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Growing smaller fish for inclusive markets? Increasing stocking density and shortening the production cycle of Nile tilapia in cages on Lake Victoria

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A B S T R A C T

Fish farmers aim to maximise fish weight relative to the feed inputs needed to turn a profit. Yet, many farmers in Africa lack the cash flow to grow large fish and many consumers prefer, or are limited to purchasing, small fish. This study aimed to intentionally produce small tilapia in cages by assessing the effects of higher stocking densities and shorter growth cycles on production and financial efficiency. An experiment with 3 treatments and 6 replicates took place on Lake Victoria. The first treatment (T1) used a stocking density of 2.9 ± 0.3 kg per m^{-3} and aimed to produce fish to an average body weight (ABW) of 400 g (final ABW = 500.33 ± 31.01 g after 138 days). Treatment two (T2) did the same but with double the stocking density (5.9 ± 0.3 kg per m^{-3}), resulting in a final ABW of 439.22 ± 22.22 g over 138 days. The third treatment (T3) partially harvested 50% of the cage (after 76 days) once reaching an ABW of 230.92 ± 22.55 g. The remaining fish in T3 were on-grown for a total of 138 days (final ABW = 499.86 ± 15.95 g). A fourth production scenario (M1) based on data from T3, modelled a 100% harvest after 76 days of culture. There were no significant differences in mortality between treatments. There were no statistical differences in the feed conversion ratio (FCR) between T1 (1.51 ± 0.03) and T2 (1.49 ± 0.02), though T3 was statistically lower (1.46 ± 0.02; p = 0.03). Cages in T1 had a higher proportion of fish between 400 and 599 g while fish in T2 were mostly between 300 and 499 g. T3 had a bimodal distribution with most fish either in 200–299 g or 400–499 g. There was little effect on average price per kg for T1 (3.0 ± 0.01 USD) and T2 (2.98 ± 0.01 USD), though T3 (2.89 ± 0.04 USD) was significantly lower (p = 0.001). Overall, T2 had significantly higher gross margins (17% ± 2.08) than T1 (13% ± 2.3, p = 0.021) and T3 (7.2% ± 2.43, p = 0.001), while M1 had the lowest gross margins (−11.8% ± 5.5). The results suggest that farmers can increase stocking densities. Some farmers can use partial harvesting strategies or shorter cycles to produce small tilapia and achieve faster cash flows, though the economic margins are lower. Such approaches can provide opportunities for poorer farmers and consumers.

1. Introduction

Aquaculture in sub-Saharan Africa is becoming an increasingly important source of food and nutrition (Mapfumo, 2020). While the contribution to fish supply from aquaculture remains low in comparison to that of fisheries, it has grown exponentially in the last decade (FAO, 2020). This increase in supply is due to the rapidly expanding tilapia farming industry, with countries such as Kenya leading the cage culture revolution on some of Africa's largest lakes (Kaminski et al., 2018; Njiru et al., 2018). Most commercial tilapia farmers manage their production to maximise body weight of fish, which are then sold in fresh form, almost exclusively to regional urban centres and capital cities (Adeleke et al., 2020). Farmed tilapia can generally fetch premium prices in the region, challenging traditional, wild-caught tilapia value chains that often produce dried/smoked products (Asiedu et al., 2015). While the contribution of aquaculture to overall per capita fish supply has grown over the years, there is some criticism that commercial tilapia cage operators produce predominantly large fish for wealthier segments of society (Genschick et al., 2018; Marinda et al., 2018). There is a wealth differentiation in tilapia consumption in Zambia for example, where

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poorer segments of society purchase smaller tilapia supplied mostly through frozen imports from Asia, while larger, domestically produced tilapia are purchased from supermarkets by wealthier consumers (Genschick et al., 2017). Similar scenarios are evident in Kenya and there are few domestic producers looking to fill this market niche (Soma et al., 2021; Munguti et al., 2022).

There seems to be an opportunity for commercial farmers and especially the small-to-medium-sized (SME) sector to actively produce and supply small tilapia. Many farmers struggle to produce large tilapia, due to the lack of cash flow to grow fish for the four to six months required to reach "optimal" market size (Ofori et al., 2010). Consumers in many African countries consume and sometimes prefer small-sized fish, including smaller or juvenile cichlids such as tilapia (Obiero et al., 2014; Murphy et al., 2020). The preference for small fish is driven by its lower price point, local culinary habits, preparing and portioning fish for the family, or the perceived health benefits of eating whole small fish (Darko et al., 2016; Ayuya et al., 2021). Such distinct preferences of various social groups are not always considered in the commercial breeding and cultivation of fish (Omasaki et al., 2016; Mehar et al., 2019).

The idea that farmers can grow tilapia to a smaller yet profitable market size is not necessarily new (Smith et al., 1985). For many practitioners and academics, maximising the biomass from a cage by increasing the weight of individual fish is a fundamental goal of aquaculture production, and is especially important for companies that grow fish for filleting. This is not the case in Kenya, where consumers prefer whole fish to fillets. Maximising the average body weight (ABW) of individual fish may not be the main objective for farmers looking to satisfy rural and/or low-income consumers who purchase small, whole fish (Chikowi et al., 2021; Soma et al., 2021). Growing small fish results in the use of less feed inputs, and lower food conversion ratios (FCR), resulting in quicker cash flows, and potentially important implications for sustainability (El-Sayed, 2002; Besson et al., 2016; Rodde et al., 2020; Genschick et al., 2021). There are potential human nutrition benefits too, as small fish are sometimes consumed whole, including the bones and viscera, resulting in greater micronutrient intake (Kabahenda et al., 2011; Fiorella et al., 2018). Producing smaller and less valuable fish may also reduce incidences of theft or reduce exposure to economic fallout from natural disasters such as floods and droughts.

Growing individually small tilapia requires shortening the production cycle, which in turn, suggests that stocking density can be increased to maximise biomass output. Assessing the effects of stocking densities, stocking rates or stocking size of fish are common research objectives in academia and the private sector (Shoko et al., 2014; Shamsuddin et al., 2022). Studies suggest that higher stocking densities generally slow growth and, in some cases, reduce fish survival (Ridha, 2006; Azaza et al., 2013; Liu et al., 2018). There is constant debate on which stocking densities are best suited for specific cages and ponds in different aquatic systems around the world, though most approaches aim to increase stocking densities to optimise carrying capacity for maximum financial returns (Conte et al., 2008).

Some farmers ensure a variety of fish sizes by conducting partial harvests of smaller fish earlier in the production cycle, allowing the remaining fish to grow to a larger size (Knud-Hansen and Kwei Lin, 1996). Partial harvests allow commercial farmers to harvest sooner and improve their cash flow, as well as to meet market demand for different sizes of fish (Saiti et al., 2007). Studies have shown that partial harvesting can decrease competition for feed, improve growth rates and yields, and increase profitability (Yu and Leung, 2006). Partial harvesting is common in many small-scale farming systems in Africa, especially in extensive earthen pond systems (Kaminski et al., 2022). This form of harvesting is useful because farming households can consume fish from their ponds/cages or have access to an immediate influx of cash through the quick sale of some fish (Kaminski et al., 2018).

The study aimed to assess the biological and financial potential of purposively growing small fish by shortening the production cycle, partially harvesting smaller fish midway through a cycle, and increasing stocking density.

The experiment took place with Nile tilapia (*Oreochromis niloticus*) in the Kenyan part of Lake Victoria. Nile tilapia, although not endemic to Lake Victoria, is an important capture fishery, along with the non-native Nile Perch (*Lates niloticus*) and small, pelagic fish such as omena (*Rastrineobola argentea*) (Munguti et al., 2022). Nile tilapia remains one of the most frequently consumed fish in Kenya and its culture has become an increasingly important source of supply in recent years (Esilaba et al., 2017). Although most aquaculture production in Kenya is dominated by a few large commercial companies, there are over 40 small-scale cage farming establishments around Lake Victoria raising fish for local markets (Njiru et al., 2018).

Many Kenyans still live in extreme poverty and fish makes up most of the animal-source protein for most households and is especially critical for poorer households (Cornelsen et al., 2016; Fiorella et al., 2014; Obiero et al., 2019). The results of this trial are intended for the commercial cage sector to assess whether a reorientation of production towards additionally supplying small, cheaper fish (lower price per kilogram for smaller fish) can be feasible and profitable. The approach, generally, aims to move the aquaculture sector into a more inclusive, nutrition-sensitive direction that includes the food and nutrition security needs of the most vulnerable in society (Rosenberg et al., 2018). The approach depicted in this study aims to produce tilapia that is more affordable for poorer people. By so doing, aquaculture becomes more accessible for producers and consumers aiming to benefit from tilapia value chain developments (Kaminski et al., 2020).

2. Materials and methods

2.1. Experiment design

The trial was conducted at Victory Farms Ltd., located in Homa Bay County in Kenya. The farm is the largest cage operator on Lake Victoria supplying around 7500 metric tonnes (MT) of Nile tilapia (*Oreochromis niloticus*) per annum. Fish were grown in metal cages sized at 27 cubic metres (3 m × 3 m × 3 m) and enclosed with polyethylene nets. Little fouling of nets occurred during the trial and no net changes or washes were necessary. The cages floated in deep water just over one kilometre from the landing site and placed side by side in two rows of nine (total 18 cages) with 0.5 m gap between cages (see Fig. 1).

Fingerlings were obtained from two nursery cages situated in the lake operated by Victory Farms Ltd. Fingerlings were transferred to the trial site when they reached an average of 39.5 ± 1.77 g (based on 5 samples of 20 fish per nursery cage). The biomass (kg) of fish was weighed in bulk upon transfer from nursery cages and fingerlings were not individually counted. The number of fish stocked in each cage was back calculated by summing all mortalities with the final number of fish harvested at the end of the trial, and this figure is used throughout our calculations.

