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Short title

Feasibility of scallop-fish integration in south China

Title

The feasibility of integrating the noble scallop *Mimachlamys nobilis* with existing fish monoculture farms in the South China Sea: a bioeconomic assessment from Hong Kong

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Abstract

The environmental implications of integrated multi-trophic aquaculture (IMTA) have been well studied in China but few studies have empirically investigated the potential economic benefits. This study investigated the technical and economic feasibility of physically integrating the noble scallop *Mimachlamys nobilis* (Reeve 1852) with existing fish monoculture farms in Hong Kong. Scallops were grown for 201 days from June – December in lantern nets hung directly from fish farm platforms at treatment depths of 1 m, 3.5 m and 6 m. Only the 1 m treatment attained the target mean height-at-harvest of 80 mm. Fitted von Bertalanffy growth functions showed significant differences in growth performance between depths. VBGFs projected that the 3.5 m and 6 m treatments would require an additional 26 and 59 days of culture to reach 80 mm. Mortality was significantly lower at 1 m (53 ± 12.5 %) compared to 3.5 m (70 ± 9.0 %) and 6 m (83 ± 4.5 %). The slower growth and higher mortality at 3.5 m and 6 m were probably caused by periodically low oxygen concentrations in deeper water which dropped to a minimum of 1.73 mg.L^{-1} in mid-summer. Growth, mortality and financial data from the field trial were used in bioeconomic assessments of two typical farm sizes; small (45 m^2) and large (315 m^2). The initial investment, discounted payback time and 10-year net present value of the projects was US$ 5,485.51, three years and US$ 20,211.33 for the small farm and US$ 27.659.03, two years and US$ 227,406.49 for the large farm. Sensitivity analysis revealed that the profitability of operations was sensitive to changes in mortality and sales price. This study has confirmed that physically integrating *M. nobilis* at existing fish farms is technically and economically feasible.

Keywords

Bioeconomic, economic, integrated multi-trophic aquaculture, feasibility, scallop

Introduction

Cage and longline aquaculture in the open sea, collectively called suspended aquaculture, has been expanding to help meet the growing global demand for seafood. A limitation to the suspended aquaculture of fed species like finfish is that cage systems are essentially open and so intensive production can pollute the supporting water body (Cao et al. 2007, Chen et al. 2007). In China, at least eighteen adverse impacts including chemical, ecological, physical and socio-economic impacts have been shown to originate from suspended aquaculture (Wartenberg et al. 2017). If the environmental, economic and social sustainability of suspended aquaculture is to be insured over the long term, then farming systems that minimise negative impacts and improve consumer perceptions are needed (Ridler et al. 2007).

One frequent recommendation for improving suspended aquaculture is Integrated Multi-Trophic Aquaculture (IMTA). Prototypical IMTA integrates low-trophic-level, extractive species with fed finfish such that the extractive species can assimilate waste and produce additional, commercially-valuable secondary products (Chopin et al. 1999, Neori et al. 2004, Barrington et al. 2009). IMTA research has shown that in some cases macroalgae, shellfish and echinoderms process dissolved nutrients, suspended particulates and settling particulates at cage farming areas thereby remediating some of the waste released from fish farms (Nobre et al. 2010, Shi et al. 2013, Chopin 2015).

In China, research on IMTA in suspended aquaculture systems has been ongoing since the mid-1990s but important knowledge gaps remain (Fang et al. 1996, Qian et al. 1996, Nunes et al. 2003). Research has been heavily focussed in northern China and few studies have quantified the economic implications of IMTA (Shi et al. 2013, Wartenberg et al. 2017). Due to the wide longitudinal expanse of China (17 - 40°N), research on IMTA candidate species from all regions is necessary to identify production opportunities and bottlenecks, and to motivate commercial adoption of engineered IMTA systems. In southern China, there is only limited information on IMTA and the question of economic viability has not been addressed (e.g. Yu et al. 2013, 2014a, 2014b, 2016). Quantitative information on the economics of IMTA is essential for the adoption of the technique because unless farmers can see a direct financial benefit, it is unlikely that IMTA would be implemented commercially.

One promising candidate species for use in engineered IMTA systems in the South China Sea is the noble scallop, or huagui scallop, *Mimachlamys nobilis* (Reeve 1852). *M. nobilis* is the primary commercial scallop species from southern China and is commonly sold at shell heights (SH) of 65 - 80 mm (Guo and Luo 2016). *M. nobilis* is naturally distributed from 19°N - 22°N and grows faster, and to a larger size, than the zhikong scallop, *Chlamys farreri* (Müller 1776), farmed in northern China and accounts for 60% of China's scallop production (Guo and Luo 2016). *M. nobilis* spat is produced in hatcheries in Guangdong and Fujian so there is an established supply of seed. Additionally, one common method of growing *M. nobilis* is in lantern nets - lantern nets are typically suspended in the water column using moored longlines but could be suspended from existing fish rafts without difficulty. Despite the suitability of *M. nobilis* for inclusion in IMTA systems in southern China, no previous study has attempted to directly integrate this scallop at existing fish farms.

Hong Kong SAR is a region in the South China Sea that has 29 designated aquaculture zones that are exclusively occupied by fish monoculture farms. Fish are farmed in square cages, typically 4 × 4 × 4 m, suspended under floating platforms. Fish cages are usually accompanied by open deck areas that provide space for husbandry activity. These collective floating structures are known as fish rafts. This style of aquaculture is used widely throughout Asia and so research findings from IMTA in Hong Kong could be applied to the rest of the South China Sea with minimal modifications. Hong Kong is situated directly adjacent to Daya Bay which, in the past, was reported to have a naturally high abundance of *M. nobilis* but have been commercially exploited in recent years (Guo and Luo 2016, Lü et al.

2017). Preliminary work on IMTA in Hong Kong used the mussel *Perna viridis* (Linnaeus 1758), stable isotope analysis and fatty acid profiling to show that *P. viridis* could assimilate fish farm waste when cultivated adjacent to fish cages (Gao et al. 2006). However, despite exhibiting good growth rates in field trials, *P. viridis* remains commercially unutilised in Hong Kong because it has a low market value (Wong and Cheung 2001). The commercially valuable *M. nobilis* is therefore a promising candidate species for use in IMTA systems in the region.

The aim of this study was to determine if the physical integration of *M. nobilis* at existing fish monoculture rafts in Hong Kong is technically and economically feasible. Technical feasibility was assessed by growing *M. nobilis* at a commercial fish raft in lantern nets suspended from the original raft structure. The 7-month field trial was carried out to establish the baseline biological, technological and economic factors associated with growing *M. nobilis* to produce a live product for distribution to local wholesale markets. Economic feasibility was assessed by coupling growth and mortality functions with empirical economic data to produce a comprehensive bioeconomic assessment of a potential scallop enterprise. To forecast the long-term viability of the operations, the bioeconomic assessment was simulated for two typical farm sizes over a 10-year period.

Methods

Site

Scallops were cultivated at Kau Sai fish culture zone (FCZ), one of 29 areas designated for suspended aquaculture in Hong Kong. Kau Sai FCZ (22°21’N, 114°19’E) lies in a small, semi-enclosed bay within Port Shelter in Hong Kong's eastern waters (Fig. 1). The FCZ has a total area of 46,200 m^2 and, at the time of the experiment, 13,057 m^2 was licensed for fish rafts. The fish stock in the culture zone is maintained up to 500 t and stocked at an average density of 4.5 $kg.m^{-3}$. The maximum depth under the fish raft used for the scallop field trial was 14 m. Typical tidal amplitudes in the area are 1 to 2 m. The water temperature in Port Shelter can range from 15°C in winter to 29°c summer while salinity is normally between 28 and 34 depending on rainfall (EPD 2016).

Scallop stock

Scallops (n = 723, SH = 44 ± 5 mm) were dry-transported in polystyrene boxes at a temperature of approximately 20°C from an open water lantern-net system in Fujian, Peoples Republic of China. Total transport time from packing to stocking at the study site was approximately 8 hours. Upon arrival at the farm each box of scallops, containing ~350 individuals, was allocated to an aerated 100 L tank for acclimation. Wild *M. nobilis* occupy habitats with water temperatures ranging from 8 – 32°C, with 20 - 25°C considered optimal (Guo and Luo 2016). While the optimal rate of temperature acclimation has not been determined for *M. nobilis*, relatively large scallops are generally resilient to changes in temperatures within their optimal range (Shumway and Parsons 2016). The water temperature of the tanks was therefore increased at a rate of $4°C.hour^{-1}$ by adding ambient seawater until it matched the temperature of the ambient seawater at 24°C. After temperature acclimation, scallops were then placed in lantern nets that were suspended directly from the platforms of the fish raft for a two-week environmental acclimation period. The stocking density of each net layer was ~ 45% surface area coverage during acclimation. Mortality that may have been caused by transport and the acclimation process was taken as the number of dead scallops at the end of the two-week acclimation (Sarkis et al. 2005).

Experimental design

Scallops were grown in 14-layer, 2 cm-monofilament, 50 cm-diameter lantern nets in the central part of fish monoculture farm that had 94 fish cages that were 4 × 4 × 4 m each. Lantern nets were hung directly from the existing fish raft platform in the space between fish cages such that normal fish husbandry activities were unaffected by the addition of scallops. The total fish stock maintained on the farm fluctuated around 27 t depending on normal husbandry activities. *Trachinotus blochii* (Lacépède 1801) was cultured in all cages directly adjacent to the scallops while various Serranidae and Lutjanidae were cultured in other areas of the raft.

Scallops were farmed for a period of 201 days from 29 May – 16 December 2016, through the peak of summer when water temperatures are warmest, because this has been identified as the optimal period for *M. nobilis* growth (Guo and Luo 2016). Each lantern net layer was considered one replicate and scallops were stocked at a density of ~ 45% surface area coverage (42 scallops·layer^{-1}). Scallop farmers in southern China will typically stock scallops covering an area of 60 – 80 % (Guo and Luo 2006). A stocking density of 45 % was used as a precautionary measure against the possibility of reduced growth at higher stocking densities in this baseline study. To avoid potential complications associated with acute lantern net biofouling, such as the inhibition of food supply to scallops, the nets were replaced with clean nets during monthly sampling events. Regular net replacement is a common measure used to reduce biofouling in suspended scallop aquaculture (Qi et al. 2014).

