Food and Agriculture Organization of the United Nations

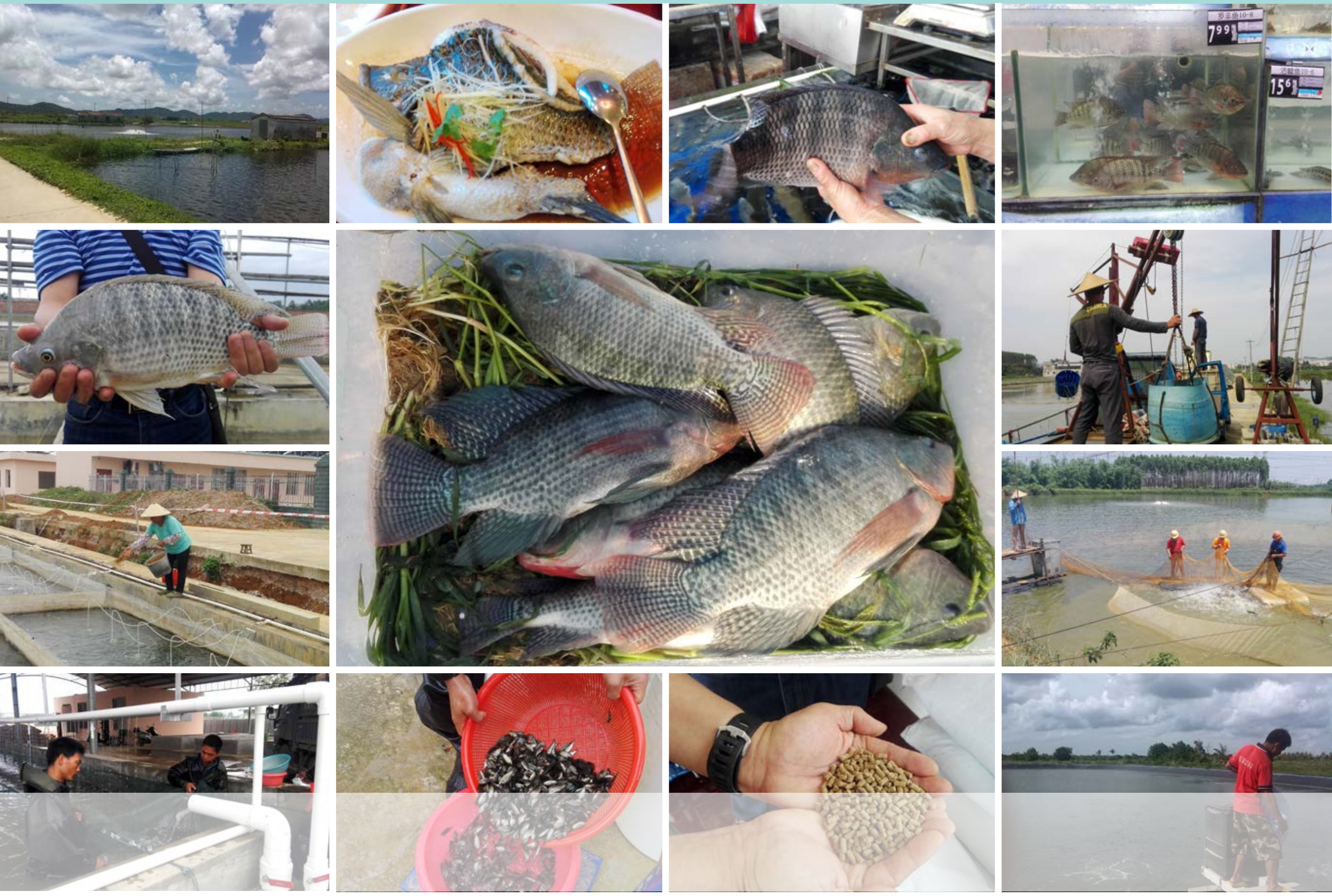
FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER

ISSN 2070-7010

608

Improving the performance of tilapia farming under climate variation

Perspective from bioeconomic modelling



***Cover photographs (farmed tilapia value chain in China; courtesy of Junning Cai)*:**

Large photo (middle):
700 g tilapia just harvested

Small photos (counter clockwise from top-left corner):
Tilapia ponds
Tilapia broodstock
Nursing tilapia fry
Sorting tilapia fingerlings for sale
Weighing tilapia fingerlings
Tilapia feed
Loading tilapia feed in an automatic feeding machine
Harvesting tilapia from a pond
Weighing and loading harvested tilapia in a truck for transportation
Live tilapia sold in a supermarket
Live tilapia sold in a seafood market
Steamed tilapia served in a seafood restaurant

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2018

ISBN 978-92-5-130162-3

Preparation of this document

A bioeconomic model has been developed by the Food and Agriculture Organization of the United Nations (FAO) based on experiences in China to show how optimal arrangements of farming operations can improve the technical and economic performance of tilapia pond aquaculture. This paper presents the methodology and results of the model. The results reveal the mechanisms and extent by which aquaculture performance can be improved through optimal farming arrangements. The methodology provides technical guidance on bioeconomic modelling in tilapia pond culture and aquaculture in general. Junning Cai, PingSun Leung, Yongju Luo, Xinhua Yuan and Yongming Yuan are acknowledged for their contribution to the development of the model and preparation of this document. Qian Chen, Zhongqiang Liu, Xiangjun Miao, Yannan Tong, Deqiang Wang, Maoyuan Wang, Jun Yang, Wei Ye, Lei Zhao, Quanfu Zhong are acknowledged for facilitating surveys of tilapia farming in China. José Aguilar-Manjarrez, Uwe Barg, Malcolm Beveridge, Qian Chen, Marc Fantinet, Emmanuel Frimpong, Mohammad Hasan, Elisabetta Martone, Francisco Javier Martínez-Cordero, Felix Marttin, Carlos Pulgarin, Melba Reantaso, Susana Siar, Weiwei Wang and Zongli Zhang are acknowledged for their valuable comments and suggestions provided in seminars or through the formal review of the paper. Danielle Rizcallah, Maria Giannini and Marianne Guyonnet are acknowledged for their assistance in editing and formatting, and José Luis Castilla Civit is acknowledged for layout and graphic design.

Abstract

Tilapia is the world's most popular aquaculture species, farmed mostly in earthen ponds. Experience in China, the largest tilapia farming country, is used to develop and calibrate a bioeconomic model of intensive tilapia pond culture. The model is used to simulate the impacts of climate, technical and/or economic factors on farming performance and examines the performance of various farming arrangements under different conditions. The simulation results indicate that: (i) an increase in feed price, an increase in mortality, or a decrease in fish price significantly reduces profitability, whereas an increase in the cost of seed, labour, rent, electricity or water management has smaller impacts on profitability; (ii) considering the impact of water temperature on fish growth, the profitability of a production cycle starting at the optimum timing may be twice as high as one starting at the worst possible time; (iii) farming arrangements that maximize the profit of individual fish crops may not maximize overall profitability because of path dependency of farming performance; (iv) optimal farming arrangements that maximize overall profitability can significantly improve economic performance; (v) given no price discrepancy against small-size fish, harvesting at about 300 g in two-year-five-crop arrangements could increase overall enterprise profitability by up to 50 percent compared with harvesting at > 500 g in one-year-two-crop arrangements; and (vi) a two-tier farming system that separates nursing and outgrowing ponds could allow one-year-three-crop arrangements that enhance profitability by up to nearly 90 percent compared with the one-year-two-crop arrangements. With more refined information on fish growth under different farming conditions, the model could become a decision-making tool to help farmers design optimal farming arrangements.

Cai, J.N., Leung, P.S., Luo, Y.J., Yuan, X.H. & Yuan, Y.M. 2018.
Improving the performance of tilapia farming under climate variation: perspective from bioeconomic modelling. FAO Fisheries and Aquaculture Technical Paper No. 608. Rome, FAO.

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Abbreviations and acronyms

CNY	Chinese Yuan
CP	crude protein
FCR	feed conversion ratio
GIFT	genetically improved farmed tilapia
WG	weight gain

1. Introduction

Aquaculture is a complicated business, both technically and economically. The performance of an aquaculture operation is affected by a variety of environmental, technical and economic factors, such as climate, infrastructure, water quality, soil quality, seed quality, fish growth, feed quality, feed conversion ratio (FCR), disease, infrastructure, feed price, seed price, labour cost, other input prices, fish price and regulations. Farmers may not have much control over factors such as climate, infrastructure, market conditions and regulations, yet they can improve farming performance through good aquaculture practices and better business and operational planning. In a nutshell, business and operational planning in aquaculture is about selecting appropriate farming practices and arrangements to achieve business and operational goals (e.g. profit maximization). In this technical paper, a bioeconomic model is developed based on experiences in China to facilitate business and operational planning for improving the technical and economic performance in tilapia pond culture.

Tilapia is one of the most popular aquaculture species and is farmed in more than 120 countries and territories. However, global tilapia aquaculture production is highly imbalanced, with the top ten countries in 2015 accounting for over 90 percent of the 5.7 million tonnes of global production. China is the largest tilapia farming country, and in 2015 its share in the global production of tilapia was over 30 percent. There is a huge untapped potential in tilapia farming in other regions of the world, such as in sub-Saharan Africa where tilapia are native species and favoured by local consumers. Low productivity, however, is a key factor that affects the performance of tilapia farming in many countries. While it is common for a tilapia farmer in China to harvest 15 tonnes/ha per crop through intensive pond culture, the yield of pond tilapia culture in Africa is often less than 5 tonnes/ha per crop (FAO, 2017). Even tilapia farmers in China face constant pressure to improve productivity in order to offset the impacts of higher input costs, for example, land rental, feed and labour.

While advancement in technology, seed quality, feed quality and husbandry are key drivers for improving the performance of aquaculture, better business and operational planning is equally important. Planning an aquaculture operation involves arrangements of stocking timing, fingerling size, feeding regime, fertilizing scheme, water quality management, fish health management, growing period (or crop length),[1] harvest timing, harvest size, among others. Fish farmers usually plan their operations based on common practices, experiences and/or expert advice. Farmers continually accumulate experiences in good farming practices and arrangements through trial and error, learning by practicing, and knowledge-sharing among peers. Through research and experiments, the research community generates information and knowledge to provide guidance on (optimal) arrangements of stocking density (Kazmierczak and Caffey, 1996; Liu and Chang, 1992); feeding regime (Esmaeili, 2005; Arnason, 1992); fertilization (Stickney *et al.*, 1979); growing period or harvest timing or harvest size (Zuniga-Jara and Goycolea-Homann, 2014; Domínguez-May *et al.*, 2011; Seginer and Ben-Asher, 2011; Yu and Leung, 2009; Yu, Leung and Bienfang, 2006; Yu and

[1] Crop length is equal to the growing period plus time used for pond preparation after harvest. In the bioeconomic models here, the time for pond preparation is treated as an exogenous constant (i.e. two weeks); thus, selections of growing period and crop length are equivalent. The two terms are therefore used interchangeably in some places. Growing period is used when the time span between stocking and harvest needs to be specified, whereas crop length is used to calculate performance indicators such as profit per week or production per week.

Leung, 2005; Leung, Shang and Tian, 1994; Springborn *et al*., 1992; Arnason, 1992; Leung *et al*., 1989; Bjørndal 1988); and business management (Engle and Neira, 2005; Sanchez-Zazueta, Martinez-Cordero and Hernández, 2013), among others.

Bioeconomic models on tilapia farming in the literature are often built on an explicit, continuous fish growth function (Zuniga-Jara and Goycolea-Homann, 2014; Domínguez-May *et al*., 2011). Optimal farming arrangements in such models can be solved through mathematical derivations. However, the model setups and mathematical derivations are usually too complicated for farmers or extension personnel to decipher, which makes the results difficult to understand.

The bioeconomic model in this paper is a discrete, daily model calibrated from fish growth patterns under a certain feeding regime. The model set-up is in line with the financial analysis commonly used in business and investment planning. A large number of arrangements are simulated in the model, and the arrangements that give the best performance are identified by comparisons. This brute force method is less elegant than solving the optimal arrangements through mathematical derivations, and in some occasions possible arrangements are too many to be simulated comprehensively. But the method makes it easy to compare optimal arrangements with suboptimal alternatives so that the results can be better understood.

In the next section, a basic version of the bioeconomic model is presented. Water temperature, fingerling size and stocking density are fixed in the basic model to facilitate the examination of an optimal growing period that maximizes the profit in a single crop. The result indicates that when stocking 1 g of genetically improved farmed tilapia (GIFT) fingerlings at 1 200 fish/mu under constant water temperature at 28 °C,[2] the optimal arrangement is to harvest 707 g fish after 21 weeks of the growing period.[3] The model is used to illustrate how technical and economic factors affect farming performance and to demonstrate that arrangements that maximize productivity may not be profit maximizing.

The model is also used to examine the impacts of technical or economic factors (fish price, input prices and mortality) on profitability and optimal growing period. The results indicate that a change in fish price, feed price or mortality tends to have a relatively large impact on profitability, whereas a change in the price of fingerlings or other inputs tends to have a relatively small impact. While a decrease in fish price, an increase in feed price or an increase in mortality would tend to shorten the optimal growing period and reduce the harvest size, an increase in the price of fingerlings or other inputs would tend to increase the optimal growing period and harvest size. The cost structure of the operation is examined to facilitate the understanding of the rationales behind these results.

In section 3, the basic model is upgraded into an advanced model where the impacts of stocking density and the water temperature on fish growth are captured. In the model, the farmer adopts a feeding regime recommended by experts and maintains proper husbandry, which is reflected in various cost items, such as the cost for water quality management and the energy cost for aeration. The advanced model sets an upper bound for fish biomass in the pond – the fish need to be harvested before the upper bound is exceeded. This feature ensures that the farming operation is conducted conservatively within the carrying capacity of the pond environment.

In the basic model where the water temperature is constant, stocking timing is irrelevant because every crop arrangement can repeat itself over time. In the advanced model where there is seasonal variation in the water temperature, the profit-maximizing crop arrangement varies for different stocking timings because crops starting at

[2] 1 ha = 15 mu (Chinese unit of land measurement); 1 mu ≈ 667 m^2.

[3] Although tilapia farmers in China use a variety of GIFT strains (*Oreochromis niloticus*) developed by different research institutes or hatcheries, they generally call them GIFT fry or fingerlings without distinguishing the specific strain.

different timings would be subject to different water temperature patterns and hence would have different fish growth patterns. Indeed, the simulation results indicate that the crop subject to the most favourable water temperature pattern could be more than twice profitable than the one subject to the less suitable water temperature pattern.

The advanced model is used to examine the impact of stocking density on profitability. The simulation results indicate that while an increase in stocking density would slow down fish growth, productivity could nevertheless be increased because more fish are stocked. However, the productivity increase may not result in higher profitability, especially when the slower growth makes the fish unable to reach a desirable size before the upper bound of fish biomass is reached. Another important finding is that the impact of stocking density on profitability is affected by the water temperature. For example, stocking 1 800 fish/mu tends to be more profitable than 1 500 fish/mu in the warm season, yet less profitable in the cold season.

In section 4, the advanced model is used to examine the performance of multiple-crop arrangements. With seasonal variation in the water temperature, the crop that gives the highest profitability because of conducive water temperature cannot repeat over time. Indeed, the simulation results show that the overall profitability of a 1-year-2-crop arrangement where one crop takes advantage of favourable weather conditions and leaves the other crop with less suitable conditions tends to be less profitable than other arrangements that have favourable weather shared by both crops. An intriguing finding is that, because of the path dependency of profitability, a 1-year-2-crop arrangement where the profit is maximized in both crops given their respective stocking timings may nevertheless not maximize the overall profitability.

The advanced model is used to examine the conjecture that harvesting small-size fish could be more profitable. The results indicate that with the price discrepancy between small- and large-size tilapia observed in the Chinese market, harvesting small-size tilapia would not be more profitable. If there is no price discrepancy, farming small-size tilapia could be more profitable through higher productivity. However, higher productivity per se does not guarantee higher profitability – in a 1-year-2-crop arrangement, increasing the stocking density and reducing the harvest size could increase productivity yet reduce profitability. Harvesting small-size tilapia in 2-year-5-crop (average 1-year-2.5-crop) arrangements through higher stocking density and a shorter growing period would tend to be more profitable than harvesting large-size tilapia in 1-year-2-crop arrangements.

The advanced model is used to examine the profitability of a two-tier system that uses nursing ponds to grow small fingerlings into large-size juveniles before stocking them in outgrowing ponds. The simulation results show that the two-tier system could allow 1-year-3-crop arrangements, the profitability of which could be nearly 70 percent higher than a 1-year-2 crop arrangement.

In the final section of this paper, the key results of the model are discussed, the limitations and potential of the model are highlighted, and some suggestions on the way forward are presented.

2. A basic bioeconomic model on tilapia pond culture

A basic bioeconomic model on tilapia pond culture is developed based on the experiences in China. The basic model is used to examine the impacts of various factors (fish price, feed price, seed price, wage and mortality) on the technical and economic performance of tilapia farming under specific farming conditions (e.g. constant water temperature) and practices (e.g. common selections of fingerling size, stocking density and feeding regime). In the next section, the basic model will be extended into an advanced model to simulate the impacts of farming conditions or practices on the technical and economic performance of tilapia pond culture and determine optimal farming arrangements and practices.

2.1 BIOLOGICAL COMPONENT OF THE BASIC MODEL

When building a bioeconomic model on tilapia pond culture or fish farming in general, a key yet challenging task is to calibrate fish growth patterns under different conditions or practices. There is research in the literature that estimates tilapia growth functions based on experimental data (Tang *et al*., 2011; Santos, Mareco and Silva, 2013). Such research usually simulates fish growth over time, but does not provide comprehensive, detailed data on the technical parameters (farming system, water temperature, fingerling type and size, stocking density, feeding regime, etc.) behind the estimated growth functions; therefore, it is difficult to use the data to calibrate a bioeconomic model for simulation. The applicability of tilapia growth patterns observed in experiments is another issue. For example, tilapia growth functions estimated from data generated by experiments in indoor recirculation farming systems (Santos, Mareco and Silva, 2013) or cage systems (Tang *et al*., 2011) may not be suitable for building a bioeconomic model of pond tilapia culture.