The experiment consisted of three treatments and six replicate cages per treatment (see Fig. 1). The standard target stocking density for cages of this size was determined to be 80 kg of fish per cage (2.96 kg per m^{-3}). The nominal operating parameters for the trial are seen in Fig. 1. Since this is a trial using actual grow-out cages as part of a commercial farm operation, the final stocking parameters differed slightly (see Table 1). Treatment 1 (T1-Standard) cages were stocked with the standard average stocking density while Treatment 2 (T2-Double) doubled the stocking density. A third treatment (T3-Partial) also doubled the stocking density except a 50% partial harvest was introduced midway through the cycle, and the remaining fish were cultured to full size. Finally, a fourth production scenario (M1) was modelled based on data from T3, where the entire biomass was harvested instead of a partial harvest (i.e., shorter production cycle labelled 'M1-Shorter-Double').

Fish were stocked on 14th of February 2022 and were fed to satiation with purchased formulated pellets five times daily with 2 mm feed (34%

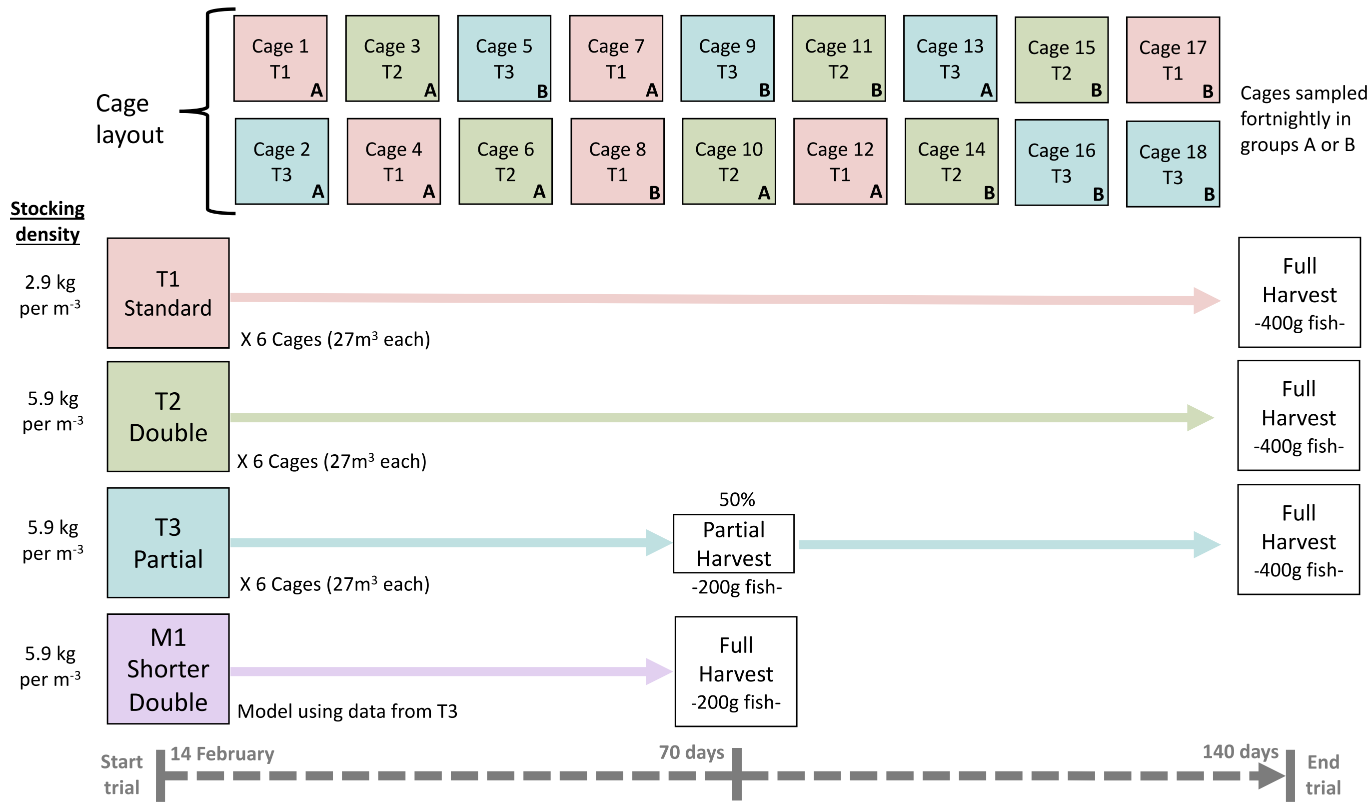

Fig. 1. Experimental design and cage layout.

Table 1
Stocking operating parameters of the trial.

Operating parameter	Standard (T1)	Double (T2)	Partial (T3)	Shorter double (M1)
	Mean ± SD	Mean ± SD	Mean ± SD	–
Total fingerlings (no.)	2227.2 ± 184.3	4560 ± 373.3	4414 ± 250.4	Modelled using data from T3
Stocking rate (no. m^{-3})	82.5 ± 6.8	168.9 ± 13.8	163.5 ± 9.3	Modelled using data from T3
Stocking biomass (kg)	79.7 ± 4.3	159.1 ± 7.2	158.1 ± 8.2	Modelled using data from T3
Stocking density (kg. m^{-3})	2.9 ± 0.2	5.9 ± 0.3	5.9 ± 0.3	Modelled using data from T3
Size of fingerling (g)	35.9 ± 2.5	35.0 ± 2.8	35.8 ± 1.1	Modelled using data from T3

CP), reduced to four times daily with 3 mm feed (32% CP), and finally three times daily with 4 mm feed (32% CP). The amount of feed in T3 cages was adjusted after approximately 50% of the fish population was removed during the partial harvest, assuming the fish that were left in the cages consumed 50% of the feed prior to partial harvesting.

2.2. Data collection and sampling

Water quality measurements were recorded using an optic sensor (Oxy Guard Handy Polaris) daily between 14 h00-15 h00. Temperature and dissolved oxygen (DO) were found to be in optimal range, typical for the region (25.1–27.6 °C; 2–7.9 mg/L) (Mengistu et al., 2019). Turbidity was measured using a secchi disk and found to be in optimal range (2–4 m). See Appendix A for graphical representation of water quality measurements.

The amount of feed consumed (kg) per cage and the number of observed fish mortalities were recorded daily. Sample fish weights were collected a total of 8 times from each cage: fortnightly until the partial harvest point (5 samples); and thereafter monthly until the end of the trial (3 more samples). Cages were organised and sampled in groups (A & B) of nine cages each with equal representation from all treatments (see Fig. 1). Fish were randomly selected from different areas of the cage (n = 30/cage, n = 6 cages/treatment) and weighed individually with a scale (0.01 g); thereafter, all fish were returned to the cage.

During the partial harvest of T3 cages, after 76 days of culture, approximately 50% of the biomass of fish were harvested. After 138 days of culture, all remaining fish were harvested from all treatments. Harvested fish were scaled and gutted at the Victory Farms Ltd. processing site and graded into ten different sizes from Grade 0 (<100 g) to Grade 10 (> 1,000 g) (see Table 2). The post-processing biomass (kg) of fish for each grade was recorded to account for the loss in weight after processing.

The costs of feed, labour, and fingerlings, and the selling price of fish in different grades, were recorded and collected via key informant interviews with farm staff. The average cost of fingerlings was 30 Kenyan Shillings (KES) per piece. The cost of labour per cage was based on the

Table 2
Size grade (weight range) and price as United States Dollar (USD).

Grade size	Weight range	Equivalent USD/kg*
Size 0	< 100 g	1.82
Size 1	100–199 g	2.25
Size 2	200–299 g	2.85
Size 3	300–399 g	2.97
Size 4	400–499 g	3.03
Size 5	500–599 g	3.01
Size 6	600–699 g	3.13
Size 7	700–799 g	3.22
Size 8	800–899 g	3.36
Size 9	900–999 g	3.36
Size 10	> 1000 g	3.36

* Exchange rate: USD 1 = KES 120.65.

daily wage for one person (600 KES per day) to feed one cage with an additional 25% wage increase for cages that were double stocked to compensate for the marginal increase in feeding labour. All units in Kenyan Shillings (KES) were exchanged into United States Dollar (USD) (120.65 KES = 1 USD). It must be noted that the costs for fingerlings and labour are context specific to Victory Farms Ltd. No other variable costs were included as they differ widely across farming operations in Kenya.

2.3. Calculations and data analysis

2.3.1. Biometric parameters

The mean weight of fish was averaged from the sample of 30 fish at each sampling event and the interquartile range was calculated to reflect the range of individual fish weights over time. Mortality was calculated as a percentage of the original number of fish stocked. The feed conversion ratio (FCR) was calculated as the amount of feed (g) divided by the biomass gained after stocking. The FCR was also calculated as a time series using each sampling event. The FCR of the M1-Shorter-Double scenario was calculated using the partial harvest data from T3 by taking the number of fish left after the partial harvest divided by the number of fish that were removed from the cage, giving the true fraction that was partially harvested in T3 (target was 50% harvest), which was then used to calculate the biomass gain up to that point. The same FCR calculation used the feed input and mortalities up until the day of the partial harvest.

Standard growth rates or other methods of estimating growth were deemed unuseful since half of the fish were removed from T3-Partial but also because the design of the sampling intervals and groups meant that too much variation was introduced as different cages were sampled at different times.