The lantern net method allows farmers to grow scallops across the full depth range of the water column. In the protected bays of Hong Kong, however, strong water column stratification is common during the summer monsoon season and areas close to the sea floor can be anoxic year-round due to sludge build up (Yin 2002, Zhou et al. 2012). To test for potential differences in scallop production at different depths, three depth treatments were selected; 1 m (n = 6), 3.5 m (n = 3) and 6 m (n = 6) (Table 1). To afford greater experimental control and to prevent pseudoreplication between and within treatments, lantern net layers above and below the depth classes were left empty. The shallowest treatment was set at 1 m because it was anticipated that this would be shallow enough to test for potential exposure to low salinities from monsoon rain – it is a common perception amongst local farmers that animals cultivated near the surface are susceptible to high mortality from monsoon rain, but no previous study has confirmed this hypothesis. The deepest treatment was set at 6 m because it was expected that 6 m would be shallow enough to avoid complications associated with hypoxic conditions periodically associated with the lower few meters of the water column (Yin 2002), but would be deep enough to provide biological data on the potential 3-dimensional use of the upper 6 m of water column.

Environmental parameters

Environmental parameters were measured on 26 occasions over the study period, at least bi-weekly, at the treatment depths. Temperature, oxygen, salinity and total chlorophyll were measured using a YSI sonde EXOII (© Xylem) which was deployed at three predetermined, discrete locations adjacent to the scallop lantern nets at approximately midday. Suspended particulate matter (SPM) concentrations were determined by using a water sampler to collect triplicate 1 L water samples from treatment depths. Water samples were immediately filtered using pre-weighed and pre-ashed glass fibre filter papers (GC-50, © Advantec) that were transported back to the laboratory for freeze drying and weighing.

Growth and mortality

Scallop shell height, and the number of dead scallops, was assessed monthly. Shell height was measured to the nearest mm using Vernier callipers. Dead scallops included gapers (newly deceased with soft tissues present), boxes (shells without soft tissue), and disarticulated shells (separated valves) that were removed from lantern nets when counted (Xiao et al. 2005).

Growth was modelled by fitting a Von Bertalanffy growth function (VBGF) to height-at-time data for the culture period. Some previous studies have employed variations of the original VBGF, referred to as the specialized VBGF, to model scallop growth (Taylor et al. 2006, Mendo et al. 2011).To avoid statistical overfitting, the original form of the VBGF was used in the present study. The VBGF was expressed as $H_t = H_\infty\,(1 - \exp(-K(t - t_0)))$, where H_t is the height at age in mm, H_∞ is the predicted asymptotic height, K is a growth coefficient representing the rate at which individuals approach H_∞ , and t_0 is the age at zero length. Curves were fitted by minimizing a negated normal log-likelihood function. A likelihood ratio test was used to test the null hypothesis that there were no differences in VBGF parameters between treatments. Parameter variability was calculated using a parametric bootstrapping procedure with 1000 iterations to determine standard errors (Efron 1982, Buckland 1984). As scallops were harvested before reaching their maximum reported height of 120 mm (Guo and Luo 2016), the VBGF was first fitted by optimising all parameters to compare H_∞ between treatments, and then by fixing H_∞ at 120 mm to compare growth coefficients (K) between treatments. To facilitate between-study comparisons of growth, the specific growth rate (%.day^{-1}) was calculated for the study period as $\mathrm{SGR} = ((\ln H_2 - \ln H_1)/t) \times 100$ where H_1 and H_2 are the initial and final shell heights, and t is the interval (in days) between H_1 and H_2.

Mortality data were used to estimate instantaneous total mortality (Z) as the inverse-variance weighted average of a catch-curve analysis (Ricker 1975). To test for differences in mortality between treatments, Kaplan-Meier survival curves (Kaplan and Meier 1958) were compared using log-rank tests (Mantel 1966, Mendo et al. 2011).

Shell biofouling index

Although lantern net biofouling was minimised by replacing nets monthly, the fouling on actual scallop shells was not removed unless it impeded measurements of shell height. Previous work, reviewed by Adams et al. (2011), has shown that shell biofouling can significantly reduce growth and increase mortality to levels that can undermine operations entirely. To test if high biofouling may explain the high mortality observed in July and August of the present study, the shells of 30 deceased scallops from each treatment were transported back to the laboratory after the August sampling. Fouled shells were dried at 60°C to constant weight and weighed. The biofouling was then removed with a scraper before weighing the cleaned shells. Biofouling dry weight was calculated as shell weight loss after biofouling removal. The biofouling index was calculated by dividing the dry weight of the biofouling by the dry weight of the fouled shell and multiplying by 100.

Condition indices

In China, high quality live scallops have a large adductor muscle and full gonad. For the assessment of the condition of these soft tissues additional scallops were held in additional lantern nets suspended at 3.5 m for periodic harvesting. Soft tissue condition was assessed at the start (29/05, n = 18), middle (03/09, n = 38) and end (16/12, n = 35) of the culture period. Adductor muscle, gonadosomatic and 'remaining tissue' indices were calculated by dividing the weight of the relevant tissue by the total weight of soft tissue and multiplying by 100 (González et al. 2002, Taylor et al. 2006).

To test for differences in biofouling and tissue indices between treatments, data homoscedasticity was tested using Levene's test and the normality of treatment residuals was tested using Shapiro-Wilk's test. ANOVAs were then used to test the null hypothesis that the treatment means were equal.

Economic feasibility

A precautionary approach was used when compiling the business model used in the economic assessment because an integrated scallop-fish farm would be the first of its kind in Hong Kong. The feasibility assessment was based on empirical growth, mortality and financial data from the field trial. The assessment assumed that all lantern nets would be suspended at a depth of 1 m because of the favourable growth and mortality demonstrated by scallops from that treatment. Potential variations in these key production parameters were evaluated by sensitivity analysis. The production system was based on a single annual stocking of *M. nobilis* at the beginning June for a final stage of grow out from 45 mm SH. Complete stock harvest occurred in December when the scallops reached 80 mm mean SH. This simple system was selected because it does not require substantial additions of equipment or labour and would be straightforward for farmers to implement as an initial scallop farming operation.

The estimated capital and operating expenses that would be incurred were used to determine the net returns from the scallop enterprise simulated over 10 years. Monetary values in the assessment were as of September 2017 and have been converted from Hong Kong dollars to US dollars at a rate of HK$7.80: US$1.00 to facilitate international comparisons. Simulations were run assuming an annual interest rate of 5 % (retrieved 07.20.2017 from HSBC Hong Kong), an annual inflation rate of 3.58% (average annual inflation in Hong Kong from 2006 – 2016) and a profit tax of 15% (as for unincorporated businesses in the region). Two representative raft sizes were evaluated; small (45 m^2, 9 fish cages, 2.6 t fish standing stock, 48 active lantern nets, 2 existing staff) and large (315 m^2, 70 fish cages, 20.2 t fish standing stock, 340 active lantern nets, 6 existing staff) based on mean raft sizes for small and large rafts in fish culture zones in Hong Kong.

Expenses

It was assumed that all fixed capital and operating expenses were carried by the existing fish monoculture operation. These included substantial infrastructure items like the raft structure, moorings, vessels, existing permanent staff and licenses. Costs associated with the scallop operation were therefore allocated to variable capital expenses, variable operating expenses and the financing costs associated with a 5-year bank loan to fund the initial expenses required to establish a scallop enterprise. Precise costing was obtained using the actual expenses from the growout trial. In cases where additional capital equipment would be necessary for larger systems, costs were based on actual quotations from relevant suppliers. For example, the cost of supplementary flotation (200 L HDPE barrels) required to support the additional weight of full and fouled lantern nets was calculated and included in the cost assessment. The costs associated with any additional labour was allocated to four tasks; scallop stocking upon arrival, bimonthly lantern net replacement to limit net biofouling, bimonthly lantern net cleaning to remove net biofouling, and final harvest and shell cleaning prior to distribution. The additional labour that would be necessary for a full-scale scallop operation was calculated based on the time taken to complete these tasks during the field trial and was costed based on the hiring of part-time staff as needed. Animal health and food safety testing were not included because routine monitoring is coordinated by the Agriculture, Fisheries and Conservation Department of Hong Kong.

Revenue

Revenue estimates were made using pricing data from the Hong Kong Fish Market Organisation (retrieved on 05.22 and 07.21.2017). The standard mass metric used in China's markets is the *catty*, but the specific mass of one catty can vary by region. In Hong Kong, one catty is equivalent to 606 g (approximately six 80 mm SH scallops). Total production volume was estimated by dividing the projected total scallop harvest by one catty. The mean wholesale market price for scallops over the period was US$5.76 (HK$45.00) per catty. A wholesale mark-up of 30%, typical in local seafood markets, was used to determine the price received by farmers per catty and was US$4.03 (HK$31.50). Annual net revenue was determined by subtracting total costs from gross revenue.

Bioeconomic assessment

The bioeconomic assessment was compiled using parameters from the VBGF, the mortality (Z) function, total expenses, and net revenue to evaluate the profitability of the scallop enterprise (Taylor et al. 2006, Mendo et al. 2011).

The number of lantern nets that could be integrated at a raft was calculated by evaluating the number of fish cage sides available for lantern net hanging at a density of 1 lantern net.m^{-1}. Key parameters used in the assessment are given in Table 2. The initial scallop stocking density per layer ($SD_{initial}$) was calculated as $\mathrm{SD_{initial}} = \mathrm{SD_{harvest}}/(1 - Z)$ where $SD_{harvest}$ is the target stocking density at harvest and Z is the anticipated mortality based on data from the field trial (Table 2).

The standard economic valuation metrics Net Present Value (NPV), Internal Rate of Return (IRR) and the discounted payback time (DPBT) were used to assess the profitability of the initial investment over a 10-year operation (Penney and Mills 2000). The NPV was calculated as $\mathrm{NVP} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$ where C_t represents the discounted annual cash flows, t is the time of the cash flow, n corresponds to the lifetime of the investment and r is the discount rate. The IRR was calculated by solving the NPV equation for r when the NPV = 0. The DPBT was calculated by adding the net revenues year-by-year to determine the year in which the total surpassed the initial investment. The DPBT was restricted to whole numbers, rounded up, because the business model was structured around a single annual harvest at the end of the year.

