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

William Johnston[a,b,*], Sophie E. Gordon[b,e], Max Wingfield[b,e], Tu'ikolongahau Halafihi[c], Damian Hine[d], Paul C. Southgate[b,e]

[a] Queensland Department of Agriculture and Fisheries, 47 Mayers Road, Nambour, Queensland, 4560, Australia
[b] School of Science & Engineering, University of the Sunshine Coast, 90 Sippy Downs Drive, Sippy Downs, Queensland, 4556, Australia
[c] Science Division, Ministry of Fisheries, Nuku'alofa, Tongatapu, Tonga
[d] University of Queensland Business School, The University of Queensland, 39 Blair Drive, St Lucia, Brisbane, Queensland, 4067, Australia
[e] Australian Centre for Pacific Islands Research and School of Science and Engineering, University of the Sunshine Coast, 90 Sippy Downs Drive, Sippy Downs, Queensland, 4556, Australia

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ABSTRACT

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 the winged pearl oyster, *Pteria 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 study determined 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 (US dollars; USD) was USD 2,027 and major production costs were labour (29%), marketing (24%), and capital purchase and replacement (16%). Annual production of 231 saleable mabé pearls generated a net present value (NPV) of USD 107,101. The modified internal rate of return (MIRR) and benefit-cost ratio of the modelled mabé pearl farm were 20.46% and 4.86, respectively, with a payback period of 4 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 of this study assist stakeholder understanding of costs, risks and production levels required for profitable mabé pearl production.

## 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; Johnston et al., 2019b). As well as potential export income, coastal communities may, for example, generate income from activities such as collection and sale of juvenile oysters (spat) to pearl farms, culture and sale of mabé pearls (half-pearls), and production of mabé pearl and pearl shell (mother-of-pearl; MOP) jewellery and handicraft items (Johnston et al., 2018; Simard et al., 2019; Johnston et al., 2019b; Southgate 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, *Pinctada margaritifera*, or investigated its potential (Friedman and Bell, 1999; Fong et al., 2005; Tisdell and Poirine, 2008; Southgate et al., 2008; Johnston et al., 2014; Johnston and Hine, 2015; Johnston et al., 2018, Johnston et al., 2019a). Among south Pacific nations, significant cultured round pearl export sectors have been developed in French Polynesia, Cook Islands and Fiji (Southgate et al., 2008; Johnston et al., 2019b). Tonga is

* Corresponding author.
*E-mail address:* bill.johnston@daf.qld.gov.au (W. Johnston).

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unique among pearl producing south Pacific nations in focusing on mabé pearl culture using the winged pearl oyster, *Pteria 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 (Strack, 2006, Taylor and Strack, 2008).

Mabé pearl production is much simpler, and requires fewer resources, than round pearl production (Johnston et al., 2019b) 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. 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. For example, in 2013 there were only three small mabé pearl farms in the Vava'u island group of Tonga, but this had expanded to 11 farms by 2016, and to 17 farms in 2017; these were distributed among the three major island groups in Tonga, with collective production of around 12,000 mabé pearls annually (Johnston et al., 2019b).

Few studies have investigated the economics of pearl culture worldwide, 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 2000 implanted *P. penguin*, reported estimated annual production of 5,400 mabé pearls and very viable economic outputs (Johnston et al., 2020). 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, socio-cultural and financial aspects. The aim of this study 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.

## 2. Materials and Methods

The fundamental basis for the economic modelling utilised in this study was first applied to assess round pearl production in Fiji, and later extended to mabé pearl production in Tonga (Johnston et al., 2018; Johnston et al., 2019a), as well as subsistence level mabé pearl production in Tanzania (Saidi et al., 2017). 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. All costs reported here relate to US dollars (USD).

### 2.1. Development of the economic model

An economic model for mabé pearl production in Tonga was developed using cost benefit analysis (CBA) methodology incorporating a discounted cash flow framework over a twenty-year period (Johnston et al., 2019b; Johnston et al., 2018; Johnston et al., 2020). This 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 may be applied when choosing among a range of investment or project options (Nas, 2016). The economic model uses a number of financial indicators to assess the viability of the investment. The Present Value (PV) of the future stream of costs and benefits is calculated using the compound interest method. The rate used to calculate the PV is the discount rate. Subtracting the future value of costs from the future value of benefits is the Net Present Value (NPV).