Since fish from the partial harvest were not sorted into different size grades in the same as way they were for the final harvest, the mean weight of the sample of fish ($n = 30$) collected on the day of the partial harvest was used to estimate the proportion of fish that would have been graded into different sizes. This proportion for each size grade is then multiplied by the actual biomass of fish that were partially harvested.

2.3.2. Financial parameters

Financial parameters are all presented in USD. The total revenue is calculated as the post-processing weight of fish (kg) multiplied by the average price of fish (USD) per kg. Using the proportion and price of fish in each grade (Table 3) we calculated an average price of fish per cage, as well as the total value of each cage, assuming all fish were sold.

The direct production costs (DPC) included the sum of the total value of feed (USD/kg) and labour (USD/day multiplied by the number of feeding days) and total cost of fingerlings (USD/fish). A gross margin was calculated as the total revenue minus the DPC. The gross margin was also calculated as a percentage of the total revenue. To make the results generalizable across different production systems in Kenya, we present both the gross margins of total revenue with and without fingerling and labour costs, as these costs vary greatly between farming operations.

The same procedure to model FCR in M1 above was used to model the financial parameters for M1: we took the biomass (kg) at partial harvest multiplied by the number of fish left after the partial harvest of T3 divided by the number of fish partially harvested.

2.3.3. Statistical analysis

All calculations and analysis were performed in R Studio, version 1.3.1056 (R Core Team, 2020). After visually checking for normality and approximating equal variances using histograms, an ANOVA was used to test for significant differences between treatments, and a Tukey post-hoc test was applied to identify which treatments were different from each other. Significance was considered at or below the 5% probability level. We specifically tested for differences in production indicators: FCR, final harvest ABW, mortality, and proportion of biomass in each size grade. We also tested for differences in financial indicators: average price of fish, total value of cages, and total gross margins as the net USD amount after subtracting the DPC, and as a percentage of total revenue. The statistical analyses were performed only for comparisons between T1, T2, and T3 and not for M1.

Table 3
Final summary of production and financial results.

Variable	Single (T1)	Double (T2)	Partial (T3)	Shorter double (M1)
	n = 6	n = 6	n = 6	–
Production parameters				
Mean survival rate	95.8%	95.1%	94.7%	95.6%
Mean size of fish (g) at partial harvest	–	–	230.1	–
Mean size of fish (g) at final harvest	500	440	500	231
Mean FCR[‡]	1.51	1.49	1.46	1.33
Input				
Mean biomass of fish stocked (kg)	79.7	159.1	158.1	158.1
Mean amount of feed until partial harvest (kg)	–	–	990	–
Total feed (kg), including partial harvest	1,457	2,597	1,853	990
Operating costs				
Fingerlings (USD)	554	1,134	1,098	1,098
Fish Feed (USD)	1,236	2,205	1,592	881
Labour (USD)	686	858	781	472
Output				
Biomass of fish (gutted and scaled) at partial harvest (kg)	–	–	412	–
Total biomass of fish (gutted and scaled) at final harvest (kg)	949	1,699	1,297	830
Revenue				
Average sale price per USD/kg of fish)[†]	3.00	2.98	2.89	2.65
Total value of fish in cage (USD)	2,851	5,067	3,745	2,199
Gross Margin (USD) – incl. all costs	376	871	275	−251
Gross Margin (%) – incl. all costs	**13%**	**17%**	**7%**	**−12%**
Gross Margin (%) – without fingerlings & labour costs	57%	57%	57%	60%

[‡] FCR based on biomass of fish before processing (gutting and scaling).
[†] Average price calculated as biomass of fish for each grade multiplied by price for each grade.

3. Results

The trial was successfully completed on 1st of July 2022 after 138 days of culture when fish averaged over 400 g. The partial harvest of T3 cages occurred on the 30th of April after 76 days of culture when fish averaged over 200 g. The results for production indicators are presented first showing only minor differences between mortality, FCR and individual sizes attained. The financial indicators are presented after this, also showing only minor differences in price per kg, total value, and gross margins, suggesting the trial was successful in showcasing the feasibility of purposively growing small tilapia.

3.1. Mortality

The cumulative mortality for each cage over time is illustrated in Fig. 2. The highest rate of mortalities occurred soon after stocking, with

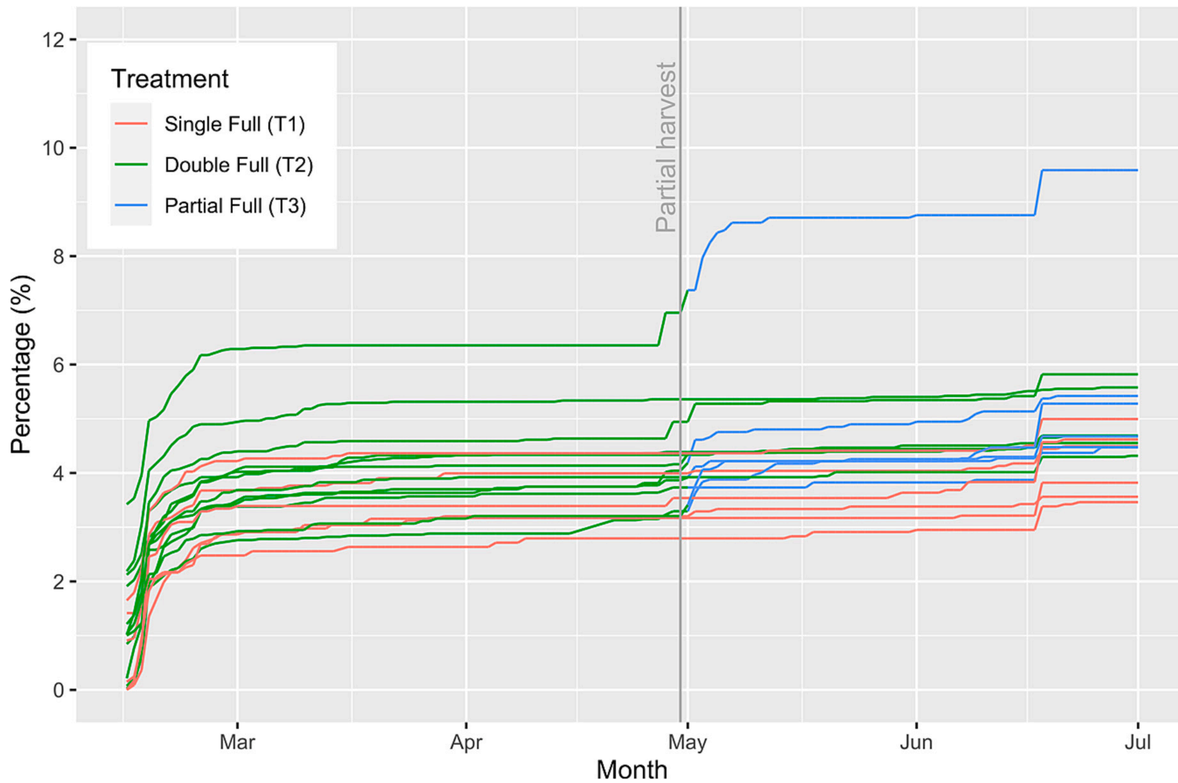

Fig. 2. Time series of observed mortality (%) as a proportion of original number of fish stocked for each cage in all three treatments. The grey vertical line reflects the partial harvest event after 76 days of culture.