A sensitivity analysis was used to simulate the effect of a ± 30% change in lantern net prices, seed stock price, transport mortality, growth (K), culture mortality (Z), minimum wage, and wholesale market price on the NPV of the investment. In running the assessment, it was assumed that the demand for live scallops was higher than supply, which is reasonable considering that this operation would be the first of its kind in Hong Kong and all scallops currently sold locally are imported.

Results

Environmental parameters

The water column at Kau Sai fish culture zone exhibited clear temperature, oxygen and salinity stratification from the start of the culture period in June until mid-September (Fig. 2). From mid-September to the end of the culture period in December these parameters were homogenous across depth classes. The warmest daytime water temperature was 29.13°C and was observed at 1 m in August. All treatments dropped to a low of 21.28 °C in December. The lowest salinity of 30.61 was observed at 1 m on 15 July following heavy monsoon rain which was the same day that the minimum oxygen concentration of 1.73 $mg.L^{-1}$ was observed at 6 m (Table 3). There was no correlation between chlorophyll and SPM concentrations at 1 m (r = -0.13), 3.5 m (r = 0.31) and 6 m (r = 0.05).

Growth and mortality

When VBGFs were fitted to the data by optimising H_∞, K and t_0 the growth curves were significantly different between the 1 m and 6 m treatments ($X^2 = 17.460$, 3 *d.f.*, P = 0.001), but the 3.5 m curve was not significantly different from the curves for 1 m ($X^2 = 4.085$, 3 *d.f.*, P = 0.252) or the 6 m ($X^2 = 2.451$, 3 *d.f.*, P = 0.484). H_∞ was highest for the 1 m treatment (128 ± 21.52 mm) but also generated the lowest growth coefficient (K = 1.00 ± 0.28) (Table 4). When the VBGF was fitted with H_∞ fixed at 120 mm, the VBGFs were still significantly different between the 1 m and 6 m treatments ($X^2 = 13.717$, 2 d.f. P = 0.001), and the 3.5 m growth curve was still not significantly different from the curves for 1 m ($X^2 = 4.187$, 2 d.f. P = 0.123) or 6 m ($X^2 = 2.272$, 2 d.f. P = 0.321). The difference, however, was that the 1 m treatment produced the highest growth coefficient (K = 1.14), compared to 3.5 m (K = 1.07) and 6 m (K = 0.97) (Fig. 3, Table 4). Shell height gain for the 1 m, 3.5 m and 6 m treatments was 35.9 ± 2.4, 32.7 ± 4.8 and 31.6 ± 3.7 mm over the 201-day culture period representing mean specific growth rates of 0.29, 0.27 and 0.26 %.day^{-1} (Table 4).

Only scallops from the 1 m treatment attained a mean shell height of 80 mm, the target size-at-harvest in this study. Projections of the VBGFs estimated that scallops in the 3.5 m treatment would require a further 26 days of cultivation to reach 80 mm SH while scallops in the 6 m treatment would require a further 59 days (Table 4).

Mortality caused by transport was 12.59 %. Catch curve analysis for the culture period estimated total mortality (Z) as 0.13, 0.21, and 0.28 for the 1 m, 3.5 m and 6 m treatments, respectively (Fig. 4). Survival at 1 m (47 ± 12.5 %) and 3.5 m (30 ± 9%) were not significantly different from each other ($X^2 = 1.64$, 1 *d.f.*, $P = 0.2$) but survival at 6 m (17 ± 4.5 %) was significantly lower than at 1 m ($X^2 = 11.39$, 1 *d.f.*, $P = 0.001$) or 3.5 m ($X^2 = 5.79$, 1 *d.f.*, $P = 0.02$). The highest mortality occurred between the June (day 33) and August (day 90) sampling events which showed a proportional mortality of 32.6 ± 12.1, 45.9 ± 4.0 and 65.7 ± 12.6 % at 1 m, 3.5 m and 6 m.

Shell biofouling index

The shell biofouling index for scallops collected from the August mortality event was significantly higher at 1 m (36.45 ± 9.02 %), than at 3.5 m (33.55 ± 7.47 %) and 6 m (25.65 ± 9.84 %) ($F_{2,87} = 12.01$, $p < 0.001$).

Condition indices

Soft tissue condition indices were similar in June and September but changed significantly in December (Fig. 5, Table 5). In December, the gonadosomatic index doubled from 11.18 ±

3.58 % in June to 22.32 ± 3.79 % ($F_{2,88}$ = 85.75, $p < 0.001$) while the adductor muscle index decreased from 44.86 ± 4.64 % to 34.39 ± 3.58 ($F_{2,88}$ = 85.07, $p < 0.001$) (Fig. 5, Table 5). There was a statistically significant drop in the condition index for remaining tissue in September ($F_{2,88}$ = 3.67, $p = 0.03$), but proportionally the contribution of these tissues changed only slightly (Fig. 5).

Economic feasibility

Expenses

The total expenses that would be incurred prior to the generation of revenue at the end of the first year would be US$5,485.51 for the small farm and US$27.659.03 for the large farm. These figures represented the value of the bank loans necessary to initiate a scallop enterprise at existing fish monoculture rafts.

Capital expenses in year 0 were US$4,573.21 and US$23,269.03 for the small and large farm (Table 6). The purchase of lantern nets represented the bulk of total capital expenses, 40.6 % (US$1,856.00) for the small farm and 56.1 % (US$13,056.00) for the large farm.

Annual operating expenses were US$912.31 for the small farm and US$4,390.00 for large farm in year 0 and increased to US$1297.00 and US$6241.00 in year 10 because of inflation (Table 7). The largest proportion of operating expenses consisted of labour which accounted for 67.9% (US$619.23) and 68.4% (US$3,003.85) of total operating expenses for the small and large farm. The largest labour expense on the small farm was the manpower required to support the annual harvest event (US$442.31, 48.5 %) and on the large farm it was the manpower necessary to support the bimonthly replacement of lantern nets with an annual cost of US$1,990.38 (45.3%).

As part of the assessment, the bank loans for the small and large farm, and their 5 % annual interest, were paid off from year 1 to 5 at a rate of US$1,267.02 and US$6,388.54 per year.

Revenue

Revenue was generated from the end of year 1 following the first harvest. Annual harvest volumes were 1,680 catties (1,018 kg) and 11,900 catties (7,211 kg) for the small and large farm.

Bioeconomic assessment

Cash flow projections from the 10-year simulation predicted positive results for both farm sizes (Fig. 6). The largest annual expenses were incurred in year 0 and year 6 because of the initial purchase of lantern nets and the need to replace them after 5 years of use (Fig. 6, Table 6). Gross revenue increased slightly over the 10-year period (Fig. 6).

The 10-year NPV for the small farm was US$20,211.33, which represented a 52% IRR and a DPBT of 3 years. The 10-year NPV for the large farm was US$227,406.49, which represented a 103% IRR and a DPBT of 2 years.

The sensitivity analysis of key variables showed that the NPV of the operations was robust to changes in seed price, minimum wage, lantern net price, mortality during transport, and growth rates (Fig. 7). The NPVs were most sensitive to changes in total mortality during growout and changes in sales price. A 30% increase in the total mortality at the small farm was the only simulation that resulted in a negative NPV_{10} (Fig. 7).

Discussion

Environmental parameters

Water column stratification is commonly observed in inshore areas of the South China Sea through the mid-summer monsoon season (Mao et al. 2011, Zhou et al. 2012). The temperature, salinity and oxygen stratification of the water column observed at Kau Sai FCZ until mid-September is therefore typical for the region. The recession of stratification from mid-September onwards was probably related to improved water column mixing during winter conditions (Yin 2002). The generally homogenous SPM and chlorophyll concentrations between treatment depths suggests that scallop food availability was not different between treatments and so food availability probably did not cause the observed differences in growth and mortality between treatments. The slightly higher chlorophyll concentrations observed at 6 m compared to 1 m and 3.5 m over the full study was due to periodically higher chlorophyll concentrations at 6 m on days 27, 53, 110 and 153 (Fig. 2, Table 3). This could have been caused by feeding in the surface layers or the vertical migration of phytoplankton in the water column (Smayda 1997, Park et al. 2001, Tan et al. 2004). Monthly monitoring data from a government monitoring site ~1.5 km away from any fish farming showed that SPM ranged from 0.6 – 8.1 $mg.L^{-1}$ and chlorophyll-a ranged from 0.15 – 18 $\mu g.L^{-1}$ from May – December 2016 (Site PM9, EPD 2016). This is in line with the SPM concentrations of 0.35 – 7.07 $mg.L^{-1}$ and total chlorophyll concentrations of 0.40 –

12.81 μg.L^{-1} from Kau Sai and suggests that fish farming activity did these parameters at the culture zone.

By December the minimum temperature of 21.28°C was reached and coincided with the planned harvest time (Fig. 2). The reported optimum temperature for *M. nobilis* growth is 20 – 25°C and so the decreasing temperatures through December and January may not favour *M. nobilis* production (Guo and Luo 2016). By the start of January 2017, the mean surface water temperature in Port Shelter dropped to ~19°C (Wartenberg, unpublished). An *a priori* hypothesis, therefore, is that Mid-December is the optimal time to harvest *M. nobilis* farmed in Hong Kong, but this should be confirmed by empirical work combined with assessments of market demand in the future.

Growth and mortality

High mid-summer mortality has been accepted as a normal event during open water scallop growout in China (Guo et al. 1999, Xiao et al. 2005, Yu et al. 2010). *M. nobilis* in the present study showed good growth and low mortality in comparison to *Chlamys farreri*, the primary aquaculture scallop species in China. Xiao et al. (2005) farmed *C. farreri* at three sites in Shandong through the peak of summer and found that the SGR of *C. farreri* ranged from 0.15 to 0.91 %.day^{-1}, depending on the culture site and month. These results are comparable to the SGRs of *M. nobilis* which ranged from 0.26 – 0.29 %.day^{-1} over the entire culture period at Kau Sai. The mortality of *C. farreri* reported by Xiao et al. (2005) was at least 85% at all sites, comparable to the 83 % mortality of *M. nobilis* in the 6 m treatment. Total mortality of the 1 m *M. nobilis* treatment was significantly lower at only 53%.