Original data on tilapia growth

Table 1 shows a tilapia growth pattern published in a technical guidebook on tilapia farming in China, prepared by experts in the China Agriculture Research System for Tilapia (Yang, 2015, pp. 55–56). The growth pattern is calibrated from field experience, experimental data and the scientific literature and used in the guidebook as a benchmark feeding schedule.

The pattern represents a growth path of GIFT tilapia in pond aquaculture under constant water temperature at 28 °C, 1 g fingerlings, 1 200 fish/mu (i.e. 1.8 fish/m^2; 1 ha = 15 mu) stocking density, and a specific feeding scheme. With daily feeding at 10 percent of the body weight, a 1 g fingerling would grow to 5 g after week 1; with daily feeding at 5 percent of the body weight, the 5 g fingerling would grow to 8 g after week 2, and so on.

TABLE 1
GIFT tilapia growth pattern provided by the literature

I	II	III	IV
Time after stocking (week)	Original average body weight (g/fish)	Original daily feeding ration (% of body weight)	Original weekly weight gain (g/fish/week)*
0	1	10	
1	5	5	4
2	8	5	3
3	12	5	4
4	18	4	6
5	25	4	7
6	35	3	10
7	50	3	15
8	70	3	20
9	90	3	20
10	120	3	30
11	150	3	30
12	180	3	30
13	220	2	40
14	260	2	40
15	330	2	70
16	380	2	50
17	440	2	60
18	510	2	70
19	580	2	70
20	660	2	80
21	710	1	50
22	760	1	50
23	790	1	30
24	840	1	50

Source: Yang (2015) with authors' calculation.
* Calculated from column II.

Adjusted tilapia growth path

The tilapia growth pattern in Table 1 needs to be adjusted before being used to build the basic model. In order to smooth extraordinarily high or low values (e.g. in week 15 or 23), the original weekly weight gains (Table 1, column IV) are adjusted by applying a three-week moving average scheme twice; [4] the results are rounded to integers and presented in Table 2 (column II). As illustrated in Figure 1, the adjusted weekly weight gain curve is smoother than the original one, and it is consistent with the normal pattern of tilapia growth (Tang *et al*., 2011). The adjusted weekly weight gains (Table 2, column II) are used to calculate the adjusted average body weights along the growth path (Table 2, column III).

[4] For example, the moving average of weight gain in week 2 is the average of weight gains in week 1, 2 and 3; that in week 3 is the average of weight gains in week 2, 3 and 4, and so on. By "twice" it means that the smoothing scheme is applied to the moving average results once again. Because there is no weight gain in week zero, the moving average of the weight gain in week 1 is a two-week average of those in week 1 and week 2. Similarly, because there are no data on the weight gain in week 25, the moving average of the weight gain in week 24 is a two-week average of those in week 23 and 24.

TABLE 2
Tilapia growth pattern used to calibrate the basic model

I	II	III	IV	V	VI
Time after stocking (week)	Weekly weight gain (g/fish/week)[1]	Average body weight (g/fish)[2]	Daily feeding ration (% of body weight)[3]	Weekly feed use (g/fish/week)[4]	Weekly feed conversion ratio[5]
0		1	10.00		
1	4	5	5.18	0.70	0.18
2	4	9	4.84	1.81	0.45
3	5	14	4.53	3.05	0.61
4	6	20	4.24	4.44	0.74
5	8	28	3.96	5.93	0.74
6	11	39	3.71	7.77	0.71
7	15	54	3.47	10.12	0.67
8	19	73	3.24	13.10	0.69
9	23	96	3.03	16.56	0.72
10	27	123	2.83	20.37	0.75
11	30	153	2.65	24.40	0.81
12	33	186	2.48	28.39	0.86
13	40	226	2.32	32.27	0.81
14	47	273	2.17	36.67	0.78
15	54	327	2.03	41.43	0.77
16	58	385	1.90	46.41	0.80
17	62	447	1.77	51.10	0.82
18	67	514	1.66	55.48	0.83
19	69	583	1.55	59.67	0.86
20	67	650	1.45	63.29	0.94
21	57	707	1.36	65.99	1.16
22	49	756	1.27	67.13	1.37
23	42	798	1.19	67.13	1.60
24	40	838	1.11	66.26	1.66

Source: Authors' calculation based on Table 1.

[1] Derived from applying a three-year moving average to the original weekly weight gain data in Table 1, column IV twice; the results are rounded to integers.

[2] Calculated from the weekly weight gain in column II.

[3] Estimated from the original feeding scheme in Table 1, column III.

[4] Calculated from the average body weight (column III) and daily feeding ration (column IV).

[5] Calculated from the weekly feed used (column V) divided by the adjusted weekly weight gain (column II).

The original daily feeding rations (Table 1, Column III) are a benchmark feeding schedule intended to help tilapia farmers determine daily feed use based on fish body weight. A tilapia farmer in practice could use the feeding rations in the schedule as a reference and adjust the actual feed amount according to fish feeding behaviour. However, for the purpose of building the basic model, the precision of the rations needs to be increased. Therefore, an exponential trend of the original daily feeding rations is used to smooth the feeding rations and make them better reflect the negative correlation between feeding ration and body weight (Figure 2). The adjusted daily feeding rations are presented in column IV of Table 2.

The daily feeding rations (Table 2, column IV) and the average fish body weight (Table 2, column III) are used to calculate the weekly feed use (Table 2, column V). The feed use in week 1 is 0.70 g (equal to 1 g × 10 percent day^{-1} × 7 days); that in week 2 is 1.81 g (equal to 5 g × 5.18 percent day^{-1} × 7 days), and so on.

FIGURE 1
Original versus adjusted weekly weight gain

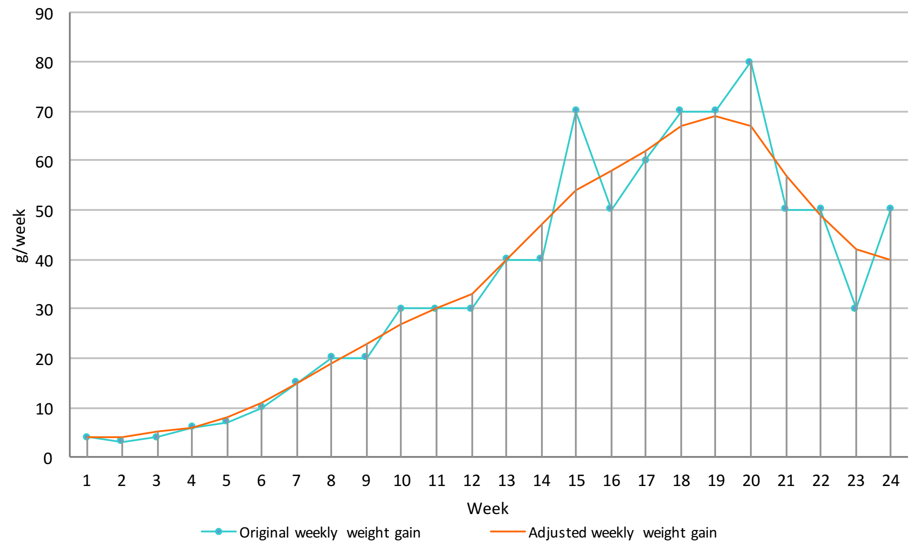
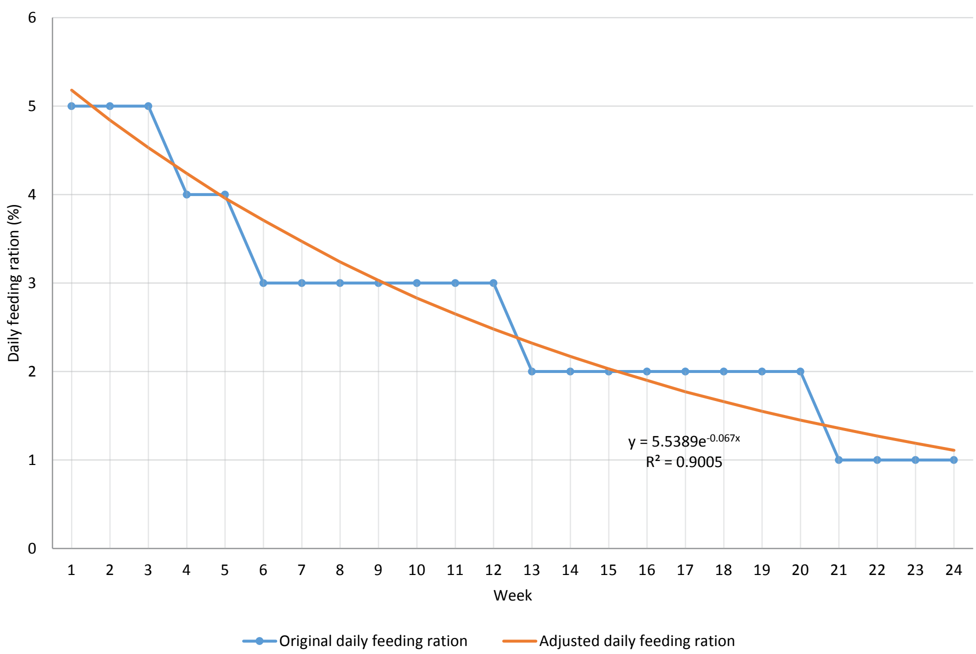
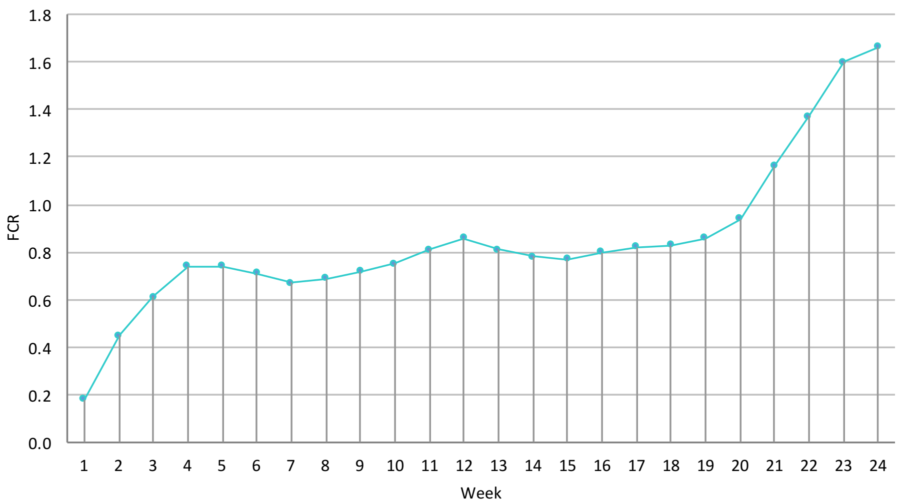


FIGURE 2
Original versus adjusted feeding ration



The weekly FCR (Table 2, column VI) is calculated by the weekly feed use (Table 2, column V) divided by the weekly weight gain (Table 2, column II). As part of the weight gain is contributed by natural food in the pond (e.g. plankton), the FCR is essentially an economic FCR that can be far below unity, especially at the early stages (Figure 3). The FCR pattern in Figure 3 is consistent with increasing FCR as fish grow bigger. The FCR trend is relatively steep at the beginning, stable in the middle and becomes steeper when fish reach a certain size. This pattern will be examined in detail later in the document.

FIGURE 3
Weekly feed conversion ratio (FCR)



2.2 TECHNICAL AND ECONOMIC PARAMETERS USED IN THE BASIC MODEL

Key technical and economic parameters used in the basic model are summarized in Table 3. These parameters are specified according primarily to field data collected by the authors during July and August of 2015 in four major tilapia farming provinces in China (Guangdong, Hainan, Guangxi and Fujian).

The model is set up in the following way; see Table 3. A tilapia farm has three ponds with 2 ha of total pond area.[5] The pond rental is CNY 30/mu per week.[6] After each harvest it takes two weeks to prepare the pond for the next crop, including such activities as strengthening the dyke, removing solid waste and unwanted organisms, and sanitization. Major pond renovation or reconstruction is needed every 20 years, which would cost CNY 5 000/mu (1 USD = CNY 6.2; 1 ha = 15 mu).

Aerators and automatic feeding machines are commonly used in intensive tilapia pond culture in China. The farm is assumed to equip each pond with two 1.5 kW aerators and one automatic feeding machine. The costs are 1 500 CNY per aerator and 650 CNY per automatic feeding machine. Depreciation period is assumed to be five years for both the aerators and automatic feeding machines.

The farm stocks 1 g fingerlings (2–3 cm) at 1 200 fish/mu (i.e. 1.8 fish/m^2; 1 ha = 15 mu); the seed price is CNY 0.10/fish. For simplicity and without the loss of generality, zero mortality is assumed. The assumption would be relaxed later to examine the impact of mortality on farm performance.

Commercial feed with 32 percent crude protein (CP) is used before the fingerlings reach 50 g; feed with 30 percent CP is used from 50 g to 300 g; and 28 percent CP is used for 300 g and over. The feed prices are CNY 4 900, CNY 4 700 and CNY 4 500 per tonne, respectively, for the three types of feed.

For simplicity, 1 kg of tilapia production costs CNY 0.40 of electricity, and the cost of water treatment (e.g. adding micro-organisms or chemicals into the water to remove pathogens, toxic elements or other harmful substances or organisms) is CNY 0.30/kg of fish production. These simplifying assumptions capture the fact that the more biomass in the pond, the more electricity (mainly for aeration) and water treatment are needed.

5 In China, 10 mu (i.e. two thirds of 1 ha) is often deemed the optimal size of a tilapia pond (Yang, 2015).
6 Many tilapia farmers in China lease their ponds from the government or local communities. The pond rental varies according to multiple factors (pond location, condition, land price, etc.). A common level of pond rental is CNY 1 500/mu per year, which implies approximately CNY 30/mu per week.

The farm hires one full-time worker who is paid CNY 650 per week. The farm outsources harvesting tasks to a professional harvest team, which would charge a lump sum of CNY 3 000.

In China, tilapia are available to consumers and the industry in various sizes. Tilapia smaller than 250 g are usually not marketable and are sold as juveniles at a very low price. Tilapia weighing less than 500 g are deemed a small-size fish and are usually cheaper than larger size tilapia. Fish processing plants prefer to collect tilapia that weigh more than 500 g. Tilapia weighing more than 1 kg are usually supplied to the food catering industry with a size premium in price. The farmgate tilapia prices specified in Table 3 capture these stylized facts.

TABLE 3
Technical and economic parameters used in the basic model

Pond	
Area (ha)	2
Number of ponds	3
Pond rental (CNY/mu/week)	30
Time for pond preparation (weeks)	2
Pond renovation/reconstruction (every 20 years) (CNY/mu)	5 000
Equipment	
Number of 1.5 kW aerators (number/pond)	2
Price of 1.5 kW aerator (CNY/aerator)	1 500
Depreciation period for aerator (year)	5
Automatic feeding machine (number/pond)	1
Price of automatic feeding machine (CNY/machine)	650
Depreciation period for automatic feeding machine (year)	5
Seed	
Fingerling price (1 g, 2–3 cm) (CNY/fish)	0.10
Stocking density (fish/mu)	1 200
Mortality (%)	-
Feed	
Feed price (32 percent crude protein, used before 50 g) (CNY/tonne)	4 900
Feed price (30 percent crude protein, used from 50 to 300 g) (CNY/tonne)	4 700
Feed price (28 percent crude protein, used after 300 g) (CNY/tonne)	4 500
Electricity and water treatment	
Electricity or other energy cost (CNY/kg of fish production)	0.40
Water treatment cost (CNY/kg of fish production)	0.30
Labour	
Number of workers	1
Wage (CNY/week)	650
Harvest team (CNY/time)	3 000
Fish price	
Farmgate tilapia price (< 250 g) (CNY/kg)	5.02
Farmgate tilapia price (> = 250 but < 500 g) (CNY/kg)	7.95
Farmgate tilapia price (> = 500 but < 1 000 g) (CNY/kg)	9.84
Farmgate tilapia price (> = 1 000 g) (CNY/kg)	11.40

2.3 ASSESSING THE PERFORMANCE OF TILAPIA POND CULTURE IN THE BASIC MODEL

The biological component (Table 2) and the technical and economic parameters (Table 3) are combined into the basic bioeconomic model. A key feature of the basic model is that the water temperature is assumed to be constant at 28 °C; the assumption would be relaxed in the advanced model.

In the basic model, most of the key farming arrangements or practices such as fingerling size, stocking density, feed choice and feeding regime are exogenously specified according to common practices in China. There is no need to specify stocking timing since the assumption of constant water temperature implies a uniform farming condition for any crop. Growing period (or crop length) is the only endogenous variable in the model, which is selected by the farmer to optimize the farming performance.

Table 4 shows the technical and economic performance of tilapia farming along the fish growth path in the basic model. For example, when harvesting the fish 21 weeks after stocking (Table 4, column I), the average harvest size would be 707 g (Table 4, column II). With 1 200 fish/m^2 stocking density and zero mortality, the number of fish harvested would be 18 000/ha, which implies 12 726 kg/ha per crop of tilapia production (Table 4, column III, equal to 0.707 kg multiplied by 18 000) and 553 kg/ha per week (Table 4, column XII, equal to 12 726 kg/ha per crop ÷ 23 weeks/crop).[7]

With CNY 9.84/fish of farmgate tilapia price (Table 4, column V), the farm revenue would be CNY 125 181/ha per crop (Table 4, column VI, equal to 12 726 kg/ha per crop multiplied by CNY 9.84/kg).[8]

When harvesting in week 21, the fixed cost (Table 4, column VII) would be CNY 12 493/ha per crop, including CNY 10 350/ha per crop of pond rental, CNY 484/ha per crop of equipment depreciation, and CNY 1 659/ha per crop of the amortized cost of pond renovation/reconstruction incurred every 20 years.