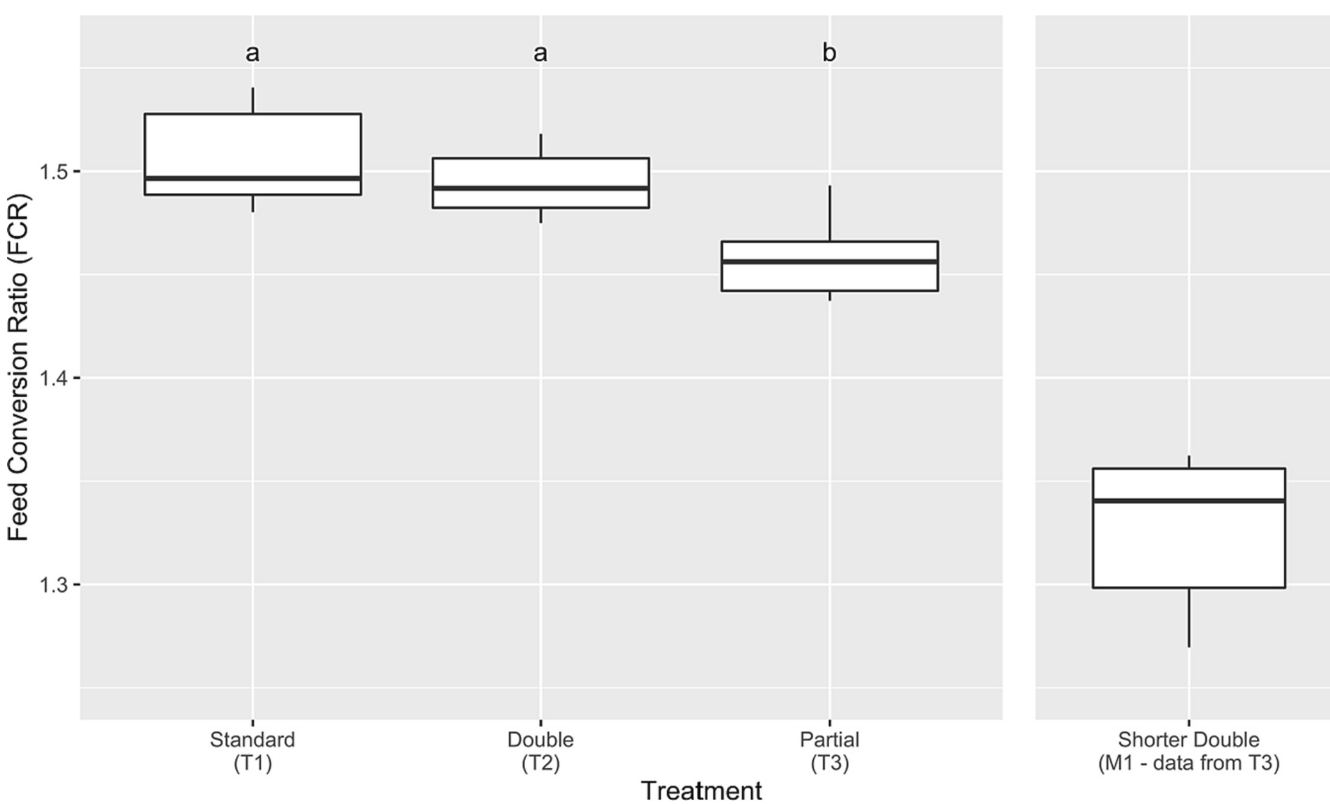

Fig. 3. Boxplot of variation in Feed conversion ratio (FCR) by treatment. Each box created from 6 replicate cages, showing median (solid line), interquartile range (box) and full range (whiskers). Left panel shows FCR by the end of the trial while the right panel shows FCR of M1 at final harvest after 76 days. Differences calculated with ANOVA and Tukey test and statistical significance ($p < 0.05$) denoted with different letters (a, b, or c). ANOVA did not include the M1-Shorter-Double scenario.

one cage (no. 18) suffering particularly higher mortalities for unknown reasons (possibly due to its location on the corner of the cage layout – see Fig. 1). An increase in mortalities occurred across all cages in the last week of June due to a seasonal algal bloom on Lake Victoria, which coincided with a drop in temperature and DO, and a sharp rise in turbidity (see Annex 1).

Treatment 1 experienced an average of 4.2 ± 0.01% cumulative mortality compared to 4.9 ± 0.01% for T2 and 5.3 ± 0.02% for T3. The cumulative mortality of T3-Partial until the day of the partial harvest was 4.4 ± 0.01%, which is also the modelled mortality value for M1-Shorter-Double. To see whether increased stocking density or partial harvesting affected mortality of fish we used ANOVA and a post-hoc Tukey test and found no statistical differences in the final mortality between treatments.

3.2. Feed conversion ratio (FCR)

ANOVA and a post-hoc Tukey test was used to determine the effects of increased stocking density and partial harvesting on FCR. The T1-Standard cages had an average FCR of 1.51 ± 0.03, with no significant difference to T2-Double (1.49 ± 0.02) (see Fig. 3). However, T3-Partial with a mean FCR of 1.46 ± 0.02 was significantly lower than T1 ($p = 0.0044$) and T2 ($p = 0.0287$). The modelled mean FCR for M1-Shorter-Double (1.33 ± 0.04), after 76 days of culture, should be read attentively as it relies on data from the partial harvest and is thus not included in the ANOVA. The model (M1) does, however, show a lower FCR at the partial harvest point.

We showcase FCR as a time series using each sample of fish ($n = 30$) by treatment, as shown in Fig. 4. The FCR before the partial harvest was notably lower, showcasing the potential production benefits of producing small tilapia.

To see how much feed was used in each cage we present a time series for the whole trial (see Fig. 5). Before the partial harvest, T2 and T3 were treated as double stocked cages. However, T3 received slightly lower feed on average (990 ± 70. kg) compared to T2 (1043 ± 95 kg), though the differences were not statistically significant when using an ANOVA and post-hoc Tukey test (not shown in figure). Notably, after the partial harvest, when T1 and T3 were treated as standard stocking density cages, fish in T3 again consumed slightly less feed in total (863 ± 55 kg) than T1 (898 ± 69 kg). There were no statistically significant differences, but these small differences could be the reason why the FCR for T3 was significantly lower than T1 and T2.

3.3. Average body weight (ABW) and size distribution

Fig. 6 shows the average body weight and interquartile range of fish over time from each of the fish weight samples (n = 30) by treatment to see how fish grew at each stage of the trial.

Despite different amounts of feed, we found that the final ABW of T1-Standard (500.33 ± 31.01 g) and T3-Partial (499.86 ± 15.95 g) were almost the same when tested with ANOVA and a post-hoc Tukey test (Fig. 7). Increased stocking density when combined with a partial harvest did not seem to affect the growth of fish, at least not in the second half of the trial. The final ABW for T2-Double (439.22 ± 22.22 g) was, however, statistically different to both T1 ($p = 0.0044$) and T3 ($p = 0.0287$) showing the effect of increased stocking density on growth. The mean weight of M1-Shorter-Double was 230.92 ± 22.55 g.

The results of an ANOVA to see if increased stocking density and a partial harvest affected size distribution of fish (% of total yield) was significant ($p = 0.0018$). Fig. 8 shows the final size distribution and standard deviation as a proportion (%) of the biomass harvested in each size grade. Most of the biomass of fish in T1-Standard was between 400 g and 600 g, while most of the biomass of fish in T2-Double was between 300 g and 400 g. The partial harvest meanwhile had a bimodal effect on size distribution for T3-Partial with roughly a quarter of the biomass of fish between 200 and 300 g and another quarter in the 400 and 499 g

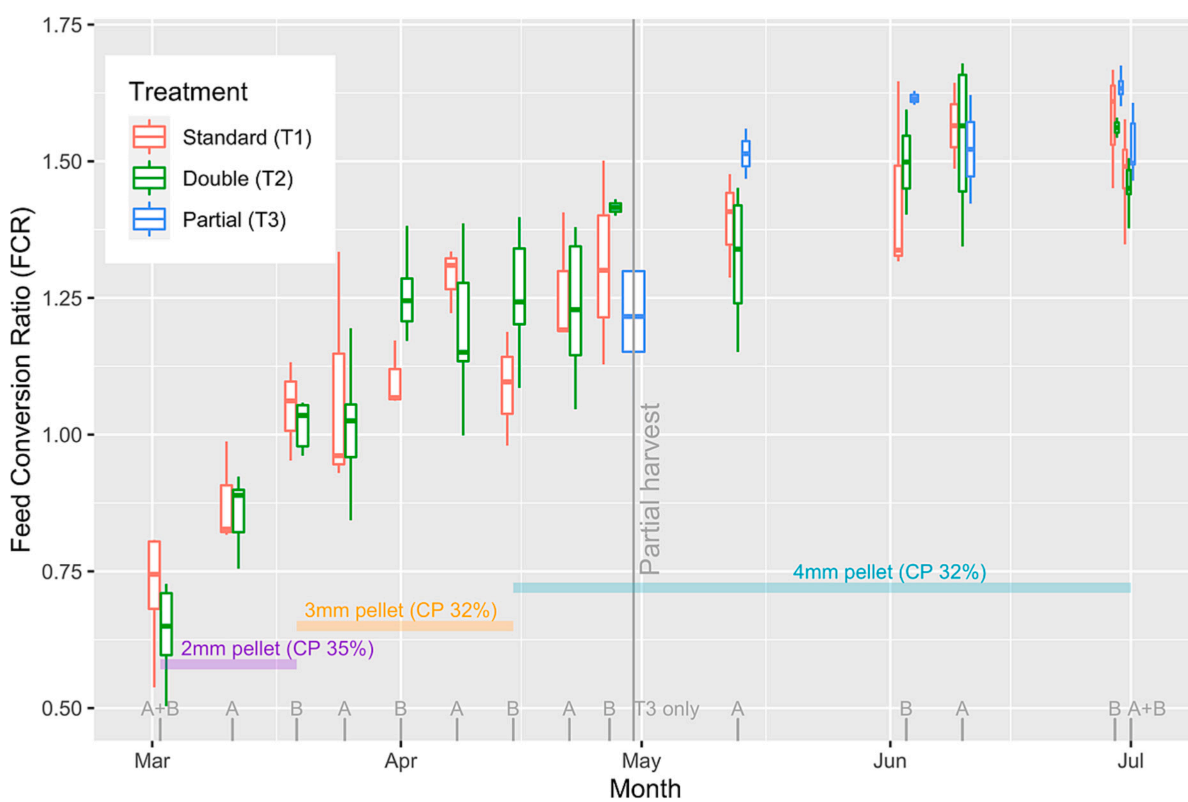

Fig. 4. Time series of Feed conversion ratio (FCR) with boxplot of variation from fish weight samples ($n = 30$) from three cages in each treatment per sampling event (shown with grey ticks, group A or B, on x-axis). Each box shows median FCR (solid line), interquartile range (box) and fill range (whiskers). The grey vertical line reflects the partial harvest after 76 days of culture. A time series of the feed pellet size including crude protein (CP) used in the trial are presented with labels.