The treatment-specific VBGFs for *M. nobilis* showed that the 1 m treatment exhibited significantly better growth performance than 3.5 m or 6 m. It is well known that food availability can affect the growth of bivalves cultured in open water (Wong and Cheung 1999, Hawkins et al. 2002). In the present study, however, there was no apparent difference in SPM and chlorophyll concentrations between depth treatments which suggests that differences in growth were probably not related to food supply. One possibility for the inferior growth at 6 m could have been the generally suboptimal environmental conditions in deeper water during mid-summer stratification (Fig. 2, Table 3). In particular, the periodically low oxygen levels could have imposed substantial physiological stress on *M. nobilis* in the 6 m treatment. Oxygen concentrations were generally lower at 6 m and reached a minimum of 1.73 $mg.L^{-1}$ in mid-July. This coincided with the peak overall mortality. The daytime low oxygen concentrations at Kau Sai could have resulted from the resuspension of fine sediment during monsoons and microbial respiration in lower layers of the water column (Gao et al. 2006, Zhou et al. 2006). It is also likely that the observed low oxygen concentrations would have fallen even lower at night during algal respiration. It is therefore possible that the culture environment for *M. nobilis* at 6 m was suboptimal and resulted in the slower growth and higher mortality. These findings have important implications for industry because the VBGF projections estimated that the 3.5 m and 6 m scallop treatments would require up to two additional months to reach an 80 mm SH. The additional time required for growout would impose additional operating expenses on farmers and may necessitate the continued cultivation of *M. nobilis* through mid-winter when water temperatures fall below the optimal range for growout.

The high mid-summer mortality of scallops farmed in open water was first observed in *Chlamys farreri* in 1994 and has since been accepted as a normal part of bivalve husbandry in China (Guo et al. 1999, Xiao et al. 2005, Yu et al. 2010). Relatively high mortality of *M. nobilis* was observed during mid-summer in all treatments in the present study. No abnormal mortality of the fish observed at any of the fish farms at Kau Sai during this time. No previous study has been able to pinpoint the causes of these annual mortality events but it has been hypothesised that they could result from a combination of generally adverse environmental conditions including high temperature, water body overuse, scallop raft overcrowding, reduced scallop immunity in summer, opportunistic predators or pathogens and reproductive stress (Zhang and Yang 1999, Xiao et al. 2005, Yu et al. 2010). The measures that have been recommended for minimising annual mortality have included maintaining responsible stocking densities, maintaining healthy seed stock, improving scallop germ plasm, and extending culture to areas with depths greater than 20 m but the benefits of these measures remain undemonstrated at any large scale (Yang et al. 1999, Zhang and Yang 1999). Until further research can identify practical methods to minimise mortality, high stock losses in summer must be accepted as a normal part of *M. nobilis* husbandry and should be accounted for when calculating seed stock requirements to ensure that target harvest volumes are met.

In the present study there as a significant increase in the mortality of *M. nobilis* with increasing culture depth from 1 m to 6 m. Lodeiros et al. (1998) found that mortality in the tropical scallop *Lyropecten nodusus* (Linnaeus 1758) was significantly different between treatments cultivated at 8, 21, and 36 m and hypothesised that differences were due to a combination of shell biofouling, reproductive stress, temperature differences and differences in the density of toxic dinoflagellates. Although the magnitude of depth was much larger in the *L. nodusus* study compared to the present study, Lodeiros et al. (1998) concluded that the overall growth environment was different between depths. In the present study there were substantial differences in temperature, salinity and oxygen between depths from May to September suggesting that the different growth and mortality between-treatments was probably caused by different growth environments during mid-summer stratification. While the *M. nobilis* environmental and mortality data from this study cannot be used to pinpoint the exact causes of the observed mortality differences, one important observation can be made - the inflow of fresh water during heavy summer monsoons did not cause higher mortality at 1 m. This is relevant because the perception amongst fish farmers in Hong Kong is that it is not possible to farm sedentary species like *M. nobilis* because monsoon rain is likely to cause total stock loss. Previous experimental trials with *M. nobilis* have shown that the species is tolerant to a wide range of salinities from 24.3 to 37.2 (Zhang et al. 2008). Therefore, the high survival of *M. nobilis* at 1 m compared to 3.5 m and 6 m shows that mortality was not overly influenced by surface water salinity flux caused by mid-summer monsoons during this study.

Shell biofouling index

The settlement of fouling organisms on shells and culture gear is a problem for scallop farmers because fouling can decrease growth and product marketability while increasing mortality and the labour required to process scallops prior to distribution (Adams et al. 2011, Qi et al. 2014). Previous work has shown that decreased growth and increased mortality have occurred because severe fouling inhibits food and oxygen supply, serves as a habitat for predatory invertebrates like crabs, and could act as a vector for pathogens (Lesser et al. 1992, Freites et al. 2000, Wu et al. 2003, Sievers et al. 2013). In the present study, the 1 m treatment exhibited the highest level of biofouling but this was also the treatment that had the best growth and survival. This suggests that biofouling was not the root cause of the lower production performance observed in the 6 m treatment. The higher biofouling load in the 1 m treatment could be due to generally better environmental conditions in the upper water column and associated higher settlement rates by fouling organisms (Claereboudt et al. 1994, Taylor et al. 2006). In the USA ,fouling of cultured bivalves is accepted as part of normal husbandry practices - the average farm-level cost of biofouling was estimated by countrywide surveys at 14.7% of farm revenue and was spent on husbandry efforts to reduce fouling and measures to remove fouling during processing (Adams et al. 2011). In this study, fouling was not a major financial concern for the small or large farm because it was removed as part of processing during harvest. This could be handled by existing farm labour and the help of two part-time workers on each harvest day (Table 6). As fouling was not the cause of increased *M. nobilis* mortality, and was not associated with high costs, fouling can be accepted as a normal part of *M. nobilis* husbandry until cost-effective methods to reduce or eliminate fouling can be developed. Future work could investigate temporal and depth-related patterns in fouling abundance and composition to help optimise scallop production cycles.

Condition indices

The doubling of the gonadosomatic index of *M. nobilis* in December, and the ~25% decrease of the adductor index, coincided well with the planned harvest time. Gonad maturation through periods of decreasing temperature has been reported for the bivalve *Atrina maura* because decreasing temperatures allow for a longer vitellogenic phase (Rodríguez-Jaramillo et al. 2001). The decrease in the proportional contribution of the adductor muscle observed in *M. nobilis* in December is typical in scallops because of the disproportionately large contribution of ripe gonads to soft tissue indices and because of the high energy demands of gamete production (Pazos et al. 1997, Mendo et al. 2011). A full gonad is necessary to insure good product marketability in China and so the favourable soft tissue indices of *M. nobilis* confirm that December a good month for harvest.

Economic feasibility

This study showed that physically integrating *M. nobilis* at existing fish rafts in Hong Kong is technically feasible because the scallops grew to optimal market size (80 mm SH) from June to December with sufficiently low mortality to warrant a comprehensive economic feasibility assessment. Cost calculations from Port Shelter in Hong Kong showed that it would cost US$5,485.51 to initiate scallop farming at a small fish farm (45 m^2) and US$27.659.03 at a large fish farm (315 m^2). The economic simulations showed that, despite high mid-summer mortality, start-up capital could be recovered within three years (Fig. 6).

Expenses

The scallop farming enterprise benefitted from the existing infrastructure of the fish monoculture operation and so the start-up expenditure was low compared to studies that established entirely new operations (e.g. Taylor et al. 2006, Mendo et al. 2011). Ongoing annual operating expenses were also low because scallops are filter feeders, which eliminates any expenses related to feed input. The requirements for supplementary labour were low because the most frequent husbandry activity was the routine replacement and cleaning of fouled lantern nets which can occur bimonthly based on observed biofouling loads at Kau Sai FCZ. On the small farm, which integrated only 48 active lantern nets at any given time, net cleaning and replacement could be covered by existing farm labour. On the large farm, only 45 worker days were required per year to cover the additional labour associated with this task, representing a relatively small expense in comparison to the revenue generated (Table 6).

Revenue

From the end of year 1 the scallop enterprises generated positive net revenues with an annual present value ranging from $1,852.00 to $3,365.00 for the small farm and from $18,142.00 to $28,611.00 for the large farm (Table 7). These values represent a considerable annual inflow of capital to relatively small-scale fish farms that are traditional family-based operations. Given that the weight of the fish farmed in Hong Kong in 2014 accounted for only 2% of the weight of fish consumed, it is possible that the industry needs additional sources of income to help sustain operations and promote progress towards more modern approaches (Lai et al. 2016). The additional revenue from an integrated scallop enterprise could help provide the capital necessary to achieve this. Additionally, the simulations in this study did not increase the total scallop production volume over the 10-year assessment period. This was a precautionary measure because a scallop enterprise would be a first for Hong Kong and so the effects of more intensive production are not predictable (Shi et al. 2013). The apparent increase in gross revenue over the 10 years resulted from the 3.58 % inflation rate. Some measures that could be tested to directly increase harvest volumes in the future could be to increase the number of lantern nets integrated at fish rafts, increase the stocking density of scallops within lantern nets, establish multiple stocking rotations or stock scallops continuously (Choi et al. 2006).

Bioeconomic assessment

The 10-year bioeconomic simulation returned favourable NPV and IRR values, and short DPBTs, partly because existing farm infrastructure and labour substantially reduced the expenditure necessary to initiate a scallop enterprise. Over the 10-year operation the largest expenses were incurred in year 0 and year 6 due to the initial purchase and subsequent replacement of scallop lantern nets at the end of their useful life.

