanaka, Y. 1990. Winged pearl shell newly found in Tonga. SPC Pearl Oyster Information Bulletin #1. Secretariat of the Pacific Community, Noumea, p. 15.

Tanaka, Y. 1997. Potential of commercial development of mabé pearl farming in Vava'u Islands, Kingdom of Tonga. FAO South Pacific Aquaculture Development project (Phase II), Field Document No. 5. FAO, Rome, pp. 26.

Taylor, J. and Strack, E. 2008. Pearl Production. In: Southgate, P.C. and Lucas, J.S. (Eds.) The Pearl Oyster. Elsevier, Oxford, pp. 273-302.

Teitelbaum, A. and Fale, P.N. 2008. Support for the Tongan pearl industry. Pearl Oyster Information Bulletin #18. Secretariat of the Pacific Community, Noumea, pp. 11-14.

Thomas, Y., Garen, P., Bennett, A., Le Pennec, M. and Clavier, J. 2012. Multi-scale distribution and dynamics of bivalve larvae in a deep atoll lagoon (Ahe, French Polynesia). *Marine Pollution Bulletin*, 65: 453-462.

Tisdell, C.A. and Poirine, B. 2000. Socio-economics of pearl culture: industry changes and comparisons focussing on Australia and French Polynesia. SPC Pearl Oyster Information Bulletin #14, Secretariat of the Pacific Community (SPC), Noumea, pp. 30-60.

Tisdell, C. and B. Poirine. 2008. Economics of Pearl Farming. In: Southgate, P.C. and Lucas, J.S. (Eds.) The Pearl Oyster. Elsevier, Oxford, pp. 473-496.

Tonga Ministry of Fisheries. 2018. National Aquaculture Management and Development Plan 2018-2022. Secretariat of the Pacific Community (SPC), Noumea, pp. 30.

Uwate, R.K., Kunatuba, P., Raobati, B., and Tenakanai, C. 1984. A Review of Aquaculture Activities in the Pacific Islands Region: General Overview by Political Entity. Pacific Islands Development Program, East–West Center, Honolulu, pp. 6-52.

van der Schatte Olivier, A., Jones, L., Vay, L.L., Christie, M., Wilson, J., and Malham, S.K. 2020. A global review of the ecosystem services provided by bivalve aquaculture. *Reviews in Aquaculture*, 12(1): 3-25.

Vitukawalu, B., Ma, F., Dulunaqio, S., Batibasaga, R. 2021. Engaging women in pearl meat farming Fiji. SPC Women in Fisheries Information Bulletin #34. Secretariat of the Pacific Community, Noumea, pp. 32-33.

Wada, K. and Komaru, A.. 1996. Color and weight of pearls produced by grafting the mantle tissue from a selected population for white shell color of the Japanese pearl oyster *Pinctada fucata martensii* (Dunker). *Aquaculture*, 142: 25–32.

Wada, K. T. and Tëmkin, I. 2008. Taxonomy and Phylogeny. In: Southgate, P.C. and Lucas J.S. (Eds) The Pearl Oyster. Elsevier, Oxford, pp. 37–75.

Wassnig, M. and Southgate, P.C. 2016. The effects of stocking density and ration on survival and growth of winged pearl oyster (*Pteria penguin*) larvae fed commercially available micro-algae concentrates. *Aquaculture Reports*, 4**:** 17-21.

Wood, B.L. 1967. Geology of the Cook Islands. *New Zealand Journal of Geology and Geophysics*, 10(6)**:** 1429-1445.

Zhu, C., Southgate, P.C., and Li, T. 2019. Production of Pearls. In: Smaal, A., Ferreira, J.G., Grant, J., Petersen, J.K., and Strand, O. (Eds.) Good and Services of Marine Bivalves. Springer Nature, Cham, pp. 73-93.