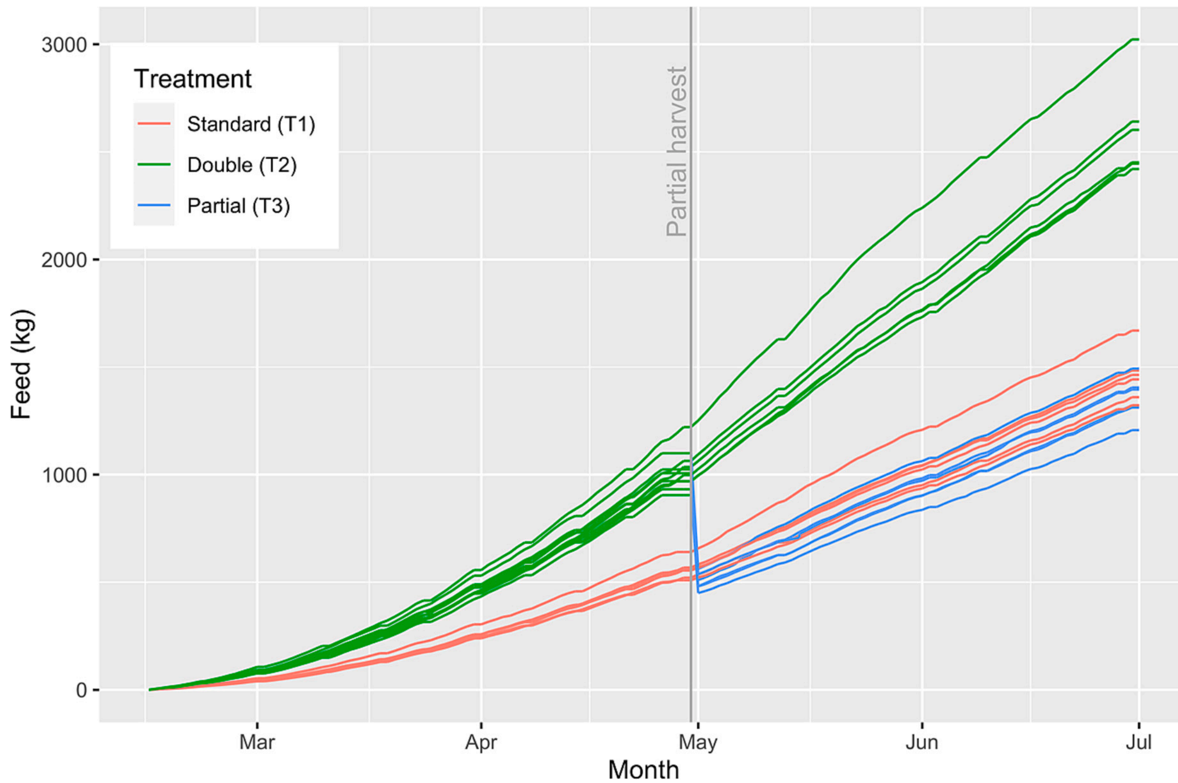

Fig. 5. Time series of amount of feed (kg) for each cage in all three treatments. The grey vertical line reflects the partial harvest event after 76 days of culture.

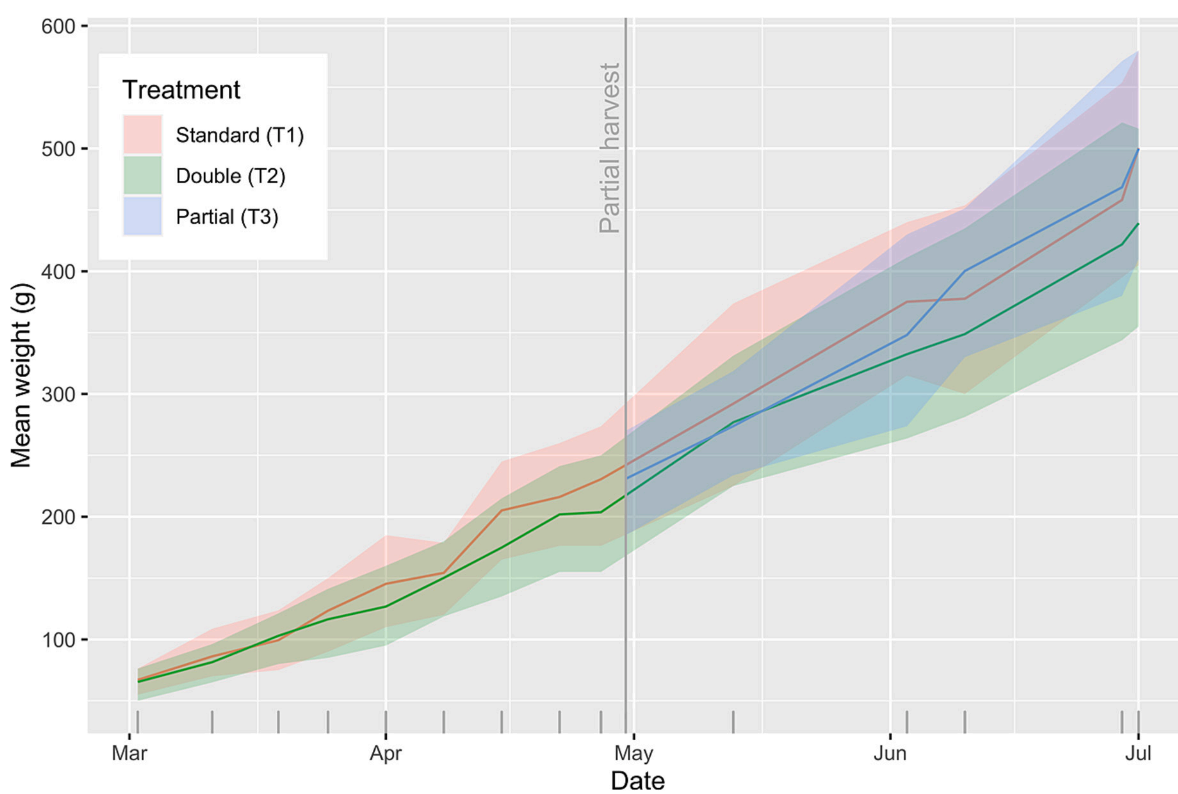

Fig. 6. The mean weight of fish (n = 30) fish per cage averaged for three cages from each treatment in sampling groups A or B (shown as grey ticks on the x-axis). The shaded area reflects the interquartile range of the fish weight samples. The grey vertical line reflects the partial harvest event after 76 days of culture.

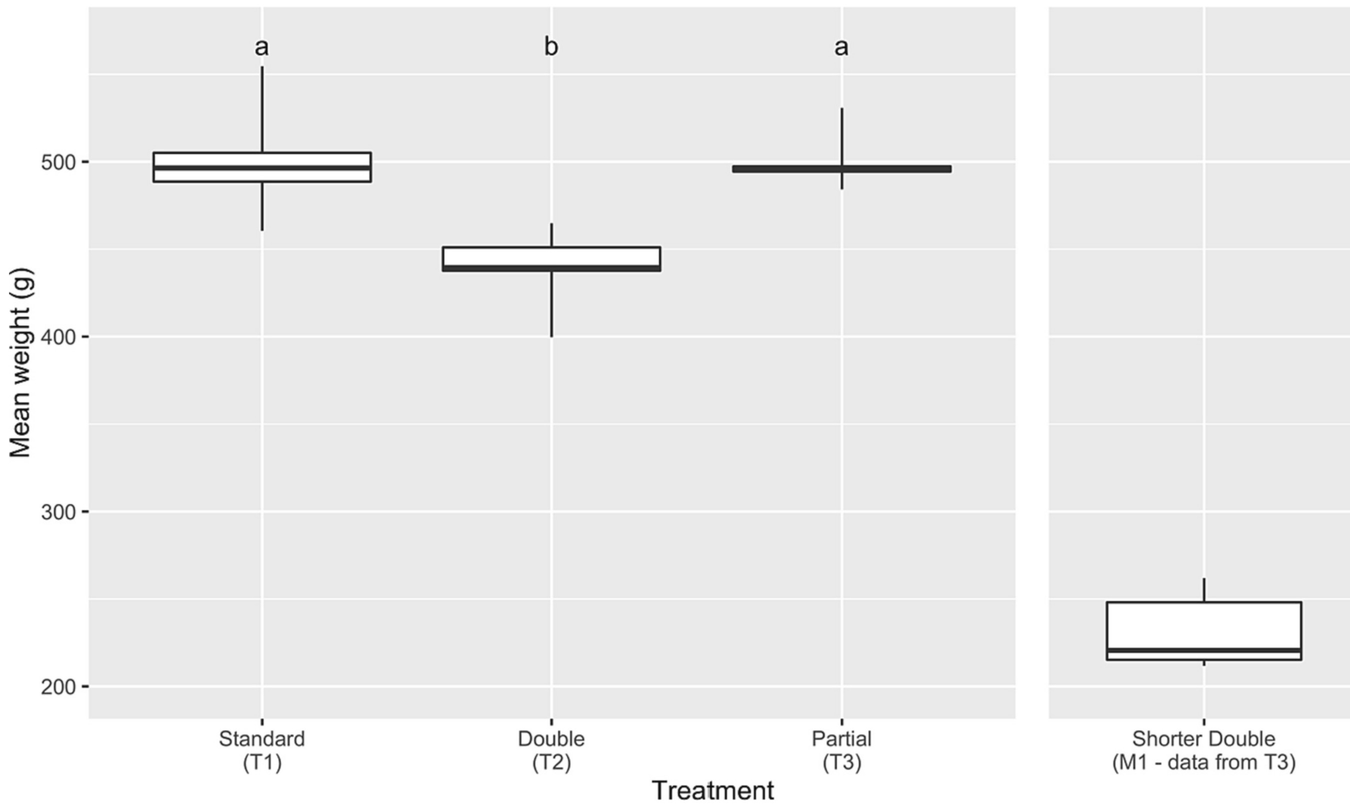

Fig. 7. Boxplot of variation of average body weight (ABW). Each box created from 6 replicate cages, showing median (solid line), interquartile range (box) and full range (whiskers). Left panel shows ABW by the end of the trial while the right panel shows ABW of M1 at final harvest after 76 days. Differences calculated with ANOVA and Tukey test and statistical significance ($p < 0.05$) denoted with different letters (a, b, or c). ANOVA did not include the M1-Shorter-Double scenario.

size category. Most of the fish in M1-Shorter-Double were in Grade 2: 200 g – 299 g.