The positive NPV for both farms suggests that it is worth proceeding with integrated scallop farming at existing fish monoculture rafts in Hong Kong and so further research and development is warranted (Engle 2010). This is supported by the high IRRs for both farms which suggest that a 10-year scallop operation would be profitable because IRR values are substantially higher than the opportunity cost of capital, typically taken as 10% (Engle 2010). The IRRs of 52% for the small farm and 103% for the large farm are higher than the IRRs calculated in similar studies with scallops. Penney and Mills (2000) reported IRRs from -9.9 % to 39.4 % for a *Placopecten magellanicus* operation in Newfoundland, Canada. Taylor et al. (2006) reported IRRs of 21.6 – 27.0 % for the scallop *Nodipecten subnodosus* cultivated on the Baja California peninsula. The comparatively lower IRRs from their studies is probably because they had to construct their culture systems without any existing infrastructure or staff. However, it is important to interpret IRRs from aquaculture operations with caution - one implicit limitation of the IRR is that it assumes that any annual net returns from year-to-year can be reinvested to earn a return equal to the IRR and so the final result is an inflated IRR value (Engle 2010). Under the business model proposed in the present study revenue is not reinvested to expand production and so the IRR is overestimating the actual rate of return. However, if interpreted correctly, the IRR is a valuable assessment tool that is well understood by investors and lenders and can be used to compare returns between similar operations (Engle 2010). The DPBTs estimated that the time to recoup the initial investments was three years for the small farm and two years for large farm, about half the time required to recoup the initial investment in an *Atrina maura* (Sowerby 1786) farm in Mexico which was estimated at 6 – 7 years (Mendo et al. 2011). The shorter DPBT of the large farm compared to the small farm is due to economies of scale; there is a proportionate saving in costs gained from an increased level of production. The large farm is approximately seven times larger than the small farm but has an NPV that is approximately 10 times higher.

Economies of scale is common in aquaculture and has been demonstrated previously for bivalves (Penney and Mills 2000, Mendo et al. 2011).

The sensitivity analysis showed that the scallop enterprise was robust to changes in lantern net price, seed stock price, transport mortality and growth rates but was more sensitive to changes in mortality and market price (Fig. 7). Changes in growth rate made no apparent change to the NPV of the small farm and had only a slight influence on the NPV of the large farm. The month-to-month husbandry expenses for *M. nobilis* are small in comparison to the revenue generated and so a decrease in growth, that would extend the culture duration, changes the NPV only slightly. However, it is important to consider that the water temperature after December usually drop below the optimal conditions for *M. nobilis* growth which would extend the culture duration even further - this possibility is not assessed as part of the sensitivity analysis. The enterprise was robust to changes in the minimum wage because the additional labour requirements of the scallop operations were minor. Changes to transport mortality and the price of growout seed stock had a very small impact on the NPV because the annual purchase of seed, and the transport of that seed, contributed only a small proportion to the overall cost of the business (Table 6). In the event of considerably higher mortality during transport, it would be cost-effective to add more seed to a shipment, or to order an additional shipment of seed to mitigate any large mortality events due to transport. Despite the high capital cost of the lantern nets, and their large contribution to cash outflow in year 0 and year 6, the operation was relatively robust to changes in lantern net price because the depreciation of the nets was spread across the full 5 years of useful life.

The 10-year NPV was most sensitive to changes in sales price and mortality, probably because these parameters directly impacted the bottom line of the enterprise. This is a common finding in aquaculture businesses that are dependent on producing a critical biomass to insure farm profitability (Stirling and Okumus 1995, Taylor et al. 2006). A 30% increase in mortality over the 10-year simulation of the small farm was the only variation that resulted in a negative NPV. In any farm situation a 30% increase in mortality would be critical. In this study, the existing farm infrastructure absorbed some of the major costs of the scallop enterprise which helped to buffer the impact of mortality on profitability. Still, it should be noted that the scallop systems were somewhat sensitive to changes in mortality which is an important consideration when assessing whether to proceed with integrated scallop farming. This is of concern in our study because relatively small changes in depth from 1 to 6 m caused a significant increase in mortality and the causes of mortality cannot be easily controlled. There are, however, measures which could be taken to minimise the financial risks associated with mortality. One measure would be to increase the initial stocking from 32 scallops·layer^{-1} (33% surface area), which was used in the economic assessment based on anticipated mortality and the target harvest volumes, to 42 scallops·layer^{-1} (45% surface area), which was used in the field trial. Future work could look to increase scallop stocking densities as high as 60% - 80% surface area. These higher densities are commonly used in scallop farming in China and could offer some insurance against mid-summer and depth-related mortality given the low cost of scallop seed and the low sensitivity of these operations to changes in seed price (Fig. 7). If higher than anticipated mortality occurs, then the higher stocking density would help to buffer losses. If higher mortality does not occur, then farmers could opt to redistribute surplus scallops to nearby farms, sell surplus scallops at suboptimal sizes, accept potentially reduced growth rates from overcrowding, or cull surplus scallops.

Study limitations

The advantages and limitations of bioeconomic studies in aquaculture have been reviewed (Llorente and Luna 2016). The primary limitation of the present study is that pilot scale data has been used to simulate the outcomes of larger-scale implementation. While it is possible to make assumptions about some variables, like additional costs associated with increasing scale, other parameters cannot be predicted. For example, in the case of the large farm from the present study, it is not possible to predict the effect of 340 lantern nets on farm hydrodynamics – reduced flow rates could adversely affect all stock at the farm (Han et al. 2013, Lin et al. 2016). This study has proposed a conservative lantern net density of 1 net.m^{-1} of platform, but it is important to note that factors like hydrodynamics must be considered in future research or when making management decisions to expand scale. On the economic front, financial extrapolation using data from cost-effective pilot studies is a necessary first step in aquaculture that helps to understand potential costs and benefits of operations (Di Trapani et al. 2014, Fonseca et al. 2017, Martínez-Cordero et al. 2017). Bioeconomic assessments of this sort also help to secure the funding that supports the expansion of operations. Numerous previous investigations have assessed the feasibility of open water bivalve aquaculture using pilot trials (e.g. Choi et al. 2006, Taylor et al. 2006, Mendo et al. 2011). It is important, however, to use a precautionary approach when making management decisions based pilot-scale results. The precautionary approach was applied in the present study by using conservative values for scallop stocking, lantern net density, and the number of production cycles conducted per year. In addition, it is important to apply the precautionary approach going forward; the next step is to modestly increase the scale of scallop aquaculture used in the present study and to fill some of the remaining knowledge-gaps. In particular, the relationship between relatively small changes in depth, the culture environment and scallop mortality must be examined in detail prior to widespread adoption of integrated scallop aquaculture.

Conclusions

This baseline study has shown that physically integrating *M. nobilis* at existing fish monoculture farms in Hong Kong is technically and economically feasible. Despite the low stocking densities used as a precautionary measure in the field trial, the bioeconomic assessment showed that the operations were profitable because *M. nobilis* grew well and showed sufficient survival to size-at-harvest. The different growth and mortality observed between depth treatments suggests that changes in the growth environment from 1 m to 6 m could significantly impact production. As the fish rafts in Hong Kong have operated under a monoculture model for more than 50 years, the alternative to an integrated scallop enterprise would be the 'do nothing' option. Integrated scallop farming is therefore recommended because the simulation of a 10-year operation produced high NPVs and IRRs, and short DPBTs for the two farm sizes assessed. The sensitivity analysis showed that the proposed scallop enterprises were robust to changes in most key variables and were moderately sensitive to changes in sales price and stock mortality. The sensitivity analysis identified that there is some inherent risk in the proposed scallop operation because changes to sales price and stock mortality cannot be easily controlled. However, integrating scallops would add a new trophic level to farm operations that would help to increase farm output and diversify production, thereby reducing risk at the farm level.

Further work could attempt to quantify the bioremediation capacity of *M. nobilis* for mitigating the negative environmental impacts of aquaculture. Predictive models should be used to simulate environmental impacts and key financial data associated with cultivating *M. nobilis* at larger scales (Ferreira et al. 2009, Shi et al. 2011, 2013, Zhao et al. 2013). The potential uptake of adverse contaminants, including pollutants that may be associated with fish aquaculture, should be investigated; if contaminant levels are high, then depuration prior to distribution may be necessary. While this study has shown the financial advantage of integrating *M. nobilis* from the perspective of fish monoculture operations, future studies could investigate the potential growth and production advantages experienced by scallops integrated at fish farms compared to scallops produced at scallop monoculture sites.

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Tables

Table 1 Experimental design for *Mimachlamys nobilis* cultivated at an existing fish monoculture raft at Kau Sai fish culture zone in Hong Kong. For statistical comparisons each layer of a lantern net as one replicate.

Treatment	Stocking density (scallops.layer^{-1})	No. of scallops	No. of layers	No. of lantern nets
1 m	42	252	6	2
3.5 m	42	126	3	1
6 m	42	252	6	2

Table 2 Baseline parameters used in the bioeconomic assessment of integrated noble scallop *Mimachlamys nobilis* farming at existing small and large fish monoculture rafts in Hong Kong.

Parameter	Unit	Value	Description
Growth (VBGF K)	VBGF *K*	1.00	Data from field trial, 1-m treatment (Table 3)
Growout duration	months	7	Based on field trial and VBGF *K*
Mortality	%	53	Data from field trial, 1-m treatment (Fig. 3)
Size-at-stocking	mm	45	Representing scallops ready for the final stage of growout
Size-at-harvest	mm	80	Common market size (Guo and Luo 2016)
Scallops·layer^{-1} at stocking	pcs	32	Back-calculated from anticipated mortality (33% surface area)
Scallops·layer^{-1} at harvest	pcs	15	Reach maximum stocking density of 50 % by harvest

Table 3 Summary statistics of environmental parameters recorded from the *Mimachlamys nobilis* culture area at Kau Sai fish culture zone, Hong Kong, from 29 May to 16 December 2016. Reference data from 12 m are included to show environmental conditions near the sea floor. Suspended particulate matter (SPM) were not monitored at 12 m (nd = no data).