- With CNY 30/mu weekly pond rental (Table 3), the pond rental cost would be CNY 10 350/ha per crop, equal to 30 CNY/mu per week × 15 mu/ha × 23 weeks/crop.[9]
- The two aerators and one automatic feeding machine cost CNY 10 950 (equal to CNY 1 500/aerator × two aerators/pond × three ponds + CNY 650/automatic feeding machine × one automatic feeding machine/pond × three ponds; see Table 3). Thus, the equipment depreciation would be CNY 484/ha per crop (equal to CNY 10 950 ÷ 5 years ÷ 52 weeks/year × 23 weeks/crop ÷ 2 ha).
- The pond renovation/reconstruction would cost CNY 5 000/mu (Table 3); thus, the amortization of this cost would be CNY 1 659/ha per crop (CNY 5 000/mu × 15 mu/ha ÷ 20 years ÷ 52 weeks/year × 23 weeks/crop).

When harvesting in week 21, the operating cost would be CNY 68 214/ha per crop (Table 4, column VIII), including CNY 1 800/ha per crop for seed, CNY 48 531/ha per crop for feed, CNY 5 090/ha per crop for electricity, CNY 3 818/ha per crop for water treatment, and CNY 8 975/ha per crop for labour.

- With the 1 200 fish/mu stocking density, the number of fish stocked is 18 000/ha per crop (equal to 1 200 fish/mu × 15 mu/ha), and the seed cost would be CNY 1 800/ha per crop (equal to 18 000 fish/ha per crop × CNY 0.10/fish), irrespective of the growing period.
- The CNY 48 531/ha per crop of feed cost is the sum of the cost of feed use in each week (Table 2, column V). For example, the feed use in week 21 is 1 187 826 g/ha (equal to 65.99 g/fish × 18 000 fish/ha). With the feed price (28 percent CP) of CNY 4 500/tonne (i.e. CNY 0.0045/g), the feed cost in week 21 would be CNY 5 345/ha (equal to 1 187 826 g/ha × CNY 0.0045/g).
- The production of 1 kg tilapia would cost CNY 0.40 for electricity and CNY 0.30 for water treatment (Table 3). Thus, the production of 12 726 kg/ha per crop would cost CNY 5 090/ha per crop and CNY 3 818/ha per crop for the use of electricity and water treatments, respectively.

[7] The crop length of 23 weeks includes the growth period (21 weeks) plus two weeks for pond preparation.
[8] Discrepancy may occur from rounding – the price CNY 9.84 is the rounding of CNY 9.83667.
[9] 1 ha = 15 mu.

- The wage for the full-time worker comes out to be CNY 14 950 (equal to CNY 650/week × 23 weeks), and hiring the harvest team would cost CNY 3 000 (Table 3). Therefore, the (internal and external) labour cost would be CNY 8 975/ha per crop (equal to (CNY 14 950/crop + CNY 3 000/crop) ÷ 2 ha).

With the CNY 125 181/ha per crop of revenue and CNY 80 707/ha per crop of total cost (Table 4, column IX, equal to the CNY 12 493/ha per crop of fixed cost plus the CNY 68 214/ha per crop of operating cost), the profit (equal to revenue minus cost) from harvesting in week 21 would be CNY 44 475/ha per crop (Table 4, column X) and CNY 1 934/ha per week (Table 4, column XI). The break-even price (Table 4, column XIII) shows that when harvesting in week 21, farmers would be able to break even (i.e. zero profit) by selling fish at CNY 6.34/kg, which would generate revenue just enough to cover the total cost. In other words, a farmer would be able to make money by selling the fish at a price higher than CNY 6.34/kg.

Profit per crop

Profit per crop, which is equal to revenue per crop minus cost per crop, is a common indicator for measuring the economic performance of an aquaculture operation. As indicated in Table 4 and Figure 4, the farmer would lose money (i.e. negative profit per crop) if the fish are harvested before week 14. The low price for undersized fish – i.e. CNY 5.02/fish for fish weighing less than 250 g – is the primary cause of this situation.

As shown in Figure 4, the loss would be increasing with the growth period before week 14. For example, harvesting the fish at 186 g in week 12 would incur less loss than harvesting the fish at 226 g in week 13. This indicates the importance of growing fish to a marketable size. Similarly, profit per crop would have a big jump in week 18 when the fish exceed 500 g and can be sold at a higher price.

From week 18 to week 24, profit per crop would be increasing with the length of the growing period. This means that harvesting the fish in week 24 would yield greater profit per crop than harvesting the fish earlier. However, is harvesting in week 24 the optimal arrangement? The answer is negative.

Although harvesting in week 24 would yield a higher profit per crop than harvesting in week 23 (CNY 47 713/ha per crop versus CNY 46 830/ha crop), it would also take up one more week of production. Generally speaking, profit per crop is not an accurate indicator for comparing the profitability of production cycles with different crop

FIGURE 4
Profit per crop for different growth periods

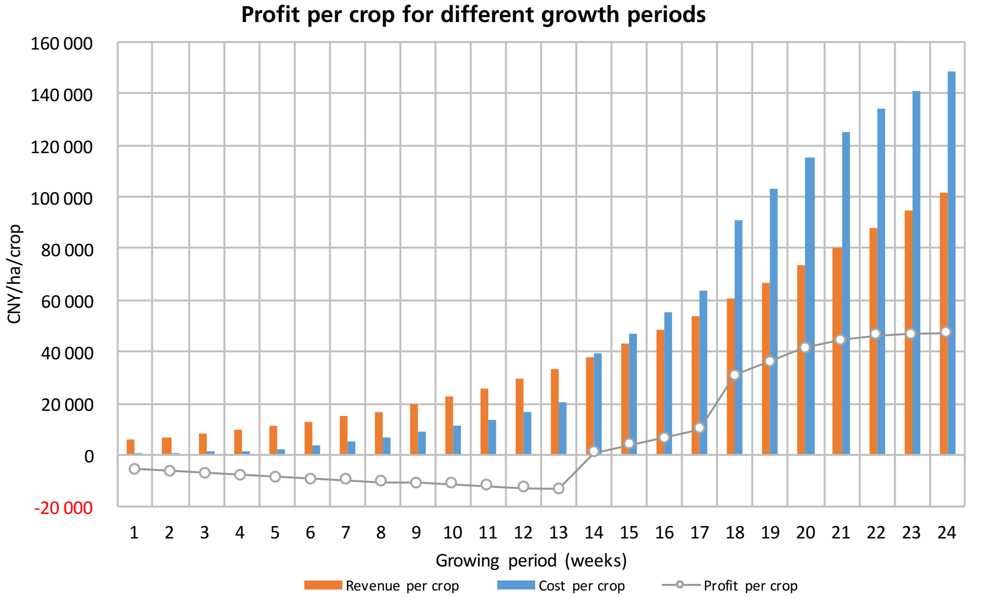


TABLE 4
Technical and economic performance of intensive tilapia pond culture in the basic model

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
Growing period (weeks)	Fish size (g/fish)	Production per crop (kg/ha/crop)	FCR	Price (CNY/kg)	Revenue per crop (CNY/ha/crop)	Cost per crop (CNY/ha/crop)			Key performance indicators			
						Fixed cost	Operating cost	Total cost	Profit per crop (CNY/ha/crop)	Profit per week (CNY/ha/week)	Production per week (kg/ha/week)	Break-even price (CNY/kg)
1	5	90	0.18	5.02	451	1 630	4 400	6 029	-5 578	-1 859	30	66.99
2	9	162	0.45	5.02	813	2 173	4 935	7 108	-6 295	-1 574	41	43.87
3	14	252	0.61	5.02	1 264	2 716	5 592	8 308	-7 044	-1 409	50	32.97
4	20	360	0.74	5.02	1 806	3 259	6 384	9 643	-7 838	-1 306	60	26.79
5	28	504	0.74	5.02	2 528	3 802	7 333	11 136	-8 608	-1 230	72	22.09
6	39	702	0.71	5.02	3 521	4 345	8 482	12 827	-9 306	-1 163	88	18.27
7	54	972	0.67	5.02	4 875	4 889	9 852	14 740	-9 865	-1 096	108	15.16
8	73	1 314	0.69	5.02	6 591	5 432	11 524	16 956	-10 365	-1 037	131	12.9
9	96	1 728	0.72	5.02	8 667	5 975	13 540	19 515	-10 848	- 986	157	11.29
10	123	2 214	0.75	5.02	11 105	6 518	15 928	22 446	-11 341	- 945	185	10.14
11	153	2 754	0.81	5.02	13 814	7 061	18 696	25 757	-11 943	- 919	212	9.35
12	186	3 348	0.86	5.02	16 793	7 604	21 838	29 443	-12 650	- 904	239	8.79
13	226	4 068	0.81	5.02	20 404	8 148	25 398	33 545	-13 141	- 876	271	8.25
14	273	4 914	0.78	7.95	39 048	8 691	29 417	38 108	940	59	307	7.76
15	327	5 886	0.77	7.95	46 772	9 234	33 779	43 013	3 759	221	346	7.31
16	385	6 930	0.80	7.95	55 068	9 777	38 594	48 371	6 697	372	385	6.98
17	447	8 046	0.82	7.95	63 936	10 320	43 839	54 159	9 776	515	423	6.73
18	514	9 252	0.83	9.84	91 009	10 863	49 502	60 366	30 643	1 532	463	6.52
19	583	10 494	0.86	9.84	103 226	11 407	55 530	66 936	36 290	1 728	500	6.38
20	650	11 700	0.94	9.84	115 089	11 950	61 825	73 775	41 314	1 878	532	6.31
21	707	12 726	1.16	9.84	125 181	12 493	68 214	80 707	44 475	1 934	553	6.34
22	756	13 608	1.37	9.84	133 857	13 036	74 593	87 629	46 228	1 926	567	6.44
23	798	14 364	1.60	9.84	141 294	13 579	80 885	94 464	46 830	1 873	575	6.58
24	838	15 084	1.66	9.84	148 376	14 123	87 081	101 204	47 173	1 814	580	6.71

length; indicators with uniform crop length, such as profit per week, profit per month or profit per year, should be used instead.

Profit per week

As indicated in Table 4 and Figure 5, harvesting the fish in week 21 at 707 g would yield the highest (average) profit per week. This means that in the basic model where the farming condition (i.e. water temperature) is uniform over time, the profit maximizing arrangement is to repeat the 21-week cycle over time and achieve the maximum profit of CNY 1 934/ha per week (Table 4, column XI), or CNY 100 551/ha per year.

The concept of diminishing marginal profit can help understand why profit per week reaches the maximum in week 21 while profit per crop still grows. Marginal profit (per week) measures additional profit that is earned from extending the growth period for one additional week. For example, harvesting in week 21 would yield a profit of CNY 44 475/ha, which is CNY 3 161/ha higher than the profit of CNY 41 314/ha

FIGURE 5
Profit per week for different growing periods

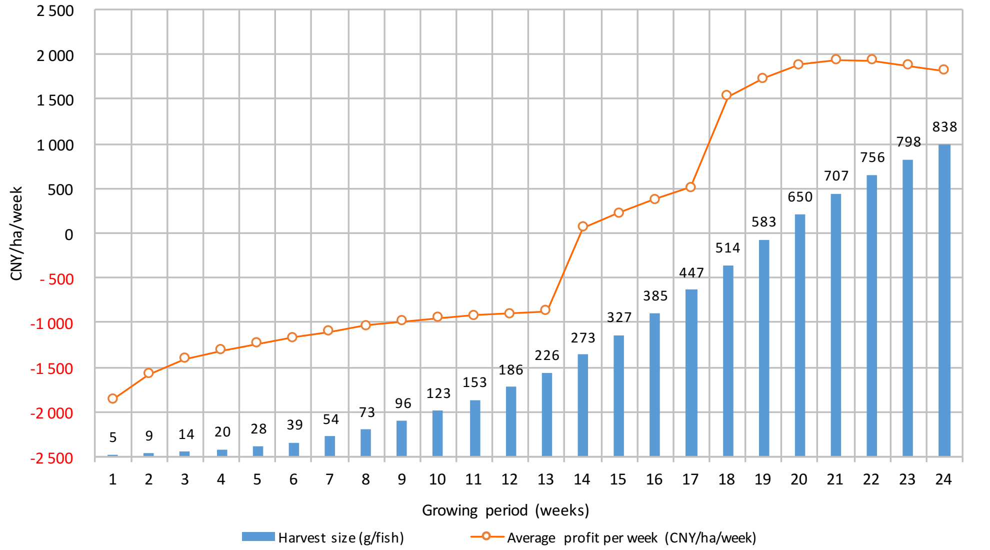
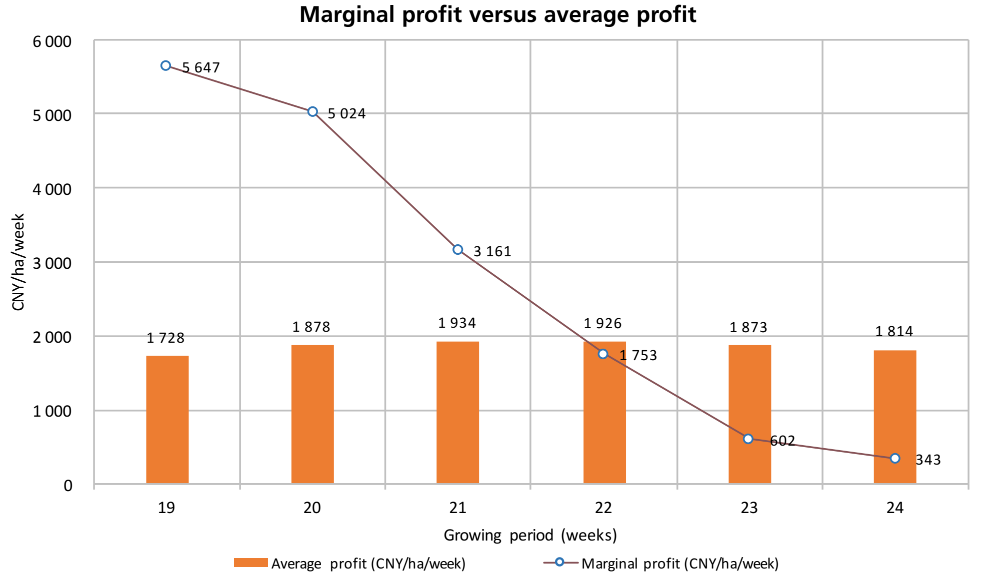


FIGURE 6
Marginal profit versus average profit



from harvesting in week 20. Thus, the marginal profit in week 21 is CNY 3 161/ha per week. As shown in Figure 6, marginal profit diminishes from CNY 5 647/ha per week in week 19 to CNY 343/ha per week in week 24.

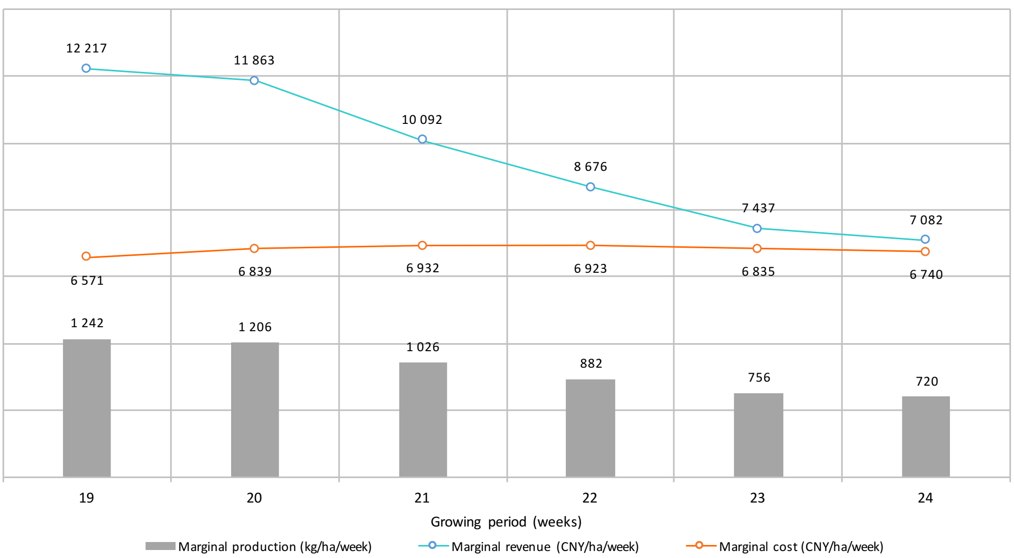
As the marginal profit in week 21 (CNY 3 161/ha per week) is higher than the average profit per week from harvesting in week 20 (CNY 1 878/ha per week), extending the growing period from 20 weeks to 21 weeks would increase the average profit per week; hence, harvesting in week 21 would be more profitable than in week 20.

As the marginal profit in week 22 (CNY 1 753/ha per week) is smaller than the average profit per week in week 21 (CNY 1 934/ha per week), extending the growth period from 21 weeks to 22 weeks would reduce the average profit per week; hence, harvesting in week 22 would be less profitable than in week 21. The diminishing marginal profit would continue to reduce the average profit per week in weeks 23 and 24. Therefore, the most profitable option is harvesting in week 21.

Marginal profit is equal to marginal revenue minus marginal cost. The primary cause of the diminishing marginal profit (Figure 6) is the diminishing marginal revenue from 12 217 CNY/ha per week in week 19 to CNY 7 082/ha per week in week 24, which is, in turn, caused by diminishing marginal production (Figure 7). As fish grow bigger and bigger, the increasing fish biomass would put increasing pressure on the carrying capacity of the ponds (natural food, oxygen, etc.). In addition, larger fish would need more energy to sustain their metabolism. Therefore, when the biomass in the pond reaches a certain threshold, the weekly weight gain of fish would start to decline (Figure 1), which would lead to diminishing marginal production.