3.4. Financial model

The final production and financial results are summarised in Table 3. The treatments had little effect on the average price of fish when using an ANOVA with post-hoc Tukey test. T1-Standard (3.0 ± 0.01 USD) and T2-Double (2.98 ± 0.01 USD) had similar overall average prices. T3-Partial (2.89 ± 0.04 USD), however, had statistically lower average price of fish compared to the other two treatments (p = 0.001), showing the effects of a partial harvest (Fig. 9). Since M1-Shorter-Double had <10% of the biomass of fish over 300 g, the average price was lower at 2.65 ± 0.1 USD.

ANOVA and post-hoc Tukey tests were used to assess whether treatments had any effect on gross margins. When factoring all the costs, including feed, labour and fingerlings, the overall gross margins were highest for T2-Double (870.66 ± 196.12 USD), more than double the other two treatments. The T3-Partial (274.61 ± 104.98 USD) and T1-Standard (375.61 ± 96.22 USD) cages had no significant difference in gross margins despite the former treatment stocking double the number of fish and removing half the population midway through the cycle (Fig. 10). The labour and fingerling costs for double stocked treatments were higher and this lowered the gross margin to below the break-even point for M1-Shorter-Double (−11.8% ± 5.52). The T2-Double cages meanwhile had the best overall gross margin as a proportion of revenue (17% ± 2.1), significantly higher to T1-Standard (13.0% ± 2.3, p = 0.0214). T3-Partial had the lowest gross margin of the three treatments (7.2% ± 2.4), which was significantly lower than T2-Double (p = 0.001), and significantly lower than T1-Standard (p = 0.001). The costs of feed, labour, and fingerlings will vary between different operations, which is why we present the gross margins with and without fingerling and labour costs (Fig. 10). When these costs were not included, the latter M1-Shorter-Double model had the best overall gross margin with 59.9% ± 1.6, while the other three treatments were similar, with around 56.7% ± 0.5 for T1, 56.5% ± 0.5 for T2 and 57.5% ± 0.5 for T3.

4. Discussion

Increasing stocking density and shortening the production cycle had few effects on biological indicators. The effects on financial indicators are more complex and require contextualisation to the Kenyan aquaculture sector. In general, the results of the trial suggest that purposively growing small tilapia over a shorter growing cycle is technically and financially feasible albeit with lower gross margins compared to growing larger fish. The costs used in the assessment, however, are highly variable and context-dependent, as are the situations of a vast array of different SME farmers. The overall efficiency and profitability will depend greatly on a cage operator's target market and ability to source fingerlings at a reasonable price. The objectives of each farmer vary (e.g., higher margins or faster cash flows), and some manoeuvrability in production systems is needed.

4.1. Production potential of growing small tilapia

Increasing stocking density and introducing a partial harvest had no effect on fish survival. The maximum stocking density (kg m^{-3}) for all cages by the end of the trial remained relatively unchanged given the low mortalities. Higher survivals in this trial compared to the Kenyan norm was likely supported by larger stocked fingerlings (30-40 g) (Gibtan et al., 2008). Cage operators that stock smaller fish, around 10-20 g, may experience higher mortalities (Ofori et al., 2009). The stocking rate in terms of number of fish per cage used in this study were specific to small-scale cages used in Kenya (Orina et al., 2018). The

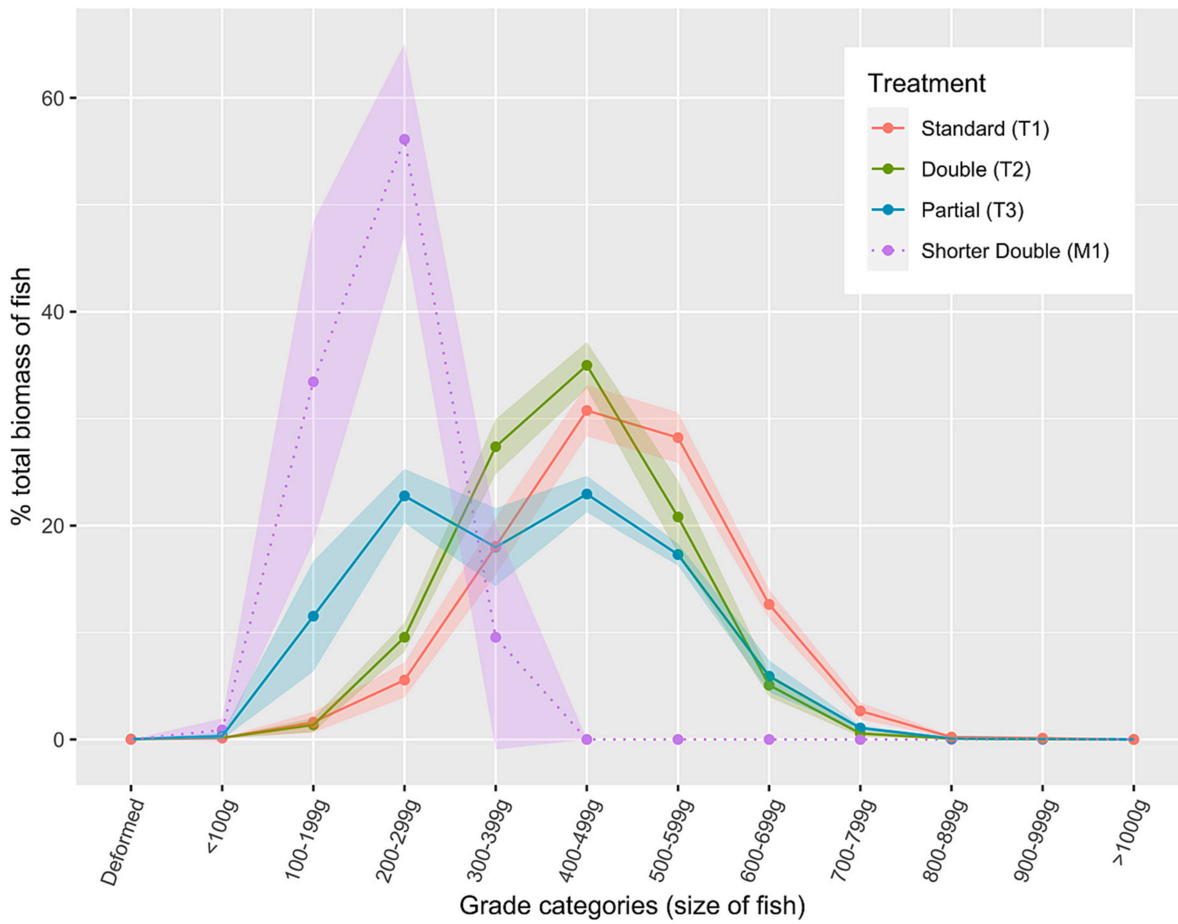

Fig. 8. Size grades of fish from the different treatments. The average proportion (%) of the final biomass of fish (after processing) in each size grade and averaged by treatment. The shaded area reflects the standard deviation from the mean. The results for Partial (T3) includes biomass of both partial harvest and final harvest.

growth differences between stocking densities in the first phase of the trial (i.e., before the partial harvest) were marginal. The low stocking density cages resulted in roughly 7% higher ABW around midway through the cycle compared to high stocking density cages, and this increased to a 14% difference by the end of the trial. The mean FCR after 76 days in a double stocked cage was lower than after 138 days, meaning that growing small fish was more economical in terms of feed efficiency in the first weeks of production. Thereafter, the costs of production rose quickly, which reduced economic returns. Shortening the production cycle suggests that farmers could produce fish to an average weight of between 200 and 230 g in half the time it would take to produce fish to an average of around 500 g.

The higher stocking density made no statistical difference to the FCR at full growth, suggesting that increasing the biomass of fish in small cages is more efficient and should be encouraged. The effect that higher stocking densities may have on water quality, potential disease outbreaks and discharge, however, should be carefully monitored (Aura et al., 2017; Njiru et al., 2018). This study did not assess the effects of increasing stocking density on environmental parameters. The negative effects of cage culture on water quality in Lake Victoria has been previously documented (Musa et al., 2022; Kashindye et al., 2015).

Our study suggests that introducing partial harvests can be an effective strategy for farmers looking to maximise the output of two distinct size grades of fish for the market, namely between 200 and 300 g as well as between 400 and 500 g. This gives the producer advantages in cash flow as well as producing and selling fish twice, rather than once in a cycle.

Interestingly, the fish that remained in the cages after the partial harvest reached a final ABW almost equal to cages with initial lower stocking densities. The partial harvest may have disrupted the dominance hierarchy of the cage, therefore improving access to feed, providing a growth rebound for subordinates and increasing feed efficiency (Azaza et al., 2010). This may explain why the FCR of the partially harvested cages were better than both the standard and double stocked cages at final harvest. Studies suggest that partial harvesting can increase productivity of tilapia systems as they decrease competition and increase individual growth rates and total yields (Brummett, 2002). Partial harvesting can be more beneficial than single-batch harvesting or gradual thinning strategies, though there is a limit to the frequency of discrete harvests in a grow-out cycle, as they can disrupt feeding, increase stress, and thus reduce efficiency (Yu and Leung, 2006). Partial harvesting is common in small-scale aquaculture in sub-Saharan Africa and should be promoted if it helps with cash flow, income generation or increasing food and nutrition security (Kaminski et al., 2022).