	Mean ± SD				Max				Min			
	1 m	3.5 m	6 m	12 m	1 m	3 m	6 m	12 m	1 m	3 m	6 m	12 m
Temperature (°C)	26.64 ± 2.22	25.96 ± 2.11	25.37 ± 2.21	24.82 ± 2.11	29.13	28.77	28.48	28.47	21.28	21.28	21.28	21.28
Oxygen ($mg.L^{-1}$)	6.46 ± 0.95	5.98 ± 1.27	5.49 ± 1.48	4.63 ± 1.58	9.64	9.10	8.14	8.12	4.96	3.08	1.73	1.73
Salinity	31.89 ± 3.75	32.65 ± 2.50	33.52 ± 2.10	33.72 ± 1.44	35.13	35.46	35.77	35.73	30.61	31.59	31.58	31.58
Chlorophyll ($\mu g.L^{-1}$)	2.04 ± 1.48	2.44 ± 1.81	2.94 ± 3.04	0.35 ± 0.28	6.54	7.25	12.81	1.11	0.40	0.49	0.46	0.07
SPM ($mg.L^{-1}$)	2.19 ± 1.12	2.23 ± 1.32	2.91 ± 1.37	nd	5.90	6.97	7.07	nd	0.35	0.60	1.37	nd

Table 4 Von Bertalanffy growth model parameter estimates (mean ± SD) for *Mimachlamys nobilis* cultivated at Kau Sai fish culture zone in Hong Kong. Common superscripts depict statistically homogenous von Bertalanffy growth functions ($\alpha = 0.05$) determined by between-treatment likelihood ratio tests.

Treatment	Height at harvest (mm)	SGR (%.day^{-1})	H_{∞} (mm)	K	t_0	Days to reach 80 mm (VBGF projection)	K when $H_{\infty} = 120$
1 m[a]	80.66 ± 2.51	0.29	128.01 ± 21.52	1.00 ± 0.28	- 0.44 ± 0.05	0	1.14
3.5 m[b]	78.01 ± 4.80	0.27	96.96 ± 17.58	1.83 ± 0.65	- 0.34 ± 0.08	26	1.07
6 m[b]	77.10 ± 4.20	0.26	90.89 ± 8.98	2.02 ± 0.50	- 0.35 ± 0.06	59	0.97

Table 5 Condition indices (mean ± SD) of soft tissues and Analysis of Variance (ANOVA) results for *Mimachlamys nobilis* cultivated at 1 m, 3.5 m and 6 m at Kau Sai fish culture zone in Hong Kong. Common superscripts depict statistically homogenous results ($\alpha = 0.05$) determined by one-way ANOVA.

Soft tissue index	**June (n = 18)**	**September (n = 38)**	**December (n = 35)**	**ANOVA results**
Adductor	44.86±4.64^{a}	45.07±3.49^{a}	34.39±3.58^{b}	$F_{2,88} = 85.07$, $p < 0.001$
Gonadosomatic	11.18±3.58^{a}	13.41±3.06^{a}	22.32±3.79^{b}	$F_{2,88} = 85.75$, $p < 0.001$
Remaining tissue	43.96±4.90^{a}	41.52±3.29^{b}	43.29±3.03^{ab}	$F_{2,88} = 3.67$, $p = 0.03$

Table 6 Capital, operating and financial expenses associated with initiating integrated scallop *Mimachlamys nobilis* aquaculture at existing small (45 m^2) and large (315 m^2) fish monoculture rafts in Hong Kong.

				Small farm		Large farm	
Expense	Description	Unit	Lifespan (Years)	Quantity	Total cost (USD)	Quantity	Total cost (USD)
Capital expenses (Year 0)							
Equipment							
Lantern net (50 cm)	14-layer, 2 cm monofilament mesh	Nets	5	58	1,856.00	408	13,056.00
Lantern net droplines	Two 3 m droplines per net	Meters	3	348	89.23	2448	627.69
Supplementary flotation	One float per two active nets	Floats	5	10	193.58	68	1,316.41
Scallop acclimation tanks	Incl. aeration hoses	Set	3	47	903.85	111	2,134.62
Scallops							
Scallop growout stock	520 scallops per box	Box	1	47	379.61	332	2,681.54
Scallop road freight	Supplier to pier	Truck	1	1	1,092.32	3	3,276.92
Scallop sea freight	Pier to farm	Boat	1	1	58.62	3	175.85
Total capital expenses		Farm			4573.21		23,269.03
Operating expenses (Year 0)							
Labour							
Scallop stocking	Acclimation & stocking over 1 day	Workers $.day^{-1}$	-	4	176.92	21	928.85
Lantern net replacement	Bi-monthly. 20% of nets replaced per day.	Workers $.day^{-1}$	-	0	0.00	45	1,990.38
Lantern net cleaning	20% of nets cleaned on per day.	Workers $.day^{-1}$	-	0	0.00	0	0.00
Harvesting & shell biofouling removal	Harvest period: Small farm = 5 days Large farm = 10 days	Workers $.day^{-1}$	-	10	442.31	20	884.62
Harvest							
Boat trip to deliver harvest	Small farm: 5 trips Large farm: 10 trips	trips	-	5	293.08	10	586.15
Total operating expenses		Farm	-		912.31		4,390.00
Total operating + capital expenses		Farm	-		5,485.51		27,659.03
Financial expenses (Year 1 – 5)							
Annual payment of 5-year bank loan	Paid off in year 1 – 5.	Payments $.year^{-1}$	-	1	1,267.02	1	6,388.54
Total financial expenses		Farm	-		1,267.02		6,388.54

Table 7 Annual cash flow (USD ‘000) for a *Mimachlamys nobilis* farming operation integrated at existing small (45 m^2) and large (315 m^2) fish monoculture farms in Hong Kong. Capex = capital expenses, Opex = operating expenses, Finex = Finance expenses. Values are not cumulative, and are adjusted for a 3.58% annual inflation. A 15% profit tax has been deducted from net revue values. The present value (PV) of net revenue was calculated using a 5% discount rate.

	Small farm					Large farm				
Year	Capex	Opex	Finex	Net revenue	Net revenue (PV)	Capex	Opex	Finex	Net revenue	Net revenue (PV)
0	4.57	0.91	0.00	-5.49	-5.49	23.23	4.39	0	-27.66	-27.66
1	1.59	0.95	1.27	2.75	2.62	6.35	4.55	6.93	27.62	26.30
2	1.64	0.98	1.27	2.88	2.62	6.58	4.71	6.93	28.80	26.12
3	1.70	1.01	1.27	3.02	2.61	6.82	4.88	6.93	30.02	25.94
4	2.91	1.05	1.27	2.19	1.81	10.24	5.05	6.93	28.59	23.52
5	1.83	1.09	1.27	3.32	2.60	7.31	5.23	6.93	32.61	25.55
6	4.42	1.13	0.00	2.41	1.80	25.32	5.42	0	24.31	18.14
7	3.23	1.17	0.00	3.64	2.59	11.38	5.62	0	37.81	26.87
8	2.03	1.21	0.00	4.89	3.31	8.13	5.82	0	42.27	28.61
9	2.10	1.25	0.00	5.07	3.27	8.42	6.03	0	43.78	28.22
10	3.59	1.30	0.00	4.05	2.48	12.65	6.24	0	42.01	25.79

Figures

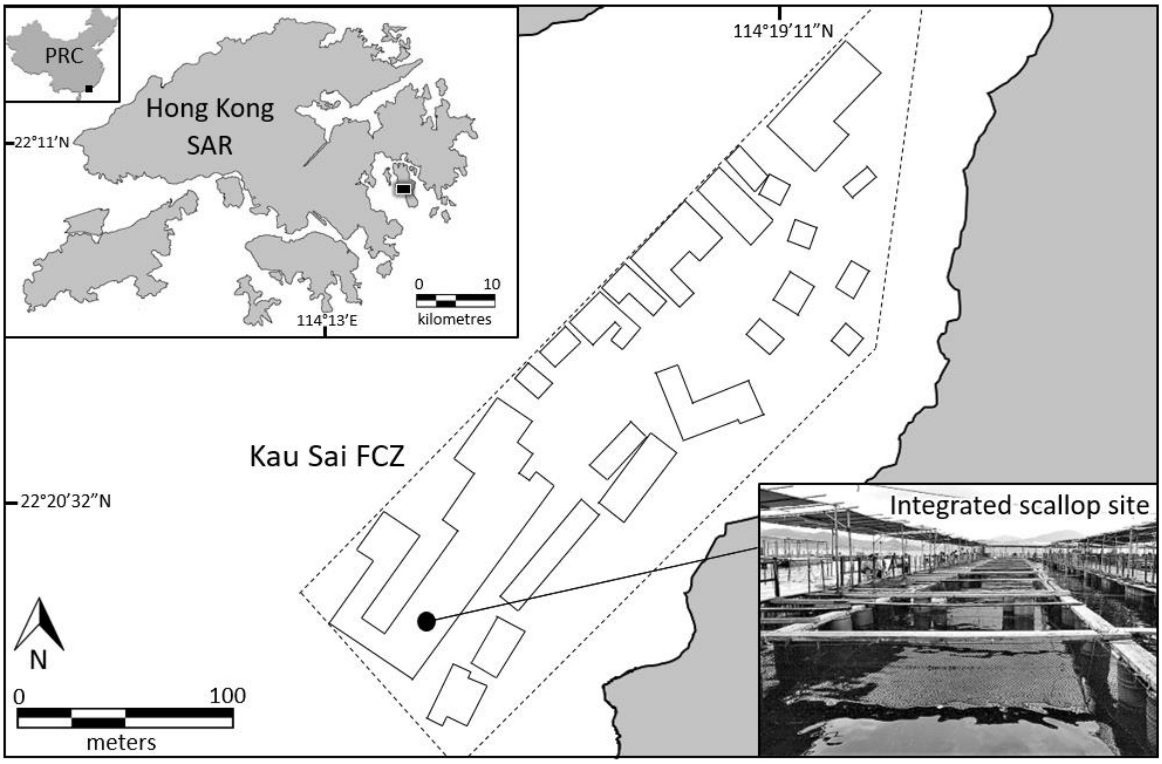

Fig. 1 Map of Kau Sai fish culture zone (FCZ) in Hong Kong SAR indicating the site used for the integrated scallop growout experiment. PRC = People’s Republic of China.