As indicated in Figure 7, marginal cost increases slightly from CNY 6 571/ha per week in week 19 to CNY 6 932/ha per week in week 21. This is a contributing factor to the diminishing marginal profit, yet the magnitude is far less than the impact of the diminishing marginal revenue. Indeed, the marginal cost peaks at week 21 and declines until week 24, which serves as a countering factor to the diminishing marginal profit. There will be a more detailed discussion on cost later in the document.

FIGURE 7
Marginal revenue and marginal cost

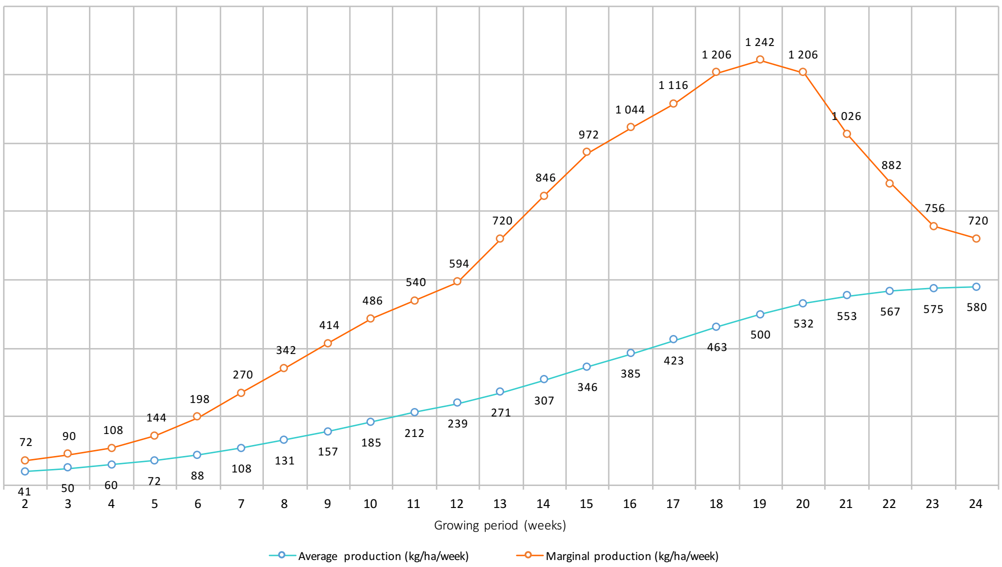


Technical performance versus economic performance

As indicated in Table 4, profit per week peaks in week 21 (column XI), whereas production per week (column XII) keeps growing to the end of the planning horizon (i.e. week 24). As shown in Figure 8, although marginal production peaks in week 19 and keeps diminishing until the end, it is always higher than the average weekly production; therefore, the average production keeps growing until the end.

An important point to highlight is that an arrangement that maximizes the technical performance (measured by productivity) of an aquaculture operation may not be the one that maximizes its economic performance (measured by profitability). If the target is to maximize productivity, the farmer should harvest the fish in week 24 at 838 g; if the target is to maximize profitability, the optimal arrangement would be to harvest the fish in week 21 at 707 g. The discrepancy will be examined further in the discussion on cost.

FIGURE 8
Marginal production versus average production



U-shape cost per unit of production, aka break-even price

The cost per unit of production is often used to measure the break-even price. An aquaculture operation would be profitable if the market price is higher than the break-even price. As indicated in Figure 9, fish harvested in week 7 (average 54 g) need to be sold at a price above CNY 15.16/kg in order to be profitable. The break-even price would decline with the growth period and reach the minimum CNY 6.31/kg in week 20.

As indicated in Table 4, when stocking 1 g fingerlings at 1 200 fish/mu stocking density, the farmer needs to harvest fish that weigh more than 250 g in order to make a profit. This is confirmed by Figure 9, which shows that the break-even price of fish smaller than 250 g is higher than its market price (CNY 5.02/kg). It is important to note that this does not mean that farming small fish cannot be profitable. The 1 200 fish/mu stocking density is a common practice for operations intended to harvest relatively large fish. When targeting a small harvest size, the farmer would usually choose a higher stocking density to produce more fish for higher profit.

The break-even price is lower than the market price for fish harvested in week 14 or later, which means that harvesting fish from week 14 onward would be profitable. Week 20, which corresponds to the lowest break-even price, is close but not the exact optimal harvest timing for profit maximization (i.e. week 21, as indicated in Table 4 and Figure 5). When harvesting the fish in week 20, the CNY 3.53/kg difference between the market price (CNY 9.84/kg) and the break-even price (CNY 6.31/kg) is the highest profit margin per unit of production. It is not difficult to verify that the average profit per week for a 20-week cycle (CNY 1 878/ha per week) is equal to the profit margin per unit of production (CNY 3.53/kg) multiplied by the average production per week (532 kg/ha per week).

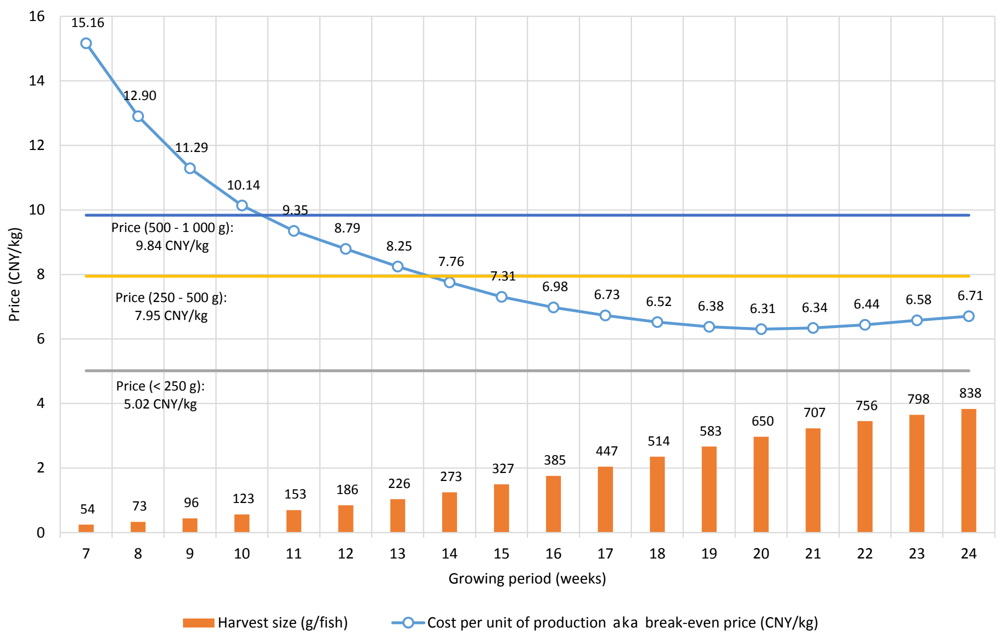
When harvesting in week 21, the profit margin per unit of production decreases slightly from CNY 3.53/kg in week 20 to CNY 3.50/kg, whereas the average production per week increases from 532 kg/ha per week to 553 kg/ha per week. The combination of the two factors results in an increase in the average profit per week from CNY 1 878/ha per week in week 20 to CNY 1 934/ha per week in week 21.

The pattern of a decreasing profit margin per unit of production and an increasing average production per week continues in week 22, yet the magnitude of the former is growing whereas that of the latter is diminishing. The combined net impact would result in a lower profit per week for harvesting the fish in week 22 than in week 21.

Now it should be clear that the discrepancy between the technical and economic performance is caused by the profit margin. Although the technical performance (measured by the average production per week) would continue growing during the planning horizon, the profit margin (measured by the difference between the market price and the break-even price) would start declining from week 20, where the breakeven price reaches the minimum. The economic performance, which is determined by the net impact of the two factors, would grow until week 21, when the declining profit margin starts prevailing over the growing technical performance in week 22.

Now the question is why the cost per unit of production, aka break-even price, declines from CNY 15.16/kg in week 7 to the lowest CNY 6.31/kg in week 20 and then keeps growing to CNY 6.71/kg in week 24, which, given the constant price for fish harvested from week 18 to 24, leads to a declined profit margin from week 20 to 24.

FIGURE 9
Cost per unit of production, aka break-even price



Increasing feed cost versus diminishing costs of other inputs

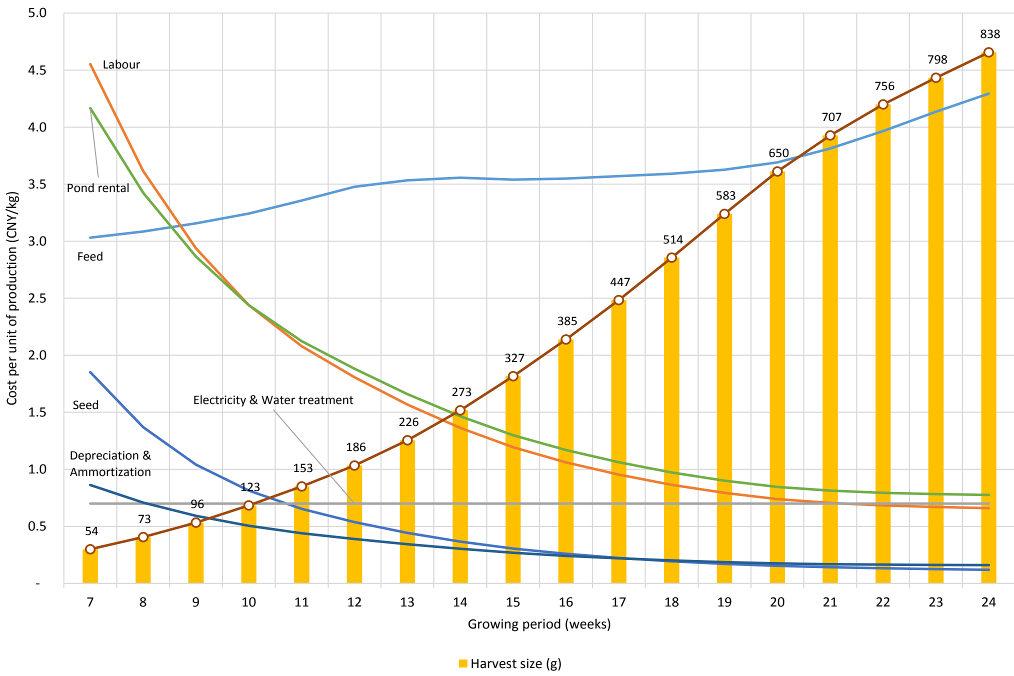
As indicated in Figure 10, the cost of seed, labour, pond rental or depreciation/ amortization is diminishing at the early stage and flattening out as the fish grow bigger. Since the total cost of seed is fixed, the larger the production, the lower the seed cost per unit of production. The total cost of pond rental would increase over time. But as the weekly rental cost is fixed while the weekly weight gain is increasing when the fish are relatively small, the rental cost per unit of production is diminishing. As the weekly weight gain starts declining when the fish become bigger, the rental cost per unit of production would flatten out. If the growing period is extended beyond 24 weeks, the rental cost per unit of production may eventually start increasing when the fish reach a certain size and the weekly weight gain reduces to a certain level. The situation of the cost of depreciation/amortization is similar to that of rental cost. The situation of labour cost is a mixture. While the cost of the employee wage is similar to the case of rental cost and depreciation/amortization, the harvesting cost follows the case of seed cost.

As the cost of electricity (used primarily for aeration) or water treatment tends to be positively correlated with the fish biomass in the pond, the cost of electricity or water management per unit of production is assumed to be constant in this model.

Unlike the other cost items, the feed cost per unit of production keeps increasing over time as the fish grow bigger. This reflects increasing FCR over time with growing fish size and fish biomass in the pond (Figure 3). When the trend of weekly FCR is steeper from week 7 to week 12 and from week 20 to week 24 (Figure 3), the trend of the feed cost per unit of production is also steeper (Figure 10).

In summary, the cost per unit of production is declining at the early stages when the fish are small because the diminishing costs of seed, labour, rental and depreciation/ amortization due to “economies of scale”[10] outweigh the increasing feed cost due to the increasing FCR. As the fish become bigger and their growth slows down, the economies of scale would be diminishing whereas the FCR would grow faster. When the feed cost increase eventually outweighs the decline of other costs driven by the economies of scale, the cost per unit of production, aka break-even price, would start rising.

FIGURE 10
Breakdown of major cost items



[10] The term “economies of scale” is usually used to explain cost advantages that an enterprise obtains from its scale of operation. The cost advantage here, which is obtained from increasing output by growing larger fish, is subject to a similar rationale.

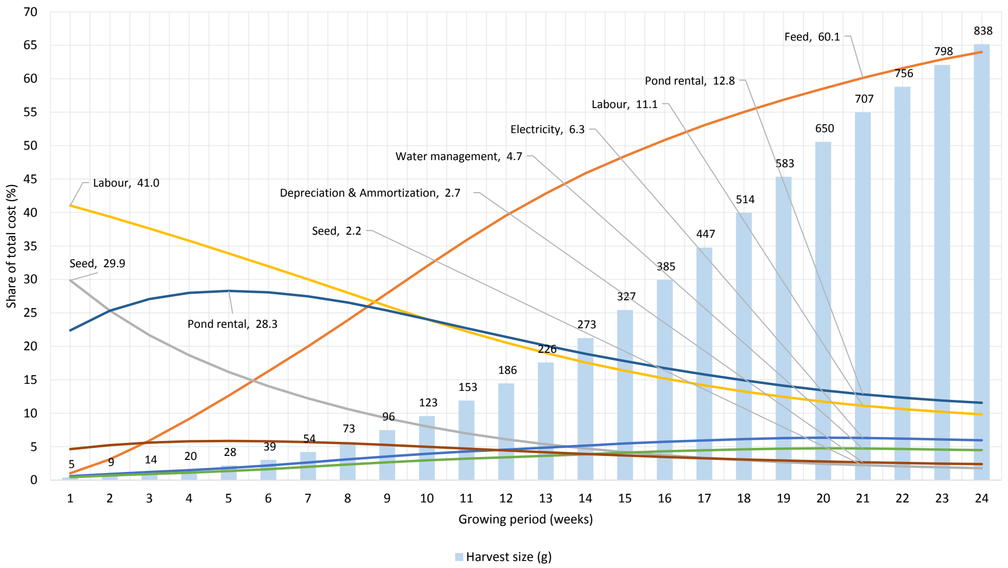
Cost structure

The common perception that feed accounts for most of the cost of tilapia farming is confirmed in Figure 11, which indicates that when harvesting in week 21 (the optimal harvest timing), feed accounts for 60 percent of the total cost. However, the share of feed or any other cost item in the total cost depends on the growing period. When the fish are harvested in week 10 with the harvest size being 123 g, feed accounts for only a little over 30 percent of the total cost.

When the fish are harvested in week 21, pond rental and labour are two relatively large cost items, accounting for 12.8 and 11.1 percent of the total cost, respectively. They would be greater than the feed cost if the fish are harvested before week 9 (Figure 11). The share of pond rental is increasing in the early stage because the seed or labour cost, which is a lump-sum expense or has a lump-sum component (i.e. the harvesting expense), has greater "economies of scale" hence declines more rapidly than the pond rental. As the feed cost grows bigger, all three start declining and yield their shares in the total cost to the feed cost.

Seed is a relatively large cost item at the beginning, but becomes the smallest cost item, accounting for only 2.2 percent of the total cost when harvesting in week 21.

FIGURE 11
Cost structure



Impacts of technical or economic factors on profitability

Table 5 shows how a technical or economic factor affects the profitability and optimal harvest time. The benchmark profitability in column V represents the situation presented in Table 4. Columns VI to X show the impacts on profitability (measured by profit per week) caused by a change in an input price, whereas column XI shows the impacts of a change in the fish price. It is assumed that the input or output price change would not alter the farmers' stocking or feeding behaviours and hence does not affect the fish growth pattern (column II) or the technical performance of the operation (columns III and IV).

Recall that the benchmark case in Table 4 assumes zero fish mortality. The last four columns (columns XII to XV) in Table 5 depict a case of the weekly fish mortality being 2 percent. With the 2 percent weekly mortality, there would be 98 percent of fish survived at the end of week 1, then 96 percent (equal to 98 percent to the power 2) survived at the end of week 2, then 94 percent (equal to 98 percent to the power 3) survived at the end of week 3, and so on.[11] The corresponding mortality rates (equal to one minus the survival rate) are presented in column XII. Unlike an economic factor affecting the profitability through an input or output price, the change in fish mortality (as a technical factor) would affect the profitability (column XV) through its impacts on fish production (columns XIII and XIV).

The impacts of the economic and technical factors on profitability are summarized as follows.