For the purpose of this modelling exercise, the discount rate was set at 6%. The current long-term domestic bond rate in Tonga is 3% (National Reserve Bank of Tonga) and is deemed too low. At 6% the 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 Modified Internal Rate of Return (MIRR) provides an additional financial indicator used in this study. The MIRR 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 is calculated using loan rates specified for agricultural activities in Tonga that are currently 10% (Tonga Development Bank, www.tdb.to, 2019), and basic savings interest rates that are currently 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. 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 1).

The equation for the Monte Carlo simulation, sampling underlying distributions for price and yield, is as follows:

$$\pi_i = \left(y_j + \left(\frac{y_{j+1} - y_j}{a_{k+1} - a_k} * (RY_i - a_k)\right)\right) * \left(p_l + \left(\frac{p_{l+1} - p_l}{b_{m+1} - b_m} * (RP_i - b_m)\right)\right) - TC$$

*where*

$j\{k\{RY_i\}\}$ *and* $l\{m\{RP_i\}\}$

Profit is denoted $\pi$, $y$ 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 and $RP$ represents the random number for price, and $TC$ represents the

**Table 1**
Risk categories for price and production of mabé pearls (Johnston et al. 2018).

| 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 |

total annual cost of the mabé 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 costs were deducted to produce and estimate of NPV.

Modelling, incorporating risk analysis, was developed internally by the authors using the Visual Basic language (Johnston et al., 2018; Johnston et al., 2019a; Johnston et al., 2019b). 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.

### 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 (*P. 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 (Gordon et al., 2019). Studies suggest that an appropriate nucleus height is between 7-9 mm with a base diameter of 15 mm for *P. 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 2). Pearl size and shape is not an objective determinant of mabé pearl quality and is instead considered a subjective characteristic.

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 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.

### 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. 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.

#### 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, 2002; Haws and Ellis, 2000; 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). Recent introduction of protective mesh cylinders to house chaplets holding *P. 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 *P. 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 are held on chaplets without protective cylinders (Fig. 1).

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 Fig. 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, and 103 oysters must be implanted to assure mabé pearl production from 100 oysters (Table 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, 11 chaplets with implanted oysters, 11 chaplets with pre-implanted oysters and 7 chaplets within protective mesh cylinders containing oyster juveniles (Table 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 3).

**Table 2**
The alphabetical grading system and grading characteristics used to classify mabé pearl quality in this study (Matlins, 1996; Ruiz-Rubio et al., 2006; 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. |