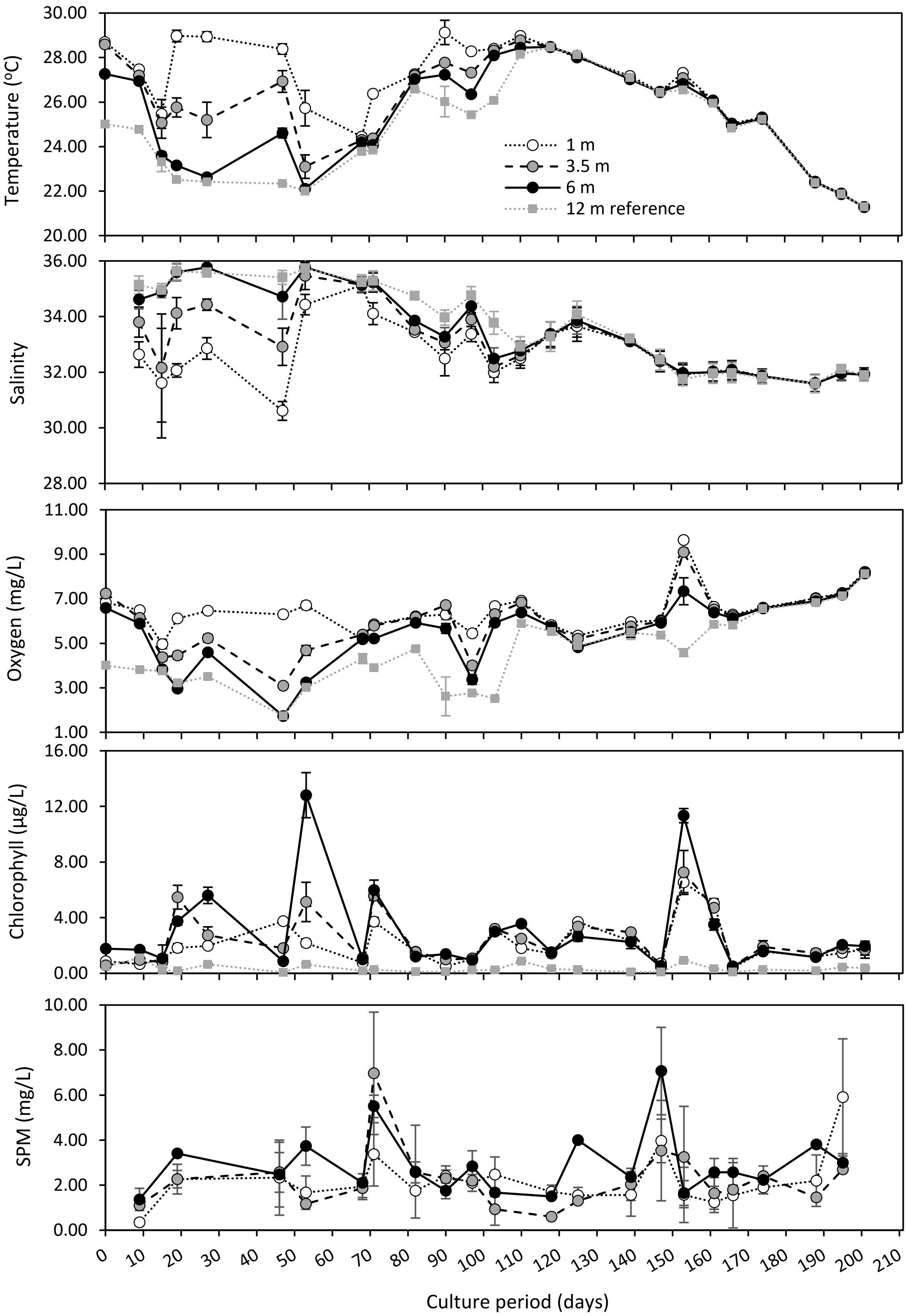

Fig. 2 Temperature, salinity, oxyen, total chlorophyll and suspended particulate matter (SPM) recorded at *Mimachlamys nobilis* treatments depths of 1 m, 3.5 m and 6 m at Kau Sai fish culture zone from 29 May – 16 December 2016. Reference data from 12 m are included to show environmental conditions near the sea floor.

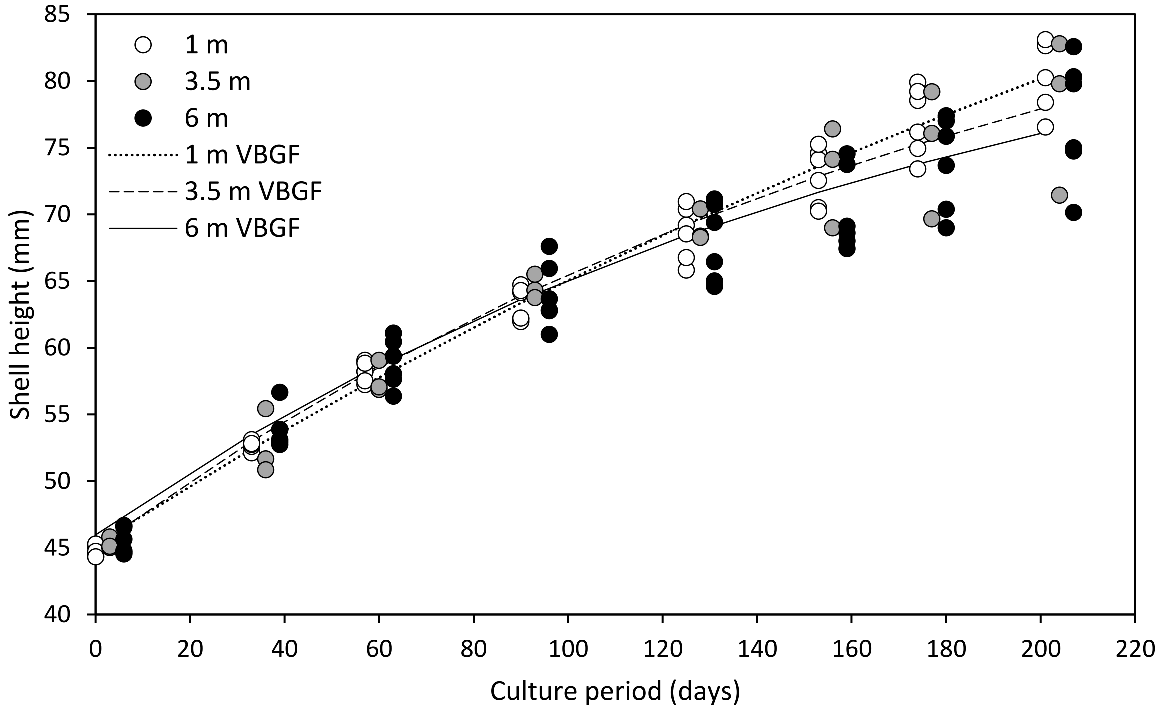

Fig. 3 Observed and von Bertalanffy growth function (VBGF) predicted height-at-time for *Mimachlamys nobilis* cultivated at Kau Sai fish culture zone in Hong Kong for 201 days from 29 May – 16 December 2016.

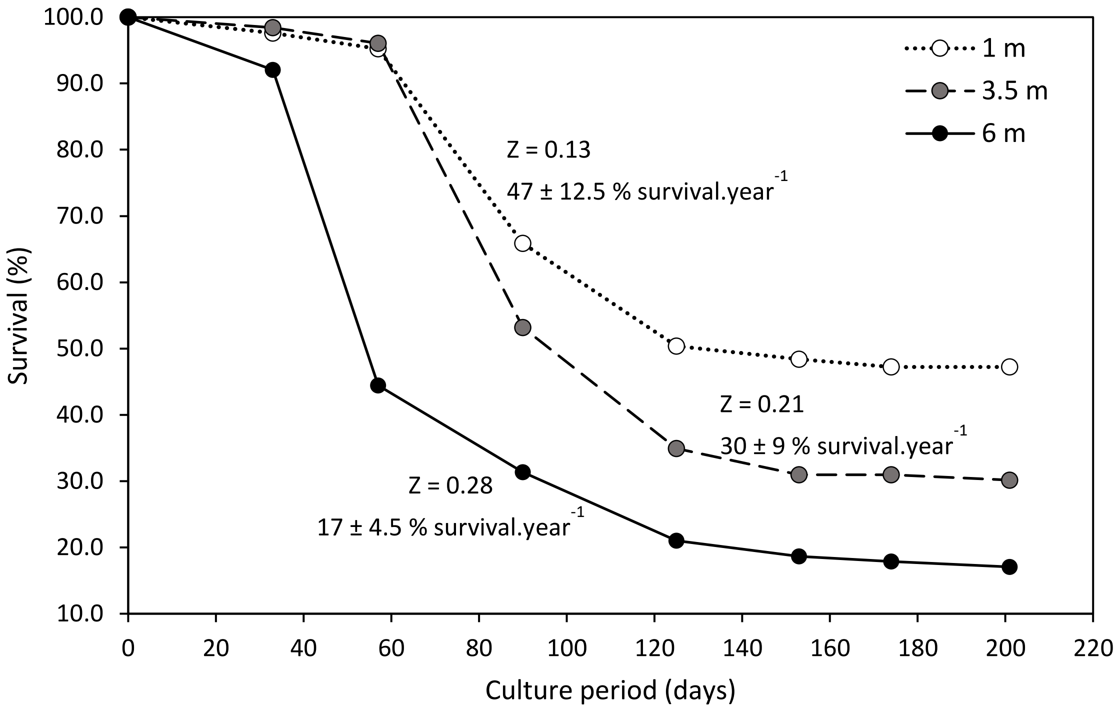

Fig. 4 Survival (%) and corresponding instantaneous rate of total mortality (Z) for *Mimachlamys nobilis* cultivated at Kau Sai fish culture zone, Hong Kong for 201 days from 29 May – 16 December 2016.