- As a minor cost accounting for only 2.2 percent of the total cost when the fish are harvested in week 21 (Figure 11), a change in the seed price would have a very small impact on the profitability. Indeed, a 50 percent increase in the fingerling price would only reduce the profitability by 2 percent from the benchmark level (CNY 1 934/ha per week) to 1 895 CNY/ha per week (Table 5, column VII). The optimal growing period is the same as that in the benchmark case (i.e. harvesting 707 g fish in week 21). However, if the fingerling price is increased by five times, the optimal growing period would be increased to 22 weeks and harvest size increased to 756 g. Intuitively, the more expensive the seed is, the more the "economies of scale" can be reaped by harvesting bigger fish.
- A 50 percent increase in the wage rate would reduce profitability by 10 percent from the benchmark level to CNY 1 739/ha per week (Table 5, column VIII). The impact is greater than seed, which reflects the higher share of labour cost than seed cost (Figure 11). Similar to the case of fingerlings, a five-time increase in wage rate would move the optimal harvest timing to week 22 (756 g). Similarly, a 50 percent increase in the electricity and water treatment cost would reduce the profitability by 10 percent to CNY 1 740/ha per week (Table 5, column IX), and a 50 percent increase in pond rental would reduce the profitability by 12 percent to CNY 1 709/ha per week (Table 5, column X).
- Being the largest cost item, a 50 percent increase in feed price would reduce the profitability by 54 percent to CNY 896/ha per week (Table 5, column VI). As opposed to an increase in the price of a cost that diminishes over time would increase the optimal growing period, the increase in the price of feed, which is a cost item increasing over time, would shorten the optimal growing period to 20 weeks and reduce the optimal harvest size to 650 g.
- A 30 percent decrease in fish price would reduce profitability by 84 percent to CNY 309/ha per week (Table 5, column XI). The lowered price reduces the profit margin per unit of production and hence would shorten the optimal growing period to 20 weeks and reduce the optimal harvest size to 650 g.
- An increase of weekly mortality from zero to 2 percent would reduce the profitability by 62 percent to 736 CNY/ha per week (Table 5, column XV). Mortality can be deemed a cost similar to feed which increases with the growing period. Therefore, the increased mortality would shorten the optimal growing period to 20 weeks and reduce the optimal harvest size to 650 g.
- In the last three cases, i.e. the 50 percent increase in feed price (Table 5, column VI), the 30 percent decrease in fish price (Table 5, column XI), and the increase of mortality from zero to 2 percent (Table 5, column XV), harvesting fish under 500 g would not be profitable given the relatively low prices for small-size fish.

Summary

A basic bioeconomic model has been developed based on the experience of intensive tilapia pond culture in China. The biological part of the model is based on the growth pattern of GIFT tilapia in China under specific farming conditions and practices,

[11] This is a simplifying assumption, whereas in reality mortality tends to vary at different stages of fish growth.

TABLE 5

Impact of technical or economic factors on profitability and optimal harvest time

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
		Production		Profitability (CNY/ha/week)							Weekly mortality 2%			
Growing period (weeks)	Average harvesting size (g/fish)	Kg/ha/crop	Kg/ha/week	Benchmark	Feed price up 50%	Fingerling price up 50%	Wage rate up 50%	Electricity & water management price up 50%	Pond rental up 50%	Fish price down 30%	Accumulated mortality (%)	Production per crop (kg/ha/crop)	Productivity (kg/ha/week)	Profitability (CNY/ha/week)
1	5	90	30	-1 859	-1 870	-2 159	-2 272	-1 870	-2 084	-1 904	2	88	29	-1 862
2	9	162	41	-1 574	-1 601	-1 799	-1 924	-1 588	-1 799	-1 635	4	156	39	-1 580
3	14	252	50	-1 409	-1 458	-1 589	-1 721	-1 426	-1 634	-1 485	6	237	47	-1 419
4	20	360	60	-1 306	-1 380	-1 456	-1 594	-1 327	-1 531	-1 397	8	332	55	-1 320
5	28	504	72	-1 230	-1 330	-1 358	-1 499	-1 255	-1 455	-1 338	10	456	65	-1 248
6	39	702	88	-1 163	-1 294	-1 276	-1 420	-1 194	-1 388	-1 295	11	622	78	-1 189
7	54	972	108	-1 096	-1 260	-1 196	-1 342	-1 134	-1 321	-1 259	13	844	94	-1 131
8	73	1 314	131	-1 037	-1 239	-1 127	-1 274	-1 083	-1 262	-1 234	15	1 118	112	-1 082
9	96	1 728	157	- 986	-1 234	-1 068	-1 217	-1 041	-1 211	-1 223	17	1 441	131	-1 045
10	123	2 214	185	- 945	-1 244	-1 020	-1 170	-1 010	-1 170	-1 223	18	1 809	151	-1 017
11	153	2 754	212	- 919	-1 274	- 988	-1 139	- 993	-1 144	-1 237	20	2 205	170	-1 004
12	186	3 348	239	- 904	-1 319	- 968	-1 120	- 987	-1 129	-1 263	22	2 627	188	-1 002
13	226	4 068	271	- 876	-1 355	- 936	-1 089	- 971	-1 101	-1 284	23	3 128	209	- 991
14	273	4 914	307	59	- 487	2	- 151	- 49	- 166	- 673	25	3 703	231	- 299
15	327	5 886	346	221	- 392	168	14	100	- 4	- 604	26	4 347	256	- 207
16	385	6 930	385	372	- 311	322	168	237	147	- 546	28	5 016	279	- 129
17	447	8 046	423	515	- 242	467	313	366	290	- 495	29	5 707	300	- 62
18	514	9 252	463	1 532	702	1 487	1 332	1 370	1 307	167	30	6 431	322	609
19	583	10 494	500	1 728	822	1 685	1 530	1 553	1 503	253	32	7 149	340	691
20	650	11 700	532	1 878	**896**	1 837	1 681	1 692	1 653	**309**	33	7 811	355	**736**
21	707	12 726	553	**1 934**	879	**1 895**	**1 739**	**1 740**	**1 709**	301	35	8 326	362	716
22	756	13 608	567	1 926	802	1 889	1 732	1 728	1 701	253	36	8 725	**364**	653
23	798	14 364	575	1 873	685	1 837	1 681	1 672	1 648	178	37	9 026	361	563
24	838	15 084	**580**	1 814	569	1 780	1 623	1 611	1 589	102	38	9 288	357	470

i.e. constant water temperature at 28 °C, 1 g fingerling size, 1 200 fish/mu stocking density, and a recommended feeding scheme under 28 °C water temperature. The economic part of the model is calibrated by various input prices and fish prices gathered in field surveys conducted in 2015 in four major aquaculture provinces in the country. The model is used to assess the technical and economic performance of intensive tilapia pond culture in China. The results indicate that:

- Harvesting the fish in week 21 at 707 g/fish is the most profitable option, yielding the maximum average profit per week of CNY 1 934 /ha.[12] However, extending the growing period further until week 24 (the longest growing period examined under the model) would achieve higher technical performance (measured by average production per week). The gain in profit due to the higher production per week would nevertheless be outweighed by the profit loss from a lower profit margin caused by the increasing cost per unit of production as the fish reach a certain size and their growth slows down.
- When harvesting the fish in week 21 (707 g), feed is the largest cost item accounting for 60 percent of the total cost, followed by the costs of pond rental, labour, electricity and water treatment. Seed cost and depreciation/amortization account for a small portion of total cost.
- An increase in feed price, an increase in mortality, or a decrease in fish price would tend to significantly reduce profitability. It tends to shorten the optimal growing period and hence reduce the optimal harvest size.
- A change in the price of a minor cost item (e.g. seed, labour, pond rental, electricity or water treatment) tends to have a relatively small impact on profitability. A 50 percent increase in seed price would only reduce the profitability by 2 percent. This result reveals an important point: contrary to many farmers' innate aversion against expensive seed, stocking expensive yet high quality seed would tend to be economically advisable.
- As opposed to an increase in feed price shortening the optimal growing period and reducing the optimal harvest size, an increase in the price of seed, labour, pond rental, electricity or water treatment, if large enough, could increase the optimal growing period and harvest size.

The results of the basic model shed light on factors affecting the technical and economic performance of tilapia pond culture. They can provide guidance to farmers who farm tilapia under farming conditions and practices similar to those specified for the model. However, the results should not be overgeneralized out of context. For example, as mentioned above, the 707 g optimal harvest size in the benchmark case should not be treated as evidence that farming large-size fish would be more profitable.

The assumption of constant water temperature at 28 °C in the basic model facilitates the examination of farming performance under the most opportune environment. But pond tilapia farmers in reality usually do not have much control over water temperature and need to alter their farming practices to adapt to climate variations. In the next section, the basic model is extended into an advanced model that captures seasonal variation in the water temperature.

[12] Under constant water temperature, the 21-week production cycle can replicate itself over time; thus, it can be deemed the optimal harvesting option that maximizes profit over time.

3. An advanced bioeconomic model on pond tilapia culture

In this section, the basic model is upgraded into an advanced model. While assumed to be constant in the basic model, the water temperature in the advanced model varies over time within a year, and the seasonal water temperature variation pattern repeats over years.

Stocking timing, which is irrelevant in the basic model, matters in the advanced model because, with varied water temperature, crops starting at different timings will be subject to different farming conditions.

Unlike in the basic model where the optimal crop arrangement can be repeated over time, farming performance in the advanced model may need to be examined based on a combination of multiple crops within an integer number of years, for example, 1 year 1 crop, 2 years 3 crops (average 1 year 1.5 crops), 1 year 2 crops, 2 years 5 crops (average 1 year 2.5 crops), 1 year 3 crops, among others. Because the seasonal change pattern of the water temperature is the same for every year, such crop combinations can repeat over time. Therefore, their performance can be measured and compared by profit per year.

In the basic model, most of the farming arrangements or practices (except the growing period) are exogenously specified in order to facilitate examining the impacts of technical or financial factors on the farming performance. In the advanced model, stocking timing, fingerling size, stocking density and growing period are subject to change in order to examine how farming arrangements and practices affect the farming performance. The feeding regime is exogenously specified in the advanced model, which the farmer has to follow with no flexibility to change.

The advanced model is used to examine the impact of the water temperature and stocking density on the farming performance in this section and simulate the performance of multiple-crop arrangements in the next section.

3.1 AN ADVANCED BIOECONOMIC MODEL THAT CAPTURES SEASONAL VARIATION IN THE WATER TEMPERATURE

In the basic model, the fish body weight on the growth path as well as weight gains between two periods are known a priori. Feed uses can be calculated from the body weights multiplied by the corresponding feeding rations based on a recommended feeding regime. The feed uses divided by the weight gains give the FCRs (Table 2).

In the advanced model, the fish growth path is not given a priori, but affected by the farmers' choices of stocking timing, fingerling size, stocking density, feeding rations, as well as technical/environmental parameters including the water temperature and FCRs. The impacts of the water temperature on fish growth are captured by temperature-related adjustments in the feeding rations. For example, feed use tends to be reduced in colder weather; consequently, the fish would grow slower.

The correlation between the FCRs and body weights in the basic model (Table 2) is used to estimate the FCRs corresponding to all possible body weights under consideration in the advanced model. These FCRs are technical parameters estimated under the 1 200 fish/mu stocking density. They can be applicable to a higher stocking density when the fish are small and the natural productivity in the pond is abundant. As the fish grow bigger, the fish biomass in the pond would eventually reach a threshold where natural productivity is fully utilized. Beyond the threshold, the FCR parameters estimated under the 1 200 fish/mu may not be applicable to higher stocking density. A simple biological model is established to estimate the fish weight gains after the threshold fish biomass has been reached.

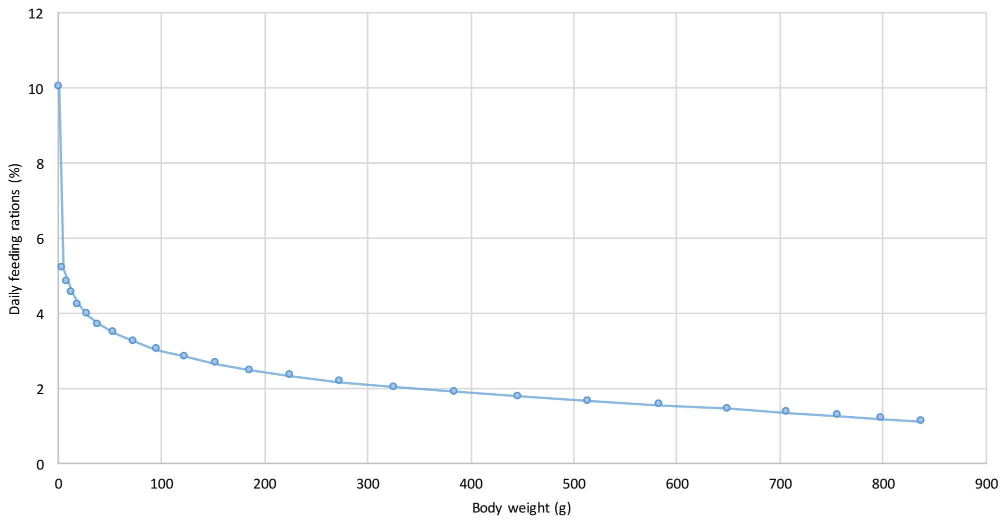
Given the initial fingerling size, the feed use in the first period can be calculated by multiplying the initial body weight of fingerlings by the corresponding feeding ration. The feed use divided by the corresponding FCR gives the weight gain in the first period. The weight gain plus the initial body weight of fingerlings gives the body weight at the end of the first period (or the beginning of the second period). With the body weight at the beginning of the second period known, the weight gain in the second period and the body weight at the beginning of the third period can be calculated in the same way. The process continues period by period to pan out body weights on the growth path. As mentioned above, as the fish biomass in the pond grows, the natural productivity in the pond will be fully exploited at some point after which the weight gain would be estimated through another process. This will be discussed in detail below.

Similar to the basic model, the biological part of the advanced model is calibrated with the technical and economic parameters in Table 3 to complete the advanced bioeconomic model on tilapia pond culture.

Interpolation of the feeding rations

Unlike the basic model that examines a specific fish growth pattern, the advanced model will be used to simulate various fish growth patterns. This entails feeding rations for all possible body weights under consideration, which can be interpolated by the feeding rations shown in Table 2. For example, the daily feeding rations are 2.32 percent and 2.17 percent, respectively, for body weight in week 13 (226 g) and week 14 (273 g). Then the linear relationship determined by these two pairs of body weights and feeding rations can be used to estimate the feeding ration for any body weight between 226 g and 273 g. As indicated in Figure 12, the feeding rations for all body weights between 1 g and 838 g can be estimated through such linear interpolations.

FIGURE 12
Linear interpolation of feeding rations



Adjustment of the feeding rations for different water temperatures

Feeding rations presented in Table 2 and extended in Figure 12 are applicable under the 28 °C water temperature. They need to be adjusted under different water temperatures. Table 6 shows factors suggested in Yang (2015) to be used for adjusting the feeding rations in Table 1 (column III) or Table 2 (column IV) under different water temperatures. For example, feeding rations under water temperature 26–28 °C would be the same as the benchmark feeding rations in Table 2, whereas feeding rations under water temperature 24–25 °C would be 80 percent of the benchmark rations, and so on. These adjustment factors reflect the impact of water temperature on fish growth (Mirea *et al*., 2013; Santos, Mareco and Silva, 2013; Qiang *et al*., 2012; Guo, Guo and Luo, 2011).

TABLE 6
Adjustment factors for feeding ration under different water temperatures

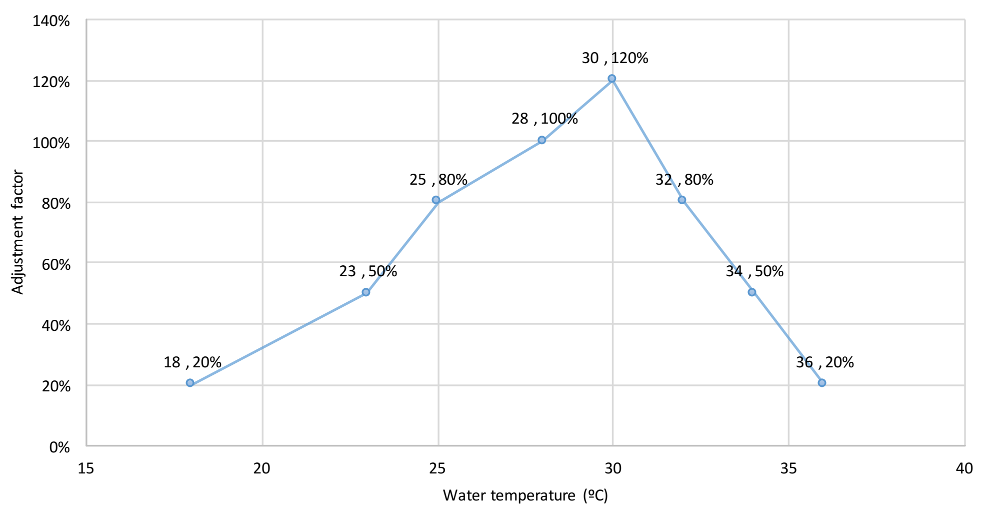
Water temperature	Adjustment factor (%)
18–20 °C	20
21–23 °C	50
24–25 °C	80
26–28 °C	100
29–30 °C	120
31–32 °C	80
33–34 °C	50
35–36 °C	20

Source: Adapted from Table 3.4 in Yang (2015, p. 56).

The adjustment factors in Table 6 provide useful yet imprecise guidance to help farmers determine the feeding amount; a farmer, in practice, usually adjusts the feeding amount according to other factors, such as the appetite of the fish.

Using the linear interpolation method discussed above, the adjustment factors in Table 6 can be used to estimate the adjustment factor under any water temperature between 18 °C and 36 °C (Figure 13). The adjustment factor for water temperature below 18 °C or above 36 °C is assumed to be zero (i.e. no feeding).

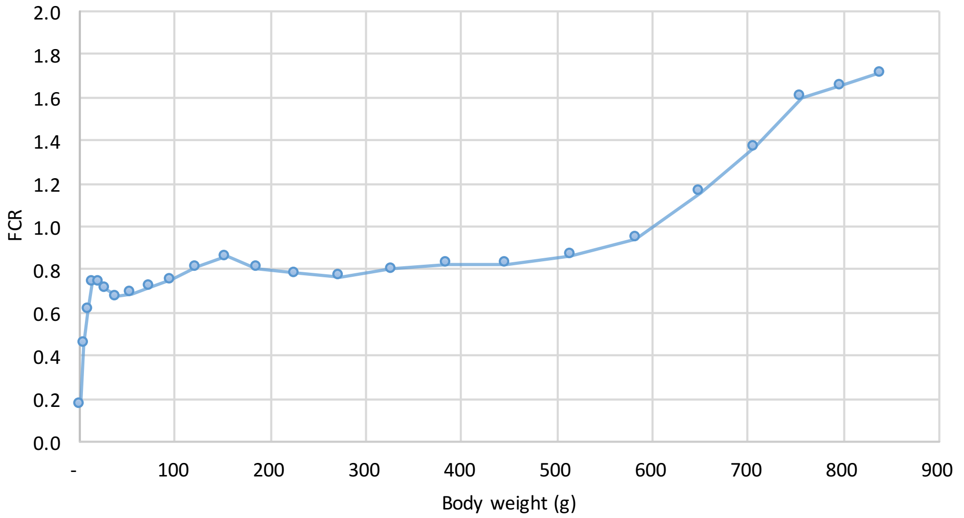
FIGURE 13
Linear interpolation of adjustment factors for feeding rations under different water temperature



Interpolation of the feed conversion ratios

Similar to the feeding rations and adjustment factors, FCRs for all possible body weights between 1 g and 838 g can be linearly interpolated based on the data in Table 2. The results are shown in Figure 14.