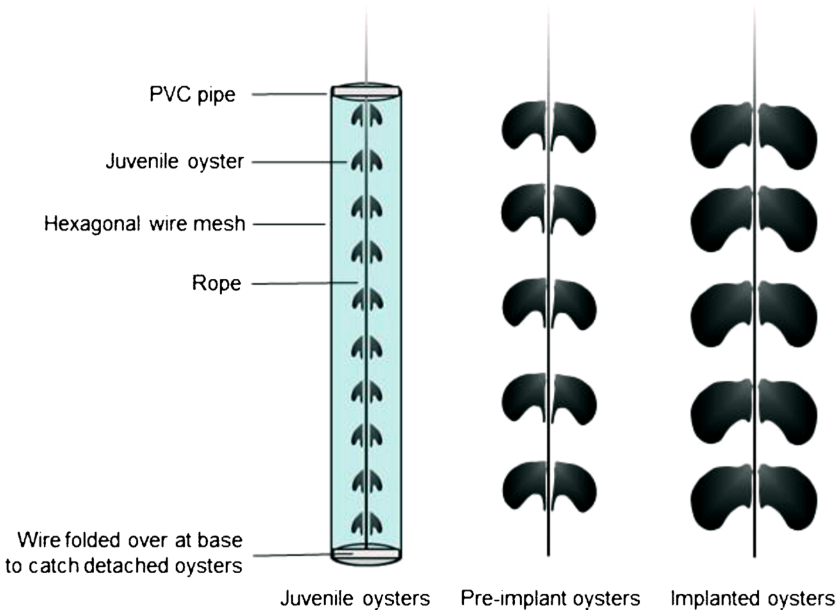


**Fig. 1.** Representation of the farming protocol for mabé pearl production using *Pteria penguin* in Tonga. Chaplets containing juvenile oysters are housed in protective mesh cylinders (left) and chaplets containing larger pre-implanted and implanted oysters (middle and right) are cultured without protective cylinders (Gordon et al., 2020).

**Table 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 | 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 |
| 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% |

### 2.3.2. *Juvenile supply*

In support of sector development, hatchery produced *P. 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.

### 2.3.3. *Nucleus profile and implantation arrangement*

Gordon et al. (2019) recently demonstrated that the number and arrangement of nuclei implanted into *P. 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 (Fig. 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 3, consisting of 103 high profile nuclei and 206 low profile nuclei.

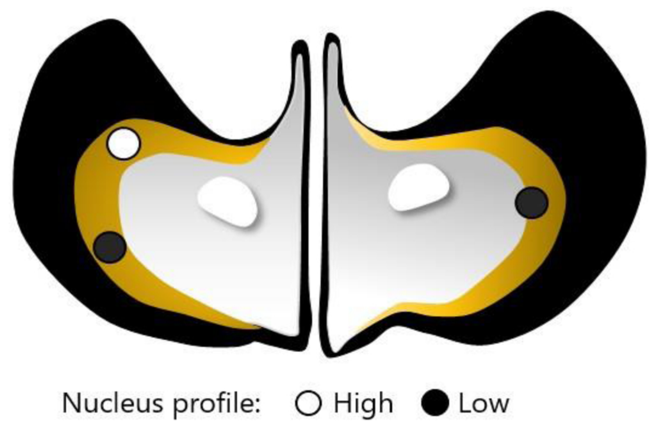


**Fig. 2.** Suggested optimal nucleus arrangement to maximise nacre thickness and quality of resulting mabé pearls produced by *Pteria penguin* (Gordon et al., 2019).

**Table 4**
Average wholesale domestic prices (US dollars; USD) for Tongan mabé pearls.

| Grade | Price per Pearl |
|---|---|
| AAA | 88 |
| AA | 66 |
| A | 44 |
| B | 22 |

### 2.3.4. *Pearl grading and marketing*

Mabé pearl quality (Table 4) 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 4.

### 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

**Table 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 |

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. Based on a 40 -h working week (allowing for four weeks leave) a flat hourly wage rate of USD 2.09 is the average (Anon., 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 5 outlines the breakdown of farming duties and description of farming tasks.

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.

#### 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 6.

#### 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 cash flow as a revenue stream in year-20. Farm infrastructure and equipment costs used in this modelling exercise are shown in Table 7.

**Table 6**
Additional annual operating expenditure (US dollars; USD) for the modelled mabé pearl farm in Tonga.

| 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 |

## 3. Results

### 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 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 8)

### 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 Fig. 3, the model indicates that it would take four years to recoup the original investment in the project.

### 3.3. Other economic indicators

Results of the analysis are shown in Table 9 with some additional economic indicators. The MIRR was 20.46%, benefit-cost ratio was 4.86, and a payback period of four years was estimated (Table 9).

### 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 and Hine, 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 $< 25$, 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 culture farm modelled here, risk analysis focused on two key parameters, price and production, and five-point distributions were used for both variables (Table 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

**Table 7**
Farm infrastructure and equipment costs for the modelled mabé pearl farm in Tonga. All costs are shown in US dollars (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 | | |

**Table 8**
Breakdown of annual production costs for the modelled mabé pearl farm in Tonga. All costs shown in US dollars (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 |

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 and Hine, 2015). Simulation output is the NPV. The highest NPV was USD 228,597, while the lowest was –USD 27,546 (Fig. 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; Fig. 4) is approximately 15%.