4.2. *Economic potential of growing small tilapia*

Increasing stocking density, according to our results, provided the best financial returns for farmers, if fish were cultivated to a full growth cycle. The financial returns diminished significantly when the partial harvest was introduced or if a production cycle was cut short. The reason for this is mainly because of the cost of fingerlings. Any future cage operators looking to adopt such techniques would need to assess the cost and availability of fingerlings as well as their target market. In the wider Kenyan sector, the marketing objectives and associated costs vary widely across cage operators (Musa et al., 2021).

Kenyan fish producers are driven by local consumer preferences for whole fish rather than fillets, and thus lack the incentive to maximise

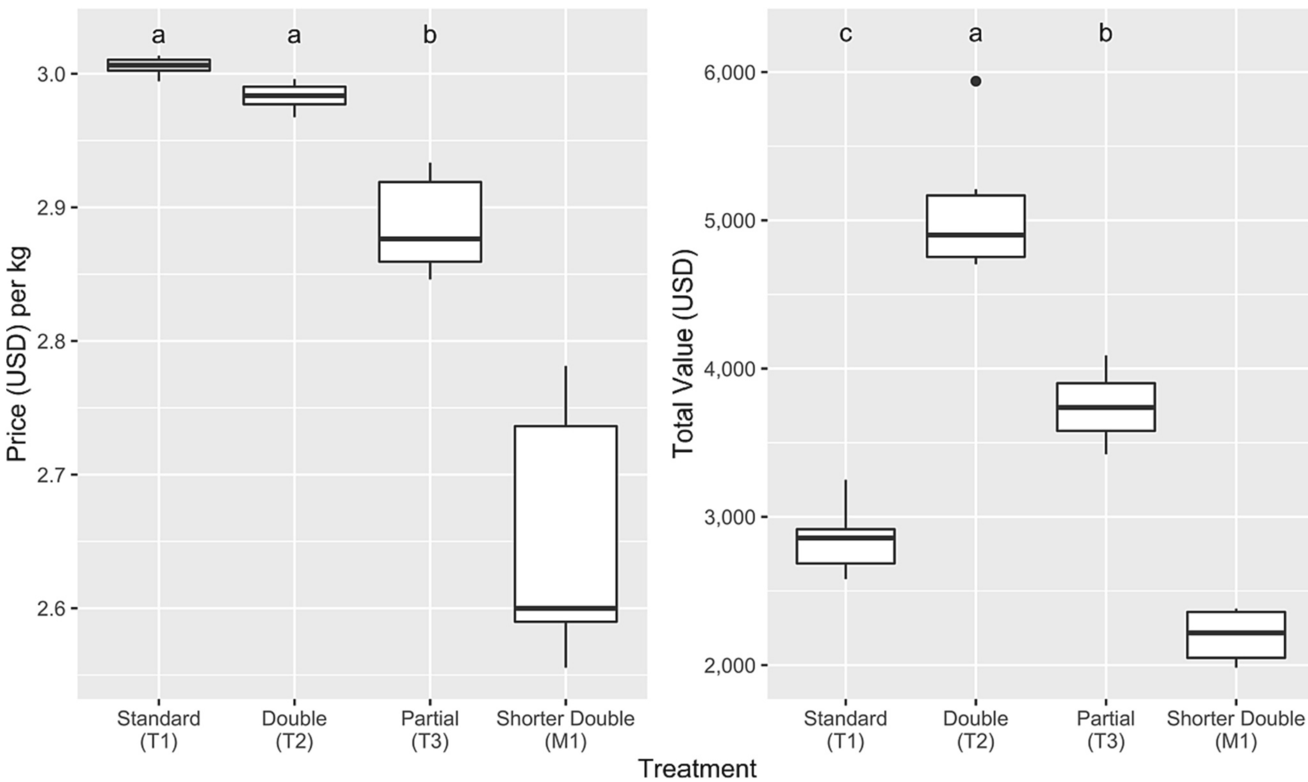

Fig. 9. Boxplot of variation of USD price per kg price (left panel) and total USD value (right panel). Each box created from 6 replicate cages, showing median (solid line), interquartile range (box) and full range (whiskers). Differences calculated with ANOVA and Tukey test and statistical significance ($p < 0.05$) denoted with different letters (a, b, or c). ANOVA did not include the M1-Shorter-Double scenario.

fillet yield through large fish production. In certain contexts, consumers in Kenya also prefer or are limited to small, more affordable tilapia, since prices are dictated on a per kilogram basis and smaller fish are cheaper than larger fish (per kilogram). Should this market exist in rural areas and peri-urban centres away from the capital and closer to producers, a significant opportunity emerges to save on transport and cold storage costs too (Musa et al., 2021). Opportunities for marketing small tilapia to urban centres are feasible, as poorer people in urban areas gradually start purchasing more foods from supermarkets (Neven et al., 2006). A majority of the urban population reside in informal settlements and can only afford small-sized fish (Soma et al., 2021). These conditions present opportunities for SME Kenyan producers.

The ability for producers to make quicker albeit lower returns in shorter time periods when growing smaller fish means that cash flow is more manageable, especially if farmers are buying feed and seed on credit. Cash flow is most challenging towards the end of the cycle when large fish exponentially increase operational feed costs – coupled with poor access to investment, the economic feasibility of cage farming for SME farmers may be limited by the long production period until sales produce a cash influx. A mid-cycle cash influx would support the higher costs of feeding larger fish. While profit may be maximised with the production of larger fish, this may not be feasible for farmers faced with cash flow challenges. This is important when considering that some producers may be operating in economic conditions characterised by volatile exchange and interest rates and where environmental conditions may provide additional uncertainties and challenges. Despite the slightly lower gross margins on smaller fish in our trial, the ability to harvest sooner may be more beneficial for lower-income farmers or new entrants into the sector. Farmers may need to find trade-offs in faster cash flows versus higher margins.

This study did not attempt to include other costs such as fuel, energy, transport, depreciation, etc. Only the costs of feed, seed and labour were introduced in the financial model, since they generally make up the bulk of costs for farming operations in Kenya (Omasaki et al., 2016; Obiero et al., 2022). The main factors affecting the differences in gross margins in our study was the cost of fingerlings. The fingerling costs need to be contextualised as they vastly vary in the region, and they should not be seen as a definitive reason why growing smaller fish resulted in lower gross margins in our model. Naturally, doubling the stocking density required doubling the number and cost of fingerlings. Introducing two shorter cycles in the time it took to grow larger, table-sized fish further doubled the fingerling cost. Since breeding and nursing of fingerlings are still major challenges in Kenya, which affects total seed supply in the region, and since SME farmers do not usually operate their own hatcheries, this presents an obstacle for the adoption of the approaches tested in this study, and for the development of the SME sector, in general (Nyonje et al., 2018). We present both the results with and without fingerling costs for this reason, as famers will have to experiment with stocking density, size of fingerlings, and days of culture that suit their needs best. Other ways of reducing fingerling costs could include forgoing costly sex reversal hormones and stocking mixed-sex fingerlings (Bostock et al., 2022). Should farmers establish economies of scale where seed and feed inputs are spread over more units of production, the returns may increase significantly. Market analyses may reveal that smaller fish are consumed in rural areas closer to site of production and thus may not incur the high costs needed to transport larger fish to urban markets.

4.3. *Opportunities for cage-culture operators in Kenya and beyond*

The approach presented in this study may be limited to the Kenyan part of Lake Victoria, though similar approaches could be trialled in other water bodies in Africa. Studies show that most SME cage farmers in the Lake Victoria region operated 2 m × 2 m × 2 m cages (Orina et al., 2018). Stocking densities of these cages ranged from around 150–500 fish per m^3. Small-scale cages experienced mortality upwards of 20%