FIGURE 14
Linear interpolation of the feed conversion ratios (FCRs)



Estimation of the weight gains

The potential weight gain (WG) in a period can be estimated by the following equation:

$$WG_{potential} = \text{feed use} \div FCR \tag{1}$$

where

$$\text{Feed use} = \text{body weight} \times \text{feeding ration} \times \text{temperature adjustment factor} \tag{2}$$

The feed use in a period is equal to the fish body weight at the beginning of the period multiplied by the feeding ration (Figure 12) and the temperature adjustment factor (Figure 13). The feed use divided by the FCR (Figure 14) gives the potential weight gain in the period ($WG_{potential}$).

As mentioned above, the FCR in equation (1) is an estimated technical parameter under stocking density 1 200 fish/mu; it may not be applicable to higher stocking densities when the natural productivity in the pond has been fully utilized. Therefore, weight gains when the limit of natural productivity in the pond is reached need to be estimated in another way.

Conceptually,

$$WG = F + N\ (b) - L\ (b) \tag{3}$$

Equation (3) means that the total weight gain of fish in the pond during a period (denoted as WG) is equal to the total feed use during the period (denoted as F) plus the use of natural food (plankton, insects, etc.) by fish (denoted as N) minus the nutrient loss (denoted as L). N is a function of the fish biomass in the pond (denoted as b) – the more the fish biomass, the larger the use of natural food. The nutrient loss (L) includes unused or undigested feed and nutrients and the loss of nutrients or fish biomass because of metabolism. L is also a function of b – the greater the fish biomass, the larger the nutrient loss.

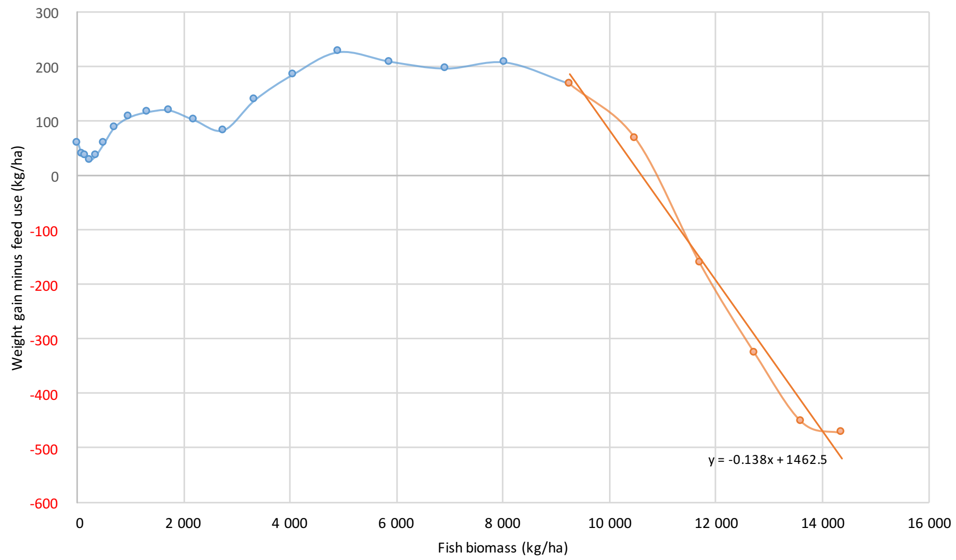
While being in line with bioenergetics growth models for fish (e.g. Yang, 1998), equation (3) is not a rigorous model based on biological processes (e.g. anabolism and catabolism), but a simplifying fish growth model intended to simulate the impact of stocking density on fish growth.

Equation (3) can be rearranged into:

$$WG - F = N\ (b) - L\ (b) \tag{4}$$

Figure 15 uses the data in Table 2 to depict the relationship between weight gain minus feed use (WG-F) and fish biomass in the basic model. WG-F is on an upward trend at the beginning, which indicates that the use of natural food (N) outpaces the nutrient loss (L) at the early stage when fish biomass in the pond is low. As the fish grow bigger and the fish biomass larger, WG-F reaches the maximum when the biomass is about 5 000 kg/ha (fish size at 273 g) and starts on a downward trend. The downward trend is mild at the beginning because the increasing nutrient loss can be partly offset by the increasing use of natural food. The downward trend starts getting steeper (the orange portion in Figure 15) when the biomass reaches 9 252 kg/ha (fish size at 514 g), which indicates that natural productivity in the pond has been fully utilized (i.e. N reaches the maximum).

FIGURE 15
Correlation between weight gain minus feed use and fish biomass



Suppose that the orange-coloured portion of the curve in Figure 15 represents a linear relationship between WG-F and fish biomass manifested when the use of natural food has reached the maximum. Specifically,

$$WG_{maximum} - F = N_{maximum} - \beta \times b + e \tag{5a}$$

where $WG_{maximum} - F$ represents the maximum weight gain minus the feed use when the fish biomass is b; $N_{maximum}$ represents the maximum utilization of natural food in the pond; β represents the nutrient loss coefficient (i.e. the ratio between the nutrient loss and fish biomass); and *e* is the error term that represents random shocks.

As indicated in the equation in Figure 15, the estimated $N_{maximum}$ is 1 463 kg/ha, indicating that the use of natural food is at most 1 463 kg/ha per week, or 209 kg/ha per day. The estimated β is 0.138, indicating that the nutrient loss is equal to 13.8 percent of the fish biomass per week, or about 2 percent per day.

This nutrient loss parameter, which is estimated under the situation of 28 °C water temperature, would need to be adjusted for different water temperatures. As the fish tend to have a lower metabolism in lower water temperature, they would lose less body weight than when they are more active in warmer water. Thus, the nutrient loss parameter would tend to be lower in a lower water temperature. It is assumed that for water temperature below 30 °C, the nutrient loss parameter would be adjusted by the adjustment factors described in Figure 13, whereas the nutrient loss adjustment factor would be 1.2 for a water temperature above 30 °C.

In summary, the maximum weight gain during a period (a day or a week) is estimated by:

$$WG_{maximum} = F + N_{maximum} - \tau \times \beta \times b \qquad (5b)$$

where F is the feed use during the period; $N_{maximum}$ is the maximum natural productivity (1 463 kg/ha per week, or 209 kg/ha per day); $\tau \times \beta$ is the temperature adjusted nutrient loss parameter (τ being the adjustment factor); and b is the fish biomass at the beginning of the period.

Finally, the fish weight gain during a period is determined by:

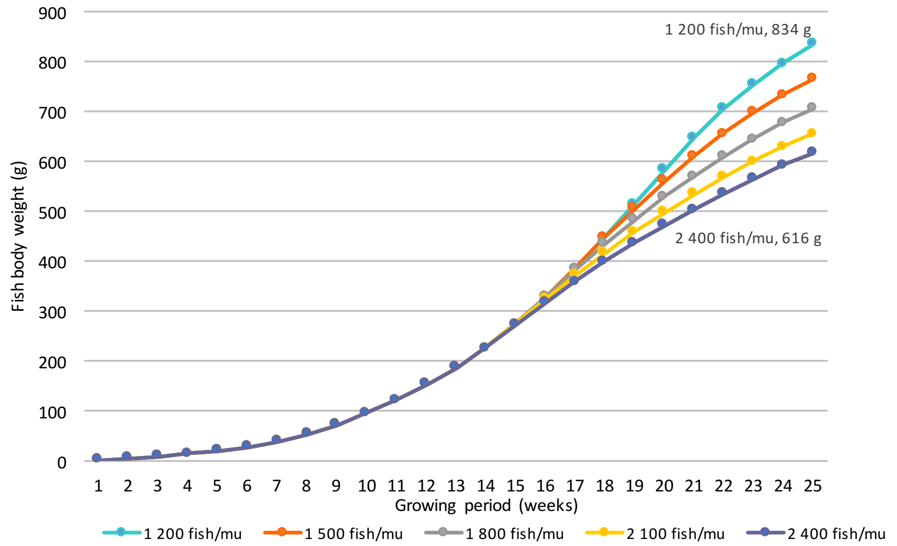
$$WG = \min(WG_{potential}, WG_{maximum}) \qquad (6)$$

where $WG_{potential}$ and $WG_{maximum}$ are defined in equation (1) and (5b), respectively.

Equation (6) means that the weight gain is calculated by equation (1) and (2) when the result (i.e. the potential weight gain) is less or equal to the maximum weight gain estimated by equation (5b); otherwise, the weight gain is calculated by equation (5b).

Figure 16 shows the growth of fish body weight under different stocking densities with 1 g fingerlings and constant water temperature at 28 °C. The results show that the advanced model captures the common pattern in fish outgrowing that a higher stocking density would tend to slow down the fish growth – while fish can grow to 838 g in 24 weeks under 1 200 fish/mu; it would only reach 616 g when the stocking density doubles to 2 400 fish/mu.

FIGURE 16
Fish growth path under different stocking densities (1 g fingerlings and 28 °C water temperature)



Carrying capacity

The original data used to calibrate the basic and advanced models (Tables 2 and 3) describe the fish growth pattern up to about 840 g. With the 1 200 fish/mu stocking density, this means that the fish biomass in the pond would be less than 16 000 kg/ha when the fish reach the maximum size.

It is therefore assumed that the carrying capacity in the advanced model is 16 000 kg/ha; the farmer would harvest the fish before the fish biomass in the pond reaches the capacity. Farming under the carrying capacity allows the farmer to avoid incurring additional costs (e.g. electricity cost for extra aeration, cost for fish health management and cost from fish mortality) that are not captured by the model.

Daily model weekly analysis

Although the advanced model simulates the daily growth of fish, it would be overly cumbersome to conduct daily analysis, which entails the examination of over 360 possible stocking dates within a year. For simplicity, only 52 weekly stocking dates (i.e. 1 January, 8 January, 15 January, and so on) will be examined.

In order to facilitate the weekly analysis, a calendar year in the advanced model includes only 364 days (i.e. exactly 52 weeks) – there are 28 days in February and 30 days in December, whereas the number of days in other months are considered normal. The date at the end of each week is used to identify that week. For example, the week of 8 January represents the week from 2 January to 8 January.

Summary

To summarize, in the advanced model the stocking timing, stocking density and initial fingerling size need to be determined first. Then the feed use and weight gain in the first day can be calculated by equation (2) and (6), respectively, and the body weight in the second day would be determined accordingly. The feed use and weight gain in the second day and body weight in the third day can be determined similarly, and so on. Finally, when the harvest date is determined, the harvest size and total feed use can be calculated, and so can other cost items similar to the basic model.

The advanced model captures the impacts of water temperature on feeding and hence fish growth, and accounts for the limit of natural productivity so that the stylized fact of higher stocking density slowing down fish growth is captured in the model.

The advanced model can be used to examine the impacts of various factors (including water temperature, stocking timing, stocking density, fingerling size and/or growing period) on farming performance and identify optimal farming arrangements.

Limited by data availability, the advanced model simulates the growth of GIFT tilapia under different situations based on the growth pattern of GIFT tilapia under a specific situation (1 g fingerlings stocked at 1 200 fish/mu density). The simulation can be improved by more data and understanding of the relationship between feed use and fish growth under different water temperature and/or stocking density.

3.2 IMPACTS OF STOCKING TIMING ON FARMING PERFORMANCE

With seasonal variation in the water temperature, the stocking timing matters for farming performance – a crop that is grown in more favourable water temperatures would tend to have better performance. The advanced model calibrated with seasonal variation in the water temperature is used to assess the profitability under different stocking timings.

Calibrating the seasonal water temperature variation

The daily temperature pattern in 2014 in Wenchang, Hainan province,[13] is used to calibrate the water temperature in the advanced model. Based on Xu, Wang and Chen

[13] Wenchang is a city in Hainan province in China. The temperature data have been obtained from the site http://tianqi.2345.com/wea_history/59856.htm (in Chinese).

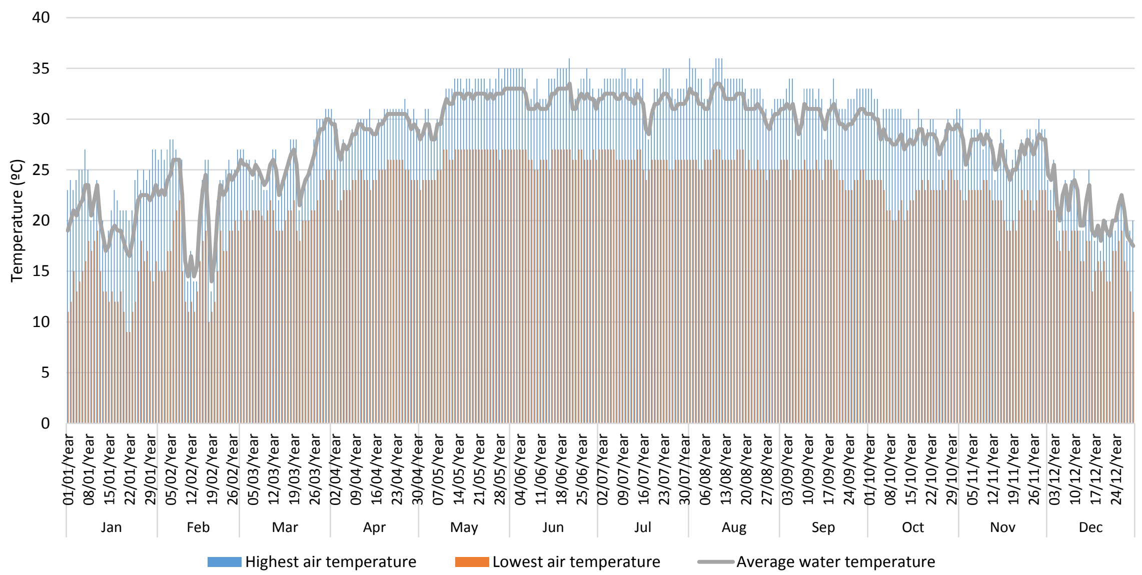
(2002), the average water temperature each day is assumed to be equal to the average of the highest and lowest air temperature plus 2 °C (Figure 17).

The seasonal water temperature variation pattern and its impact on the feeding ration is illustrated in Figure 18 and summarized as follows.

- Low temperature: 12 weeks, from week 10 December to week 26 February, during which the weekly average water temperature is around 20 °C and the weekly average adjustment factor is below 0.5.
- Mild temperature: 7 weeks total (including four weeks from week 5 March to week 26 March, and three weeks from week 19 November to week 3 December), during which the weekly average water temperature is around 25 °C and the weekly average adjustment factor is around 0.8.
- High temperature: 15 weeks, from 14 May to 20 August, during which the weekly average water temperature is above 30 °C and the weekly average adjustment factor is around 0.8.
- Most favourable water temperature: 18 weeks total (including six weeks from week 2 April to week 7 May, and 12 weeks from week 27 August to week 12 November), during which the water temperature is about 30 °C and the adjustment factor is around 1.

The pattern of the seasonal water temperature variation in Figure 17, which is assumed to replicate itself every year, is used to calibrate the seasonal variation of the water temperature in the advanced model.

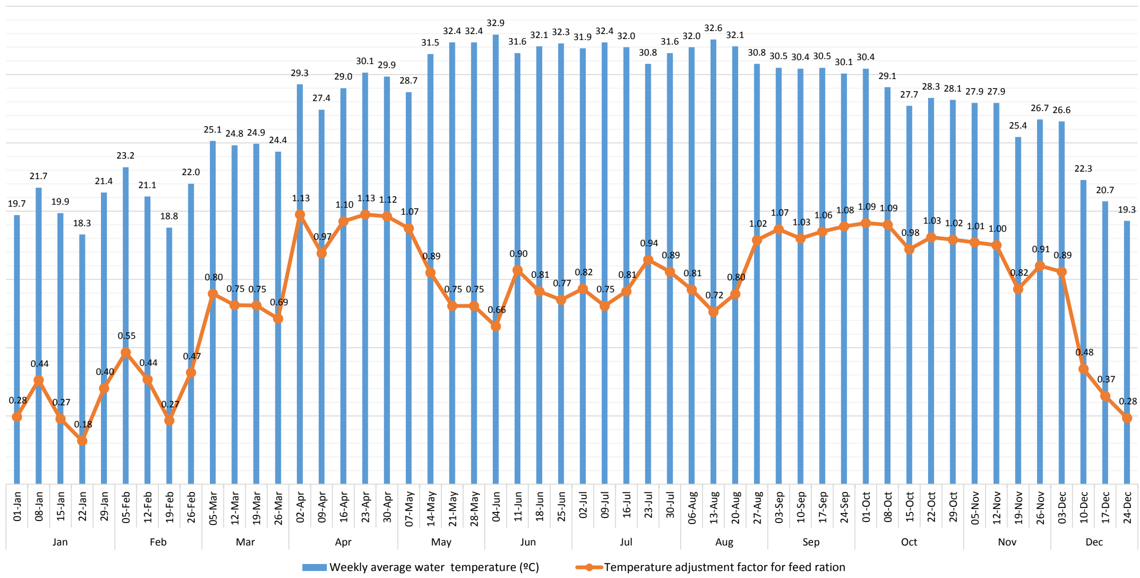
FIGURE 17
Calibrating the seasonal variation of water temperature in the advanced model



Profitability under different stocking timings

Given the fingerling size (1 g), stocking density (1 200 fish/mu, or 1.8 fish/m^2) and the feeding regime (feeding rations in Figure 12 and temperature adjustment factors in Figure 13), the profit of a crop is determined by the stocking timing and crop length. For each of the 52 weekly stocking timing under examination, the profit per week is calculated for all possible crop lengths, among which the greatest profit per week is considered the profitability for the specific stocking timing. The profitability for all the 52 stocking timings and associated key variables (growing period and harvest size) are presented in Figure 19.