**Table 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% |
| Benefit-cost ratio | 4.86 |
| Payback period | 4 years |

**Table 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% |

## 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

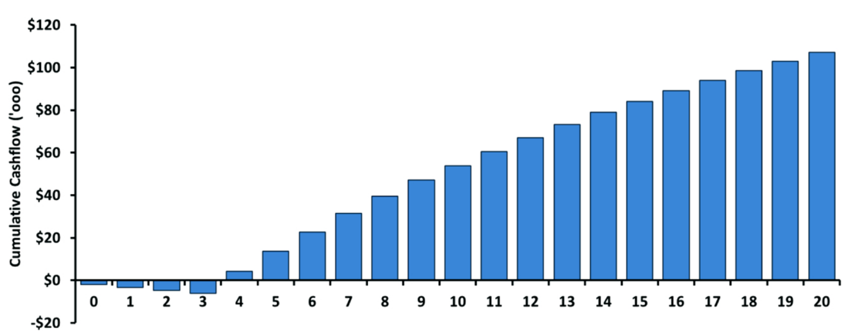


**Fig. 3.** Discounted cumulative cashflow for the modelled mabé pearl farm in Tonga.

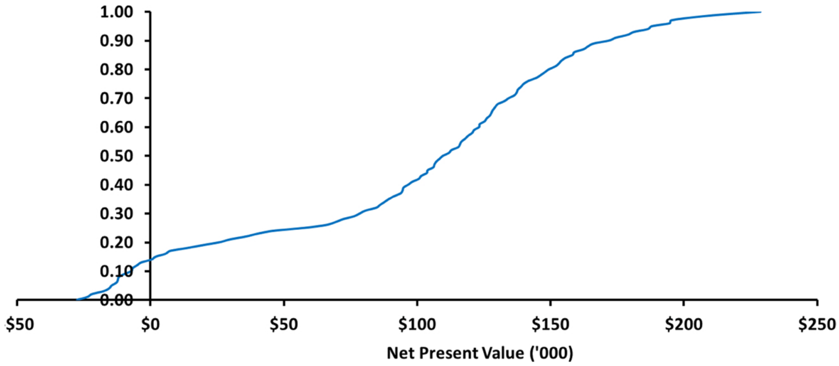


**Fig. 4.** Cumulative probability distribution of Net Present Value (NPV) for the small-scale Tongan mabé pearl farm modelled in this study (variables: price and production).

average annual income in Tonga of USD 4,020 (Anon., 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 (Johnston et al., 2019b). 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 mother-of-pearl (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.

### *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. The number of mabé pearl farms has increased from three to 17 since 2013, with mabé pearl farming becoming a national activity that now occurs in all three island groups within the Tongan archipelago (Vava'u, Ha'apai and Tongatapu; Johnston et al., 2019b). 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 was made possible through investment in research to simplify methods for hatchery production of *P. penguin* spat (Southgate et al., 2016; Wassnig and Southgate, 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 12,000 (Johnston et al., 2019b). 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. 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).

### *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 and Hine, 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 spat and juveniles are currently supplied to farmers from the government hatchery free of charge and the government is considering the possibility of charging farmers for spat as a means of cost-recovery. Prior economic research has examined hatchery production of *P. penguin* in the Tongan Government run hatchery and determined that the production cost of each oyster juvenile provided to mabé pearl farmers is USD 2.01 (Johnston, unpublished data). 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 of 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 *P. penguin* in the Vava'u island group of Tonga has 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. 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 10 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; Johnston et al., 2019b).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**William Johnston:** Investigation, Software, Conceptualization, Methodology, Formal analysis, Writing - original draft. **Sophie E. Gordon:** Investigation, Data curation, Writing - review & editing. **Max Wingfield:** Investigation, Data curation, Writing - review & editing. **Tu'ikolongahau Halafihi:** Resources. **Damian Hine:** Supervision, Writing - review & editing. **Paul C. Southgate:** Funding acquisition, Conceptualization, Data curation, Supervision, Writing - review & editing.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aqrep.2020.100347.

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