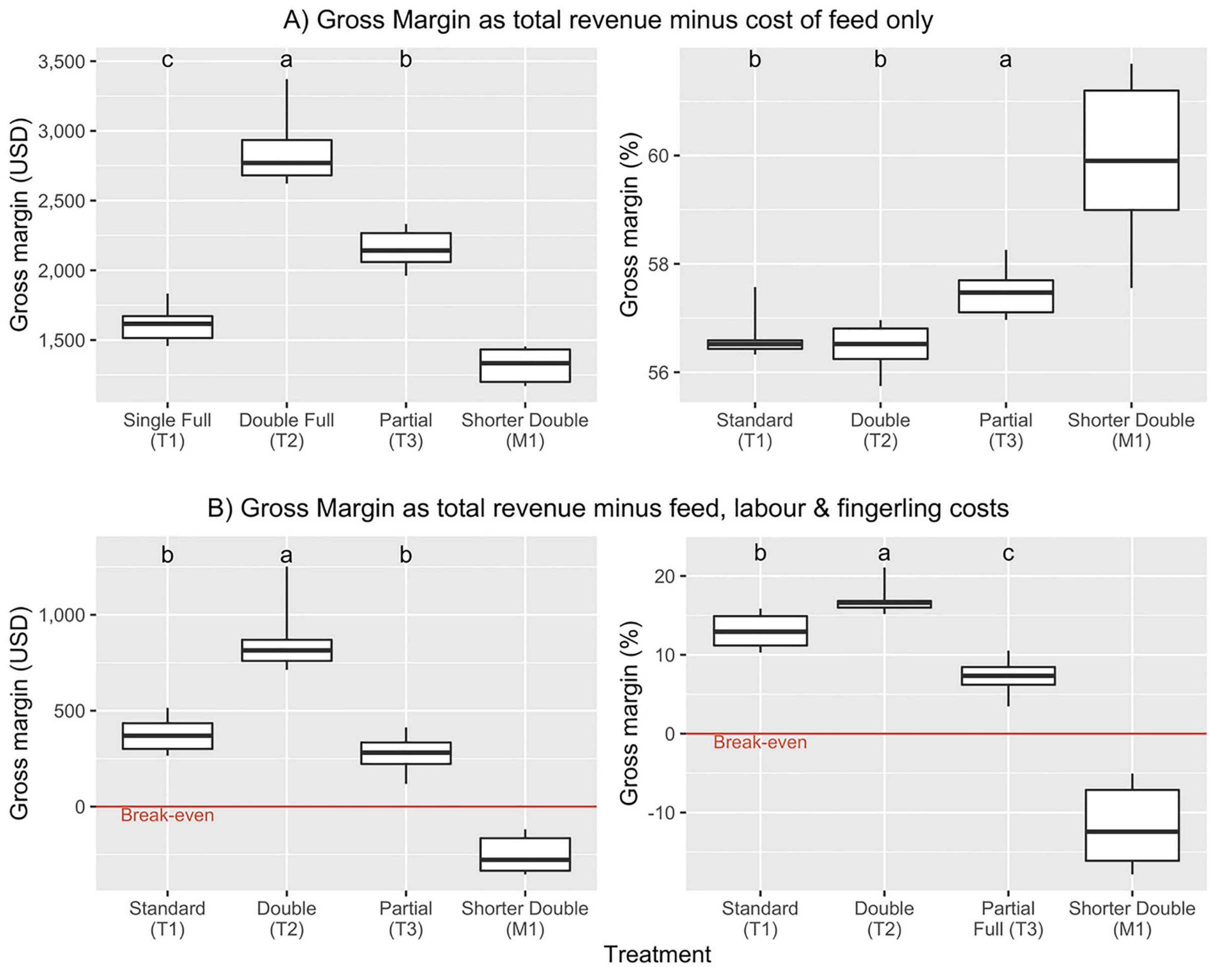

Fig. 10. Boxplot of variation of gross margin as total USD value and percentage of total revenue. Each box created from 6 replicate cages, showing median (solid line), interquartile range (box) and full range (whiskers). The top two panels (A) include calculation with feed costs only, while the bottom two panels (B) include sum of feed costs, labour, and fingerlings. Differences calculated with ANOVA and Tukey test and statistical significance ($p < 0.05$) denoted with different letters (a, b, or c). ANOVA did not include the M1-Shorter-Double scenario.

signifying that these farmers likely stocked smaller-sized fish (Ibid.). The Kenya aquaculture industry may benefit from a more robust nursing value-chain node, as shown in Ghana where the development of nursing cage operations resulted in decreased mortality of tilapia in grow-out cages (Asase et al., 2016).

The trial in this study took place at a large, commercial cage farm, albeit in cages that would be classified as small-scale. The production interventions explored in this study are not limited to the small-scale sector and larger cage farmers can attempt to grow small fish in addition to large fish. Some farmers could opt to only grow small fish in shorter cycles although stocking densities and costs would need to be reconfigured to extract the best economic returns. Victory Farms Ltd. sell their fish to traders and retail outlets all over Kenya but predominately in the capital city, Nairobi. While the company manages to sell fish to different market segments, the smaller-sized tilapia makes up a significantly lower proportion of total yield. This could mean that the poorest segments of the market rarely purchase farmed tilapia and are still relying on wild-caught fish. A significant market niche thus emerges and should be explored further.

Targeting lower-income consumers with small fish would mark a significant shift for aquaculture in the region by accommodating the bottom-of-the-economic-pyramid (Kaminski et al., 2020). Furthermore, when eating smaller fish, generally more of the fish is consumed compared to fillets consumed on larger fish, which may result in better health and nutrition outcomes as people consume parts that are richer in micronutrients. Globally, small fish plays a crucial role in impoverished people's diets (Kawarazuka and Béné, 2011). The production methods presented in this study can be described as a nutrition-sensitive approach to aquaculture as it actively seeks to accommodate and maximise the nutrient requirements of the most vulnerable people in society. It allows those who were previously disadvantaged more opportunities to access the value chain and increase their intake of a valuable animal-source protein (Hotz et al., 2015).

5. Conclusion

The study tested the technical and financial feasibility of purposively growing small tilapia. The production strategy included increasing stocking density and shortening the growth cycle. The results show that there were no significant effects on fish survival, while increasing stocking density resulted in slower individual growth. Using partial harvesting as a production strategy together with higher stocking densities significantly improved FCR and had no effect on growth. Increasing stocking density had no effect on average price of fish at final harvest while partial harvesting provided an opportunity to grow and sell small and large fish at notably different price points. The gross margins were relatively similar among treatments, though once the cost of seed was introduced, increasing stocking density and shortening the production cycle lowered gross margins, significantly. Farmers could experiment with different stocking densities and harvesting strategies to try and increase their margins. The economic outcomes will depend on the market demand for small fish as well as the accessibility of seed. The approaches introduced in this study offer alternative methods to grow and sell tilapia challenging the notion that "larger is always better for all producers". More research is required to contextualise such approaches in different production systems, markets and seed/feed value chains. It is important to find ways to make aquaculture value chains more inclusive of lower-income enterprises and consumers. Adopting approaches that move away from maximising the growth of single species opens the doors for innovation in aquaculture, which is perhaps more adaptable to aquaculture in the African context.

Ethical approval

The trial was approved by the University of Stirling Animal Welfare Ethical Review Body (AWERB), No: 2021 3511 3034.

CRediT authorship contribution statement

Alexander M. Kaminski: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Alexandra M. Pounds:** Data curation, Methodology, Resources, Writing – review & editing. **Bruce McAdam:** Formal analysis, Software, Visualization, Writing – review & editing. **John Bostock:** Validation, Writing – review & editing. **Mary A. Opiyo:** Validation, Writing – review & editing. **David C. Little:** Conceptualization, Resources, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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.

Data availability

The data that has been used is confidential.

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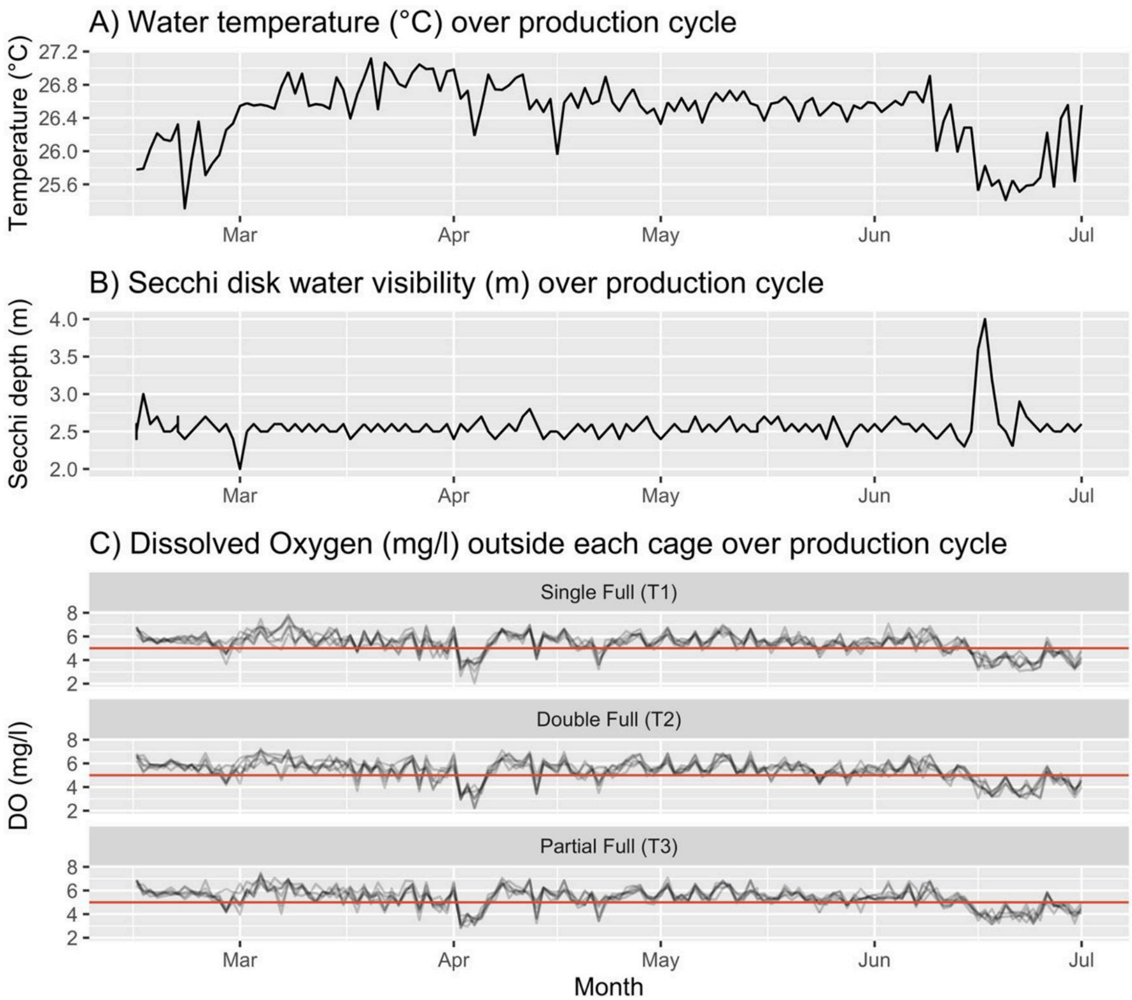
Appendices



Appendix A. Water parameters including A) water temperature (°C); B) Secchi disk water visibility (m); and C) Dissolved Oxygen (DO) (mg/l), as an average of each cage over the whole production cycle. Red line depicts optimal DO level of 5 mg/l.

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