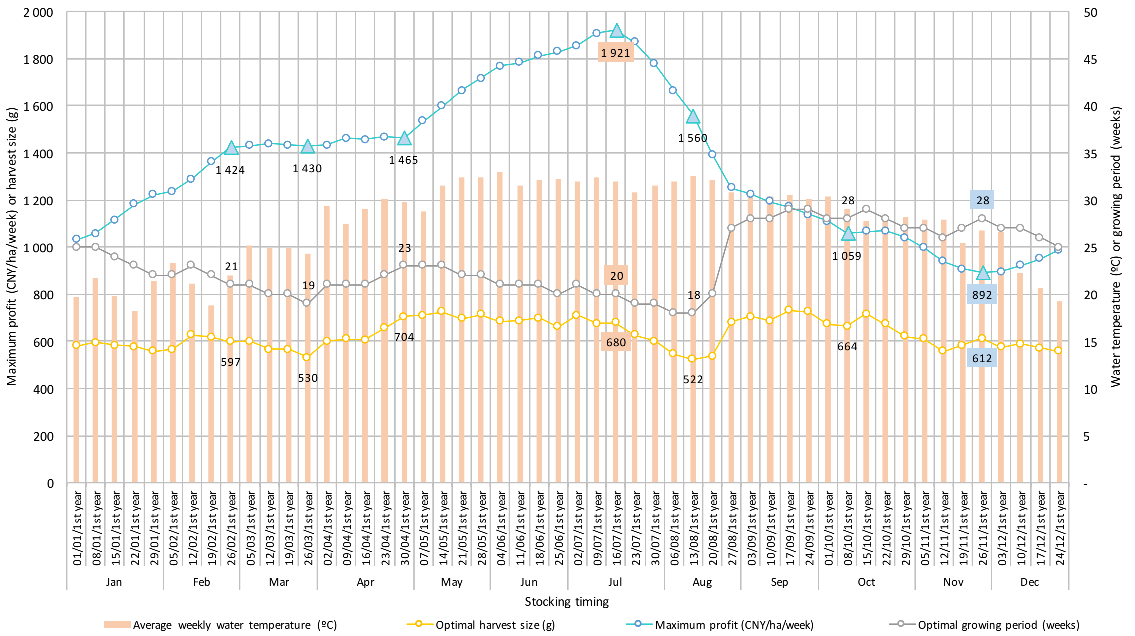
FIGURE 18
Average weekly water temperature and corresponding temperature adjustment factors



December to February (26 November to 26 February)

When stocking the fish on 26 November (1 g fingerlings, 1 200 fish/mu), the maximum achievable profit would be CNY 892/ha per week when harvesting 612 g fish after 28 weeks on 11 June the next year. This is the lowest profitability among all 52 stocking timings (Figure 19).

FIGURE 19
Profitability of individual crops under different stocking timings



The low profitability is due to slow growth at the fingerling stage in winter – it would take 17 weeks from 26 November to 26 March the next year for the fish to reach 105 g, whereas it would take only 11 weeks in the warmer water from 26 March to 11 June for the fish to reach 612 g (Figure 20).

Moving the stocking timing from 26 November forward would increase the profitability by reducing the time in the low temperature, less productive season and increasing the time in the more productive season; the upward trend would continue until 26 February (Figure 19).

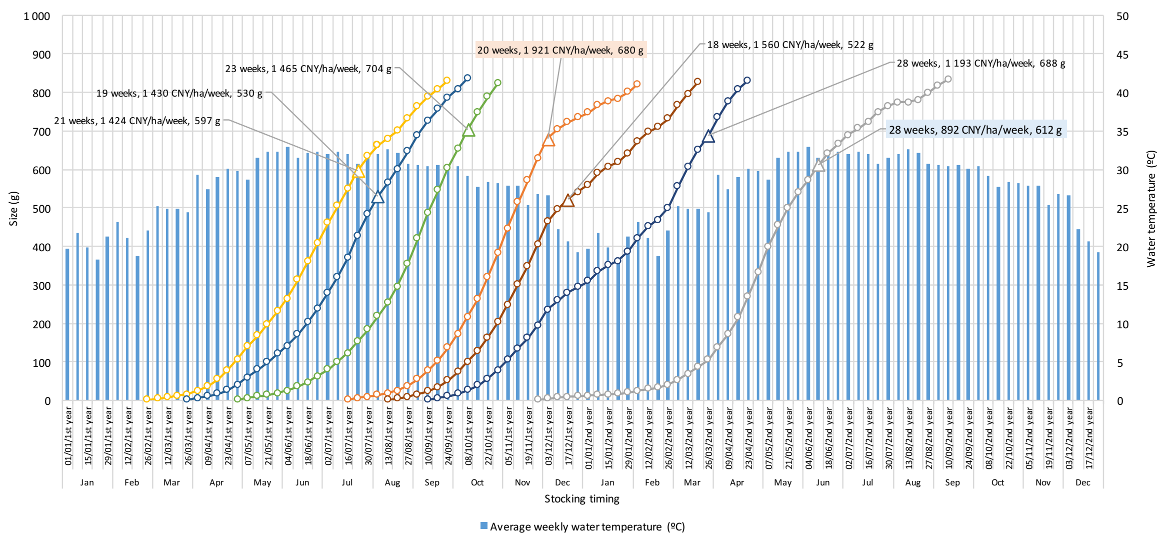
March and April (26 February to 30 April)

The profitability of stocking the fish on 26 February would be CNY 1 424/ha per week, achieved when harvesting 597 g fish after 21 weeks on 23 July (Figure 20). Postponing the stocking timing a little within March would not affect the profitability much, but the optimal growing period tends to be shortened; hence, the optimal harvest size is reduced in order to avoid the inefficiency of growing large fish in the hot summer (Figure 19). For example, when stocking the fish on 26 March, the maximum achievable profitability would be CNY 1 430/ha per week when harvesting 530 g fish after 19 weeks on 6 August (Figure 20).

Moving the stocking timing from the end of March towards the end of April would slightly increase the profitability (Figure 19). The profitability of stocking on 30 April would be CNY 1 465/ha per week, achieved when harvesting 704 g fish after 23 weeks on 1 October. The optimal growing period is four weeks longer than stocking on 26 March because the cooler weather in September is more suitable for growing large fish.

FIGURE 20

Growth patterns and farming performance of individual crops under different stocking timings (1 g fingerlings, 1 200 fish/mu)



May to mid-July (30 April to 16 July)

Moving the stocking timing from the end of April towards mid-July would significantly increase profitability (Figure 19) because of reducing the exposure to a high temperature, relatively less conducive season from May to August and increasing exposure to a more conducive season in September and October. The optimal growing period is declining so as to reduce the exposure to the low temperature, less conducive season in December. Accordingly, the optimal harvest size is declining.

Stocking the fish on 16 July would be the most profitable among the 52 weekly stocking timings; the maximum profit is CNY 1 921/ha per week, achieved when harvesting 680 g fish after 20 weeks in early December before the low temperature season starts (Figure 20).

Mid-July to August (16 July to 27 August)
Moving the stocking timing from mid-July towards the end of August would reduce the profitability because the farmer would need to shorten the optimal growing period in order to reduce the exposure to the low temperature season in December (Figure 19). For example, the profitability of stocking on 13 August would be CNY 1 560/ha per week, achieved when harvesting 522 g fish after 18 weeks on 17 December (Figure 20).

September to November (27 August to 26 November)
Starting during late August, the growing cycle has to enter the low temperature season from December on in order to reach a desirable size (over 500 g). Moving the stocking timing forward during the period from September to November would increase the exposure to the low temperature season and hence reduce profitability. The growing period would be much longer than stocking from February to August, whereas the optimal harvest size would not differ much (Figure 19).

For example, the profitability of stocking on 8 October would be CNY 1 059/ha per week, achieved when harvesting 664 g fish in 28 weeks on 23 April. This cycle also covers the entire winter, but its profitability is higher than the one with the lowest profitability (i.e. stocking on 26 November) because the fish enter the low temperature season with a relatively large size – in this situation, the fish would reach about 70 g on 26 November (seven weeks after stocking).

Summary

In summary, stocking 1 g fingerlings (1 200 fish/mu) in the summer on 16 July would be the most profitable; CNY 1 921/ha per week maximum profitability (20-week growing period, 680 g harvest size) is more than double the minimum profitability (CNY 892/ha per week, 28-week growing period, 612 g harvest size) when stocking at the beginning of the low temperature season on 26 November.

3.3 IMPACTS OF STOCKING DENSITY ON FARMING PERFORMANCE

Generally speaking, fish growth tends to slow down under higher stocking density because there would be more fish competing for food, oxygen and space. This stylized fact is captured in the advanced model (Figure 16).

Given the 1 g fingerling size and the feeding regime, the fish growth pattern under different stocking density from 1 200 fish/mu to 2 400 fish/mu is simulated and their profitability examined. The results indicate that, generally speaking, increasing the stocking density from 1 200 fish/mu onwards would tend to push the optimal stocking timing from 16 July forward,[14] shorten the optimal growing period and reduce the optimal harvest size, and profitability would increase until the density reaches around 2 000 fish/mu and then decline (Table 7).

Increasing the stocking density from 1 200 fish/mu to 1 300 fish/mu or 1 400 fish/mu would not change the optimal stocking timing or growing period. Although the harvest size would decrease slightly, the fish biomass would increase because more fish would be harvested under the higher density. The profitability would be higher accordingly. Under the 1 200 fish/mu stocking density, the farmer can grow the fish longer than 20 weeks for higher fish biomass at harvest, but doing so would reduce the profit because of the inefficiency (i.e. higher FCR) in farming large fish.

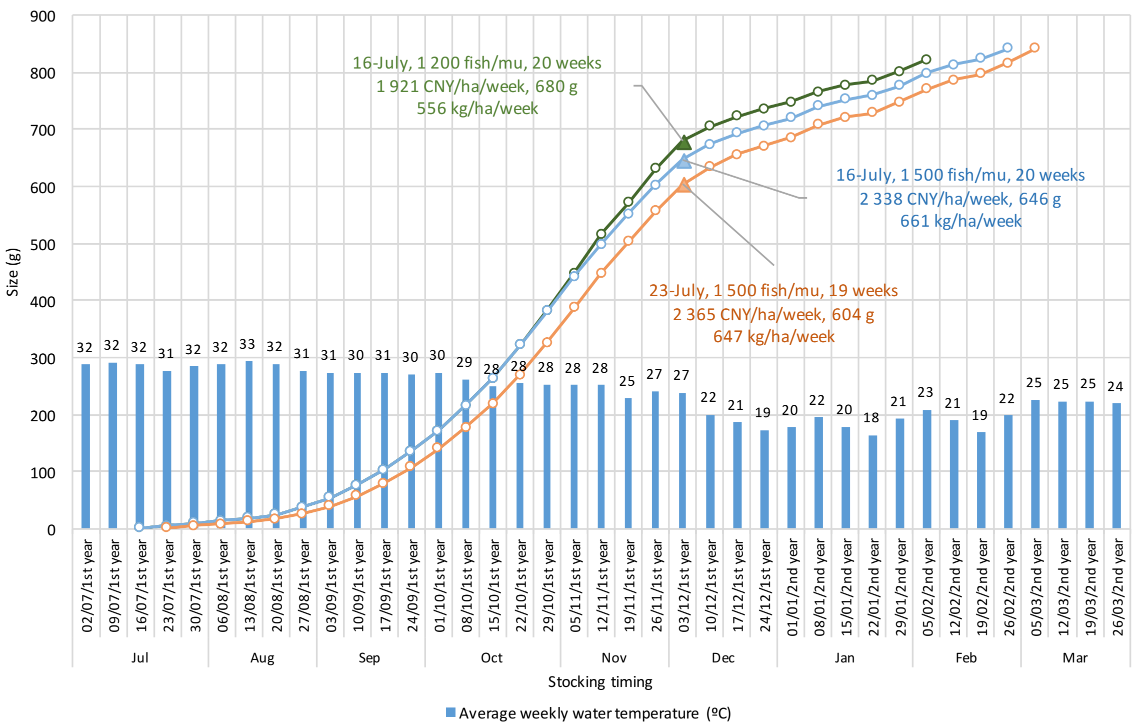
The profitability of stocking 1 500 fish/mu on 16 July would be CNY 2 338/ha per week (Figure 21), higher than the profitability under 1 200, 1 300 or 1 400 fish/mu (Table 7). However, the stocking timing of 16 July is not optimal for 1 500 fish/mu – postponing the stocking timing by one week on 23 July, yet harvesting at the same

[14] One exception is for the stocking density 2 100 fish/mu, under which the optimal stocking timing is 2 July so that the harvest size can be greater than 500 g for the higher price.

TABLE 7
Optimal farming arrangements and performance under different stocking density

Stocking density (fish/mu)	Optimal farming arrangement					
	Stocking timing	Growing period (weeks)	Harvest size (g)	Fish biomass at harvest (kg/ha)	Productivity (kg/ha/week)	Profitability (CNY/ha/week)
1 200	16/07/1st year	20	680	12 234	556	1 921
1 300	16/07/1st year	20	673	13 121	596	2 105
1 400	16/07/1st year	20	661	13 875	631	2 239
1 500	23/07/1st year	19	604	13 591	647	2 365
1 600	30/07/1st year	19	580	13 925	663	2 471
1 700	30/07/1st year	19	572	14 577	694	2 595
1 800	30/07/1st year	19	561	15 144	721	2 687
1 900	06/08/1st year	19	540	15 388	733	2 797
2 000	06/08/1st year	19	531	15 929	759	2 887
2 100	02/07/1st year	19	505	15 902	757	2 470
2 200	20/08/1st year	17	446	14 721	775	1 588
2 300	20/08/1st year	17	441	15 216	801	1 644
2 400	20/08/1st year	17	436	15 682	825	1 677

FIGURE 21
Growth patterns and farming performance of individual crops under different stocking density (1 g fingerlings)



time (i.e. reducing the growing period by one week) would increase profitability to CNY 2 365/ha per week, even though the one-week delay in stocking and the one-week decrease in the growing period would reduce the harvest size from 646 g to 604 g, and productivity from 661 kg/ha per week to 647 kg/ha per week (Figure 21). This is another example showing that technical and economic performance may not be consistent.

From 1 500 fish/mu to 2 000 fish/mu, the optimal growing period is the same at 19 weeks, whereas the stocking timing could be slightly different. The increased stocking density with the same growing period would result in a smaller harvest size. But the higher density is more than adequate to compensate the loss in size and hence the productivity increases with the stocking density.

When the stocking density is 2 000 fish/mu, the fish biomass at harvest under the optimal arrangement nearly reaches the 16 000 kg/ha limit set for the operation. When the density is increased to 2 100 fish/mu, following the same arrangement is not viable because the fish biomass at harvest would exceed the 16 000 kg/ha limit. Advancing the stocking timing to 2 July, however, would result in a 19-week crop with the harvest size over 500 g and the fish biomass within the limit.

However, when the stocking density is increased to 2 200 fish/mu, it would not be feasible to have the harvest size over 500 g within the 16 000 kg/ha capacity limit – the limit would be reached when the fish are 485 g. As a consequence, the optimal growing period is shortened to 17 weeks with the optimal harvest size at 446 g. Even with a smaller harvest size, the productivity is nevertheless higher, but the profitability is lower because of the lower price for fish below 500 g.

From 2 200 fish/mu to 2 400 fish/mu, the optimal growing period is the same; hence, the optimal harvest size is diminishing, while both productivity and profitability are increasing (Table 7).

The profitability of a higher stocking density may be higher under some stocking timings, but lower under other stocking timings. As indicated in Figure 22, the profitability of stocking the fish at 1 800 fish/mu would be higher than 1 500 fish/mu in high temperature seasons from 7 April to 5 November, yet lower in low temperature seasons from 12 November to 2 April.

For example, stocking 1 500 fish/mu would be more profitable than stocking 1 800 fish/mu when the stocking timing is 19 March, yet less profitable when the timing is 20 August (Figure 22). As indicated in Figure 23, when stocking the fish on 19 March, the fish growth paths under the stocking density 1 500 fish/mu and 1 800 fish/mu start diverging in week 15 when the fish are about 300 g. When the fish are harvested at 532 g in week 20 to realize the CNY 1 619/ha per week profitability under the 1 500 fish/mu density, the fish under the 1 800 fish/mu density are only 476 g. Because of the high water temperature which results in reduced feeding, it would take two extra weeks for the fish to grow to a desirable size and be harvested at 510 g in week 22 (Figure 23). The resulting CNY 1 369/ha per week profitability is lower than that under the 1 500 fish/mu density.

When stocking 1 500 fish/mu on 20 August, the optimal arrangement is to harvest 536 g fish in week 20 with CNY 1 975/ha per week profit (Figure 23). Raising the density to 1 800 fish/mu has little impact on fish growth because the growth paths start diverging in the low temperature season when fish are fed less yet need less energy. Therefore, the fish can still be harvested in week 20 at a little smaller but acceptable size (i.e. 529 g) and with a much higher profit (CNY 2 495/ha per week) because of more fish stocked.