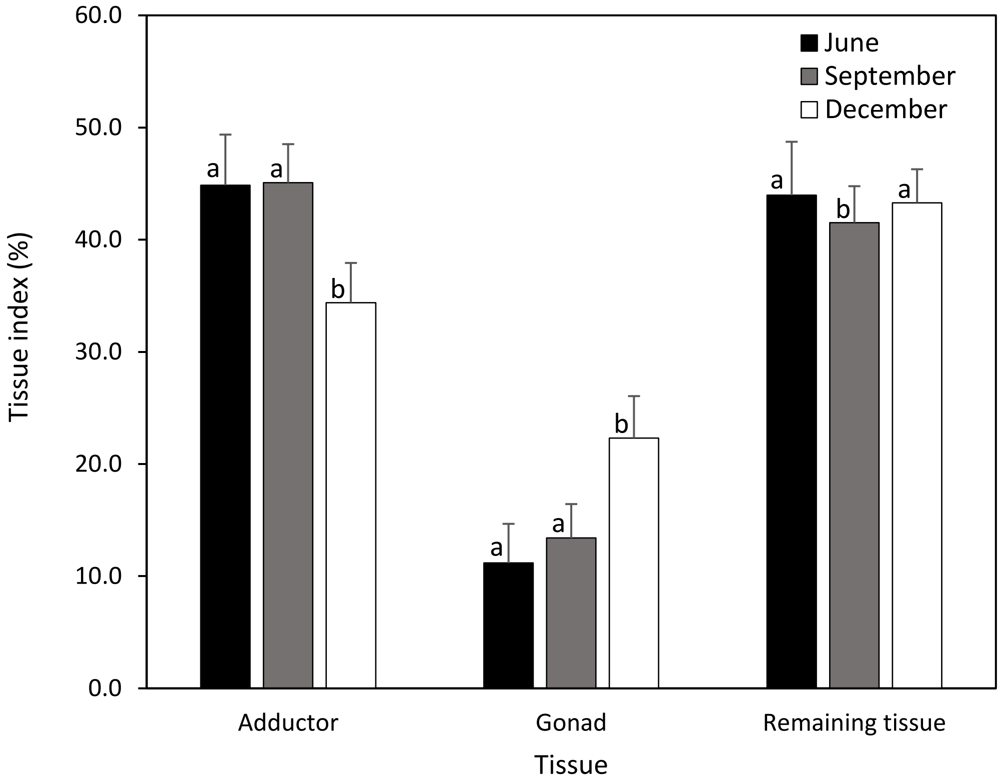

Fig. 5 Adductor, gonadosomatic and remaining soft tissue condition indices for *Mimachlamys nobilis* cultivated at Kau Sai fish culture zone in Hong Kong for 201 days from 29 May – 16 December 2016. Common superscripts depict statistically homogenous results ($\alpha = 0.05$) determined by one-way ANOVA.

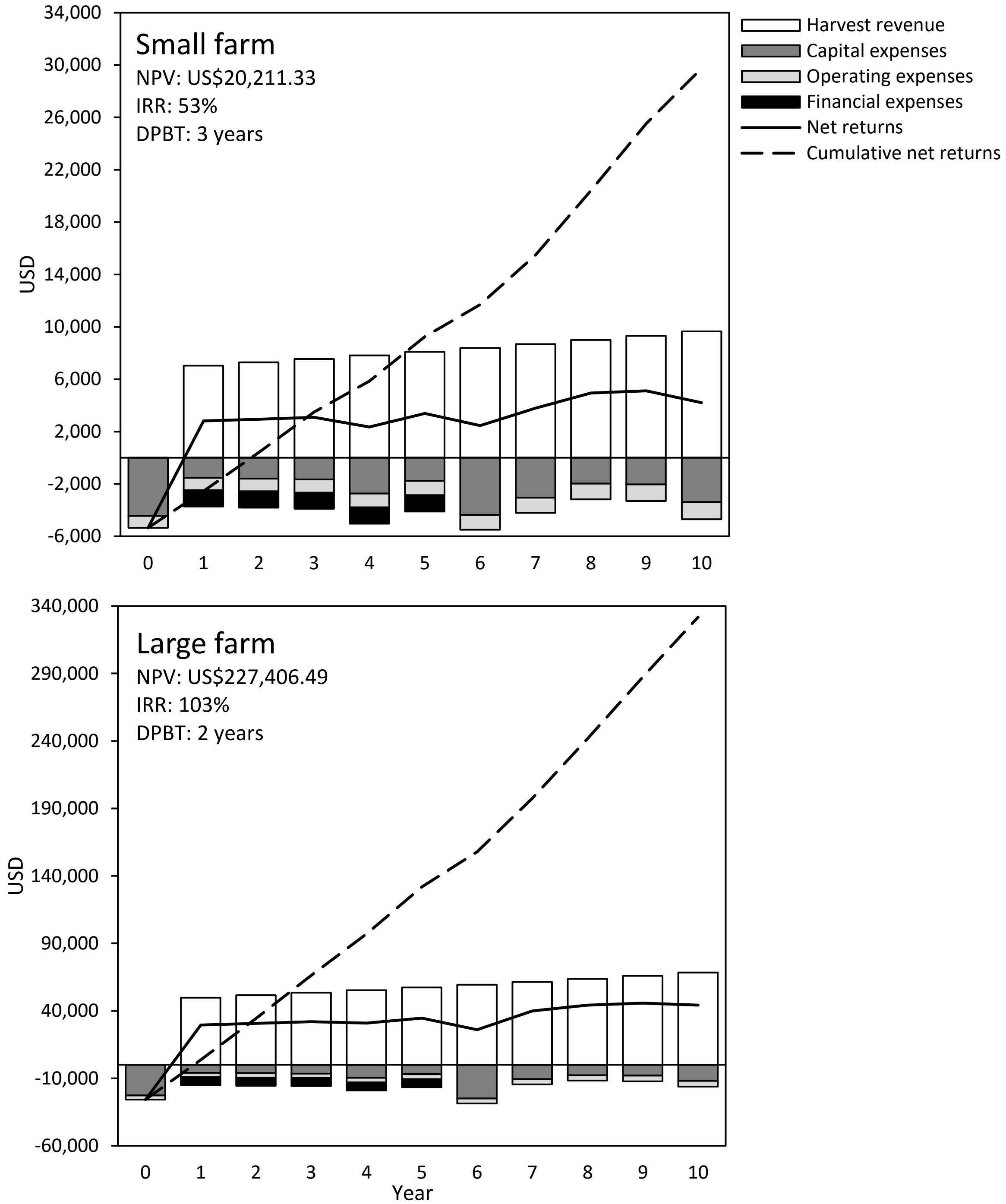

Fig. 6 10-year cash flows (US dollar), Net Present Values (NPV), Internal Rates of Return (IRR) and the Discounted Payback Time (DPBT) results for the integration of the scallop *Mimachlamys nobilis* at existing small (45m^2) and large (315m^2) fish monoculture rafts in Hong Kong.

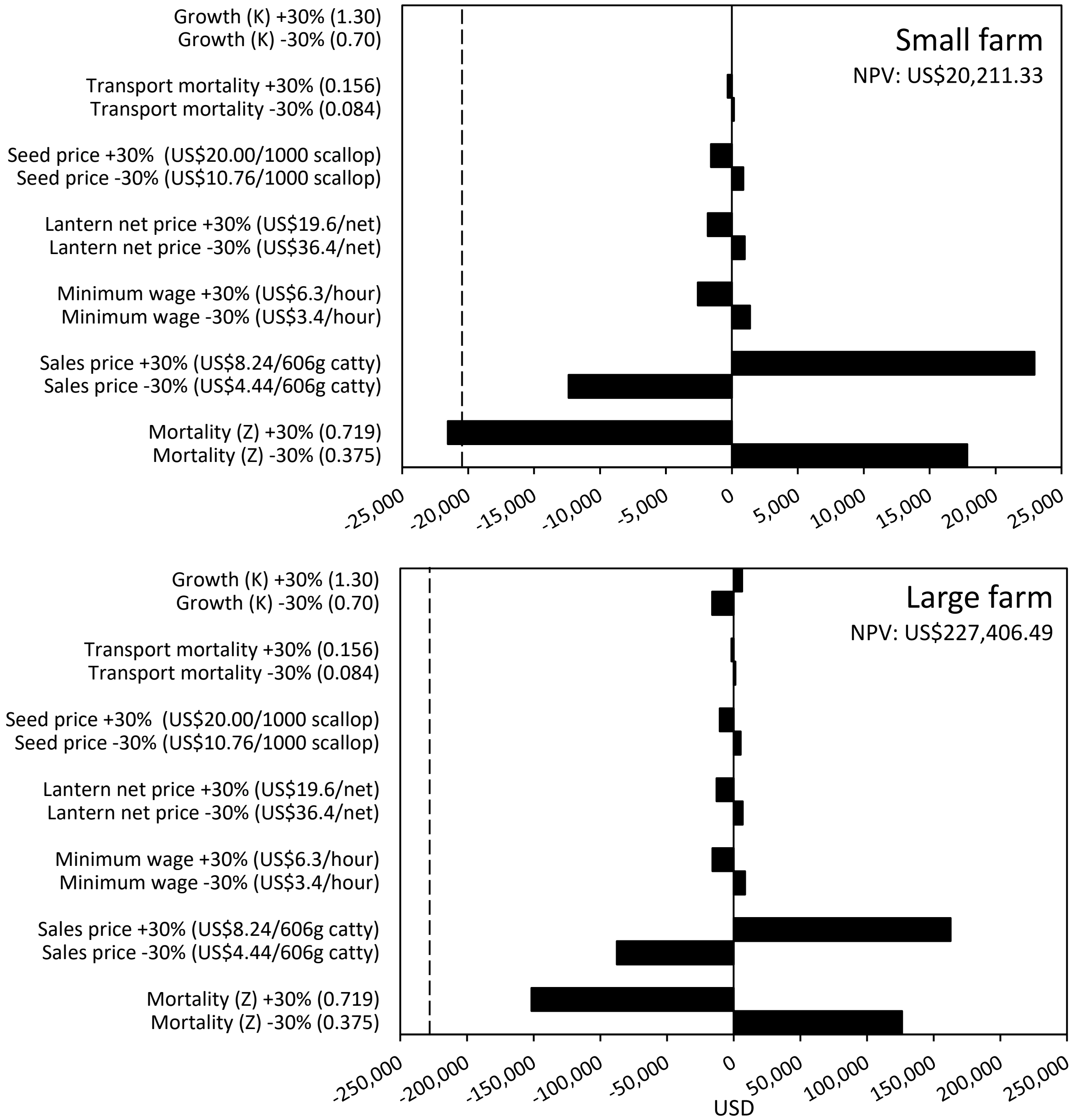

Fig. 7 Sensitivity analysis of the US dollar change in the Net Present Value (NPV_{10}) for a 10-year integrated *Mimachlamys nobilis* operation at existing fish monoculture farms in Hong Kong. The dashed line depicts the point at which the NPV_{10} would be negative.

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