FIGURE 22
Impact of stocking timing and density on profitability

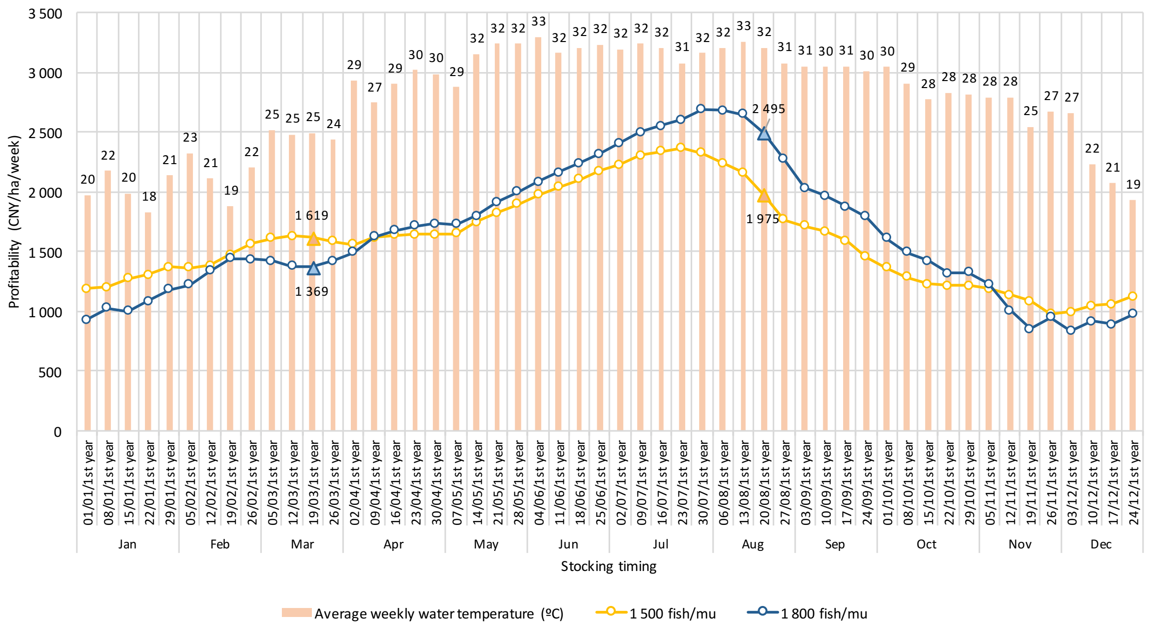
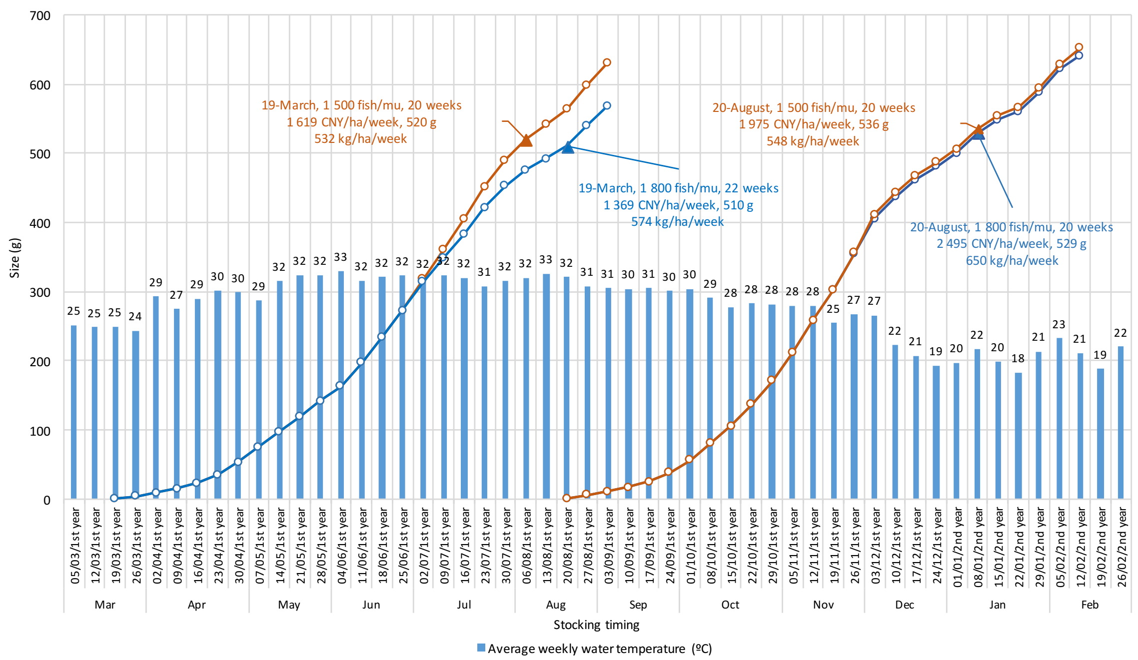


FIGURE 23
Impact of stocking density on profitability under seasonal variations in the water temperature



4. Optimizing crop arrangements for better performance

The examination of the impacts of farming arrangements on the profitability of an individual crop in the previous section provides useful guidance for farmers to improve their farming performance. However, an arrangement that maximizes the profitability of an individual crop may not be optimal for the overall profitability of a multiple-crop production cycle.

In this section, the advanced model is used to simulate the performance of various crop arrangements and identify the crop arrangement that maximizes the overall profitability of a production cycle. As seasonal water temperature variation tends to repeat over years, the duration of a production cycle repeatable over years should be equal to an integer number of years (e.g. 1 year, 2 years, 3 years, and so on). A production cycle could be 1 year 1 crop, 1 year 2 crops, 1 year 3 crops, 2 year 2 crops, 2 year 3 crops, 2 year 4 crops, 2 year 5 crops, and so on. The overall profitability of a production cycle is gauged by the sum of the profits of all crops in the cycle divided by the duration of the cycle and can be measured by profit per hectare per week or by profit per hectare per year.

In the advanced model, crop arrangements for a production cycle include the selection of four key variables (stocking timing, fingerling size, stocking density and growing period) for each crop in the cycle. Given the feeding regime built in the model, the harvest size is endogenously determined when the four variables are selected.

Although daily fish growth is simulated in the model, the analysis is conducted weekly. Therefore, only 52 weekly stocking timings are considered. For simplicity, only 1 g fingerlings are considered in most simulations except for the examination of a two-tier farming system where the farmer can select four fingerling sizes (1 g, 50 g, 100 g and 150 g) for stocking in outgrowing ponds. The range of stocking density varies in different simulations. For example, for arrangements with 1 g fingerlings and over 500 g harvest size, 17 stocking densities from 800 fish/mu to 2 400 fish/mu with a 100 fish/mu increment (i.e. 800 fish/mu, 900 fish/mu, 1 000 fish/mu, and so on) are considered,[15] whereas for arrangements intended for the production of large fingerlings, the range of stocking density is set at 1 500–110 000 fish/mu with a 500 fish/mu increment. In total, 28 growing periods from 3 weeks to 30 weeks are considered because there is no relevant crop arrangement outside this growing period range that would result in a positive profit or fish biomass within the 16 000 kg/ha limit.

The combination of the four key variables within their ranges would result in a number of relevant single-crop arrangements. These single-crop arrangements are used as "building blocks" to simulate all cases of a multiple-crop production cycle (e.g. 1 year 2 crops, 2 year 5 crops,[16] or 1 year 3 crops) from which profit maximizing arrangements can be identified.

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[15] The upper bound is set at 2 400 fish/mu because there is no crop arrangement for density equal to or higher than 2 500 fish/mu that would result in a positive profit. The 800 fish/mu lower bound is selected because crop arrangements with stocking density lower than 800 fish/mu tend to be less profitable; and farmers in reality usually do not stock the fish below it.

[16] There are too many possible cases for 2 years 5 crops to be simulated comprehensively. Thus, only part of the possible cases are examined.

4.1 PROFIT MAXIMIZATION FOR INDIVIDUAL CROPS ≠ OVERALL PROFIT MAXIMIZATION

In the basic model where the water temperature is constant, the profit maximizing arrangement for a single crop can be repeated over time. However, in the advanced model, which captures seasonal variation in the water temperature, farmers would need to maximize the overall profitability of multiple crops that are usually subject to different water temperature patterns.

A stepwise strategy is to first determine the profit maximizing arrangement for the first crop, then determine the one for the second crop, the third crop, and so on. This seemingly straightforward strategy may nevertheless not maximize the overall profitability.

For example, when stocking 1 g fingerlings at 1 200 fish/mu on 28 May, the most profitable arrangement is to harvest after 22 weeks on 29 October, with CNY 1 716/ha per week of profit. After two weeks for pond preparation, another crop should start on 11 November with the same stocking density. The most profitable arrangement for the second crop is to harvest after 26 weeks, on 14 May of the next year, with CNY 939/ha per week of profit. The two crops plus the time for pond preparation (two weeks for each crop) would take 52 weeks, which means that they constitute a 1-year-2-crop production cycle repeatable over years. As the maximum profitability is achieved in both crops, one may expect that their overall profit (CNY 1 297/ha per week) would be the maximum profitability for 1 year 2 crops starting on 28 May. This is, however, not the case.

If the farmer harvests the fish one week earlier on 22 October, the 21-week first crop would yield CNY 1 709/ha per week of profit, a little less than the maximum profitability (CNY 1 716/ha per week) achieved under the 22-week arrangement. However, shortening the first crop by one week allows the second crop to start one week earlier on 4 November and last one week longer (i.e. 27 weeks) when harvesting on 14 May the next year. The resulting profitability in the second crop of CNY 996/ha per week is about CNY 57/ha per week higher than the CNY 939/ha per week achieved under the 26-week second crop starting on 11 November. As the profitability gain from the second crop (57 CNY/ha/week) outweighs the profitability loss from the first crop (7 CNY/ha/week), the overall profitability of these two crops (CNY 1 311/ha per week) is greater than the CNY 1 297/ha per week profitability under the arrangement of stepwise profit maximization in both crops.

In the example above, the arrangement that maximizes the profitability of the first crop would result in a less opportune stocking timing for the second crop. Even with the maximum profitability achieved in both crops, the overall profitability is suboptimal, which can be improved by shortening the growing period of the first crop by one week.

In summary, as the harvest timing of a crop affects the stocking timing of the next one, the arrangement of an individual crop would affect not only its own performance but also that of the next crop. With such path dependency, the stepwise strategy that maximizes the profitability of individual crops separately is not necessarily a strategy that maximizes the overall profitability; farmers should take a holistic approach to maximize the overall profitability of multiple crops.

4.2 BENCHMARK ARRANGEMENT: 1 YEAR 2 CROPS

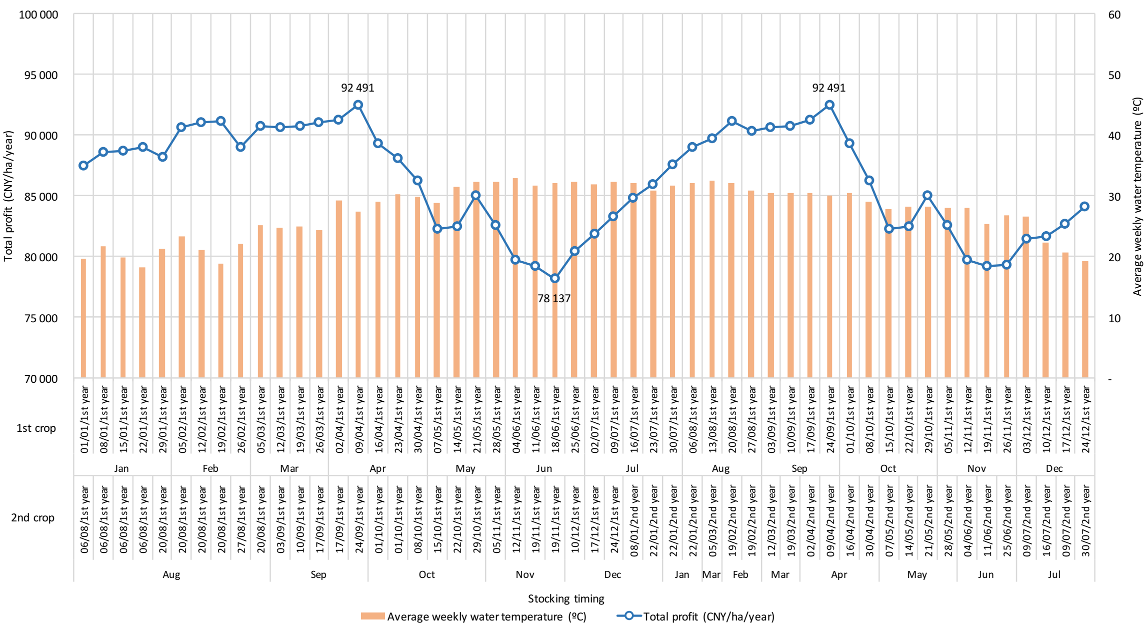
Farmers normally have control over stocking timing, stocking density and crop length. They may not have access, however, to large-size fingerlings when there are no readily accessible commercial nurseries around, and they also lack technology, facilities or manpower to have on-farm nursing operations. Therefore, the situation where the farmer can only stock 1 g fingerlings will be considered first. This assumption would be relaxed later.

Five arrangements – 1 year 1 crop, 1 year 2 crops, 1 year 3 crops, 2 years 3 crops, and 2 years 5 crops – are simulated. The results indicate that, given 1 g fingerlings, 1 year 2 crops is more profitable than other arrangements.

Given the water temperature pattern, the suitable growing period is from 15 to 30 weeks, depending on the stocking timing. Therefore, 1 year 1 crop or 2 years 3 crops (average 1 year 1.5 crops), under which the average growing period exceeds 30 weeks, would have to include a crop with an inefficiently long duration. On the other hand, 1 year 3 crops, under which the average growing period is about 15 weeks,[17] would not be able to have a long enough growing period for all the three crops to be profitable – while a 15-week crop could be profitable under the most favourable water temperature, the growing period needs to be longer in the low-temperature season for the fish to reach desirable size. The arrangement of 2 years 5 crops (average 1 year 2.5 crops) is possible, but its overall profitability is generally lower than 1 year 2 crops.

Table 8 presents the profit maximizing arrangements under 1 year 2 crops for each of the 52 initial weekly stocking timings. The results are illustrated in Figure 24 and summarized below.

FIGURE 24
Overall profitability under 1 year 2 crops (1 g fingerlings)



Symmetric arrangements

Stocking on 27 August for the first crop and on 19 February the next year for the second crop would generate a total profit of CNY 90 352/ha per year, which is the maximum profitability for 1 year 2 crops starting on 27 August. Symmetrically, one may expect that stocking the first crop on 19 February and the second crop on 27 August would also be the profit-maximizing arrangement for 1 year 2 crops starting on 19 February. This is nevertheless not the case. For a 1-year-2-crop cycle starting on 19 February, the profit-maximizing arrangement would be to stock the first crop on 19 February and the second crop on 20 August, which would yield CNY 91 172/ha per year (Table 8).

However, among the 52 weekly stocking timings, there are 28 stocking timings (i.e. 14 pairs) with symmetric arrangements that are both profit maximizing. They

[17] Excluding six weeks for pond preparation (two weeks for each crop), there are 46 weeks in total for three crops, which means the average crop length is about 15 weeks.

TABLE 8
Profit maximizing arrangements under 1 year 2 crops (1 g fingerlings)

Stocking timing		Stocking density (fish/mu)			Growing period (weeks)			Harvest size (g)			Productivity				Profitability			
											Weekly (kg/ha/week)			Annual (kg/ha/year)	Weekly (CNY/ha/week)			Annual (CNY/ha/year)
1st crop	2nd crop	1st crop	2nd crop	Average	1st crop	2nd crop	Average	1st crop	2nd crop	Average	1st crop	2nd crop	Overall		1st crop	2nd crop	Overall	
01/01/1st year	06/08/1st year	1 200	2 000	1 600	29	19	24	701	531	595	407	759	549	28 549	866	2 887	1 682	87 469
08/01/1st year	06/08/1st year	1 200	1 900	1 550	28	20	24	689	559	609	413	724	545	28 327	934	2 754	1 704	88 609
15/01/1st year	06/08/1st year	1 200	1 800	1 500	27	21	24	681	585	623	423	687	539	28 054	1 005	2 591	1 706	88 729
22/01/1st year	06/08/1st year	1 300	1 700	1 500	26	22	24	648	619	632	451	657	547	28 418	1 078	2 450	1 711	88 990
29/01/1st year	20/08/1st year	1 200	1 900	1 550	27	21	24	712	545	610	442	675	545	28 342	969	2 612	1 696	88 185
05/02/1st year	20/08/1st year	1 200	1 900	1 550	26	22	24	698	557	611	448	661	547	28 428	1 058	2 541	1 743	90 620
12/02/1st year	20/08/1st year	1 300	1 800	1 550	25	23	24	658	588	617	475	635	552	28 688	1 145	2 406	1 751	91 059
19/02/1st year	20/08/1st year	1 300	1 700	1 500	24	24	24	650	625	636	488	613	550	28 617	1 228	2 279	1 753	91 172
26/02/1st year	27/08/1st year	1 200	1 800	1 500	24	24	24	680	582	622	471	605	538	27 969	1 192	2 229	1 711	88 969
05/03/1st year	20/08/1st year	1 600	1 600	1 600	22	26	24	550	664	607	550	569	560	29 121	1 443	2 002	1 744	90 700
12/03/1st year	03/09/1st year	1 400	1 900	1 650	23	25	24	606	560	580	509	591	552	28 699	1 286	2 167	1 744	90 666
19/03/1st year	10/09/1st year	1 400	2 000	1 700	23	25	24	620	533	569	521	592	558	29 025	1 333	2 125	1 744	90 686
26/03/1st year	17/09/1st year	1 400	2 100	1 750	23	25	24	637	507	559	535	592	565	29 362	1 368	2 104	1 750	91 004
02/04/1st year	17/09/1st year	1 600	1 900	1 750	22	26	24	564	557	561	564	567	566	29 431	1 502	1 972	1 755	91 270
09/04/1st year	**24/09/1st year**	**1 700**	**2 000**	**1 850**	**22**	**26**	**24**	**554**	**530**	**541**	**588**	**568**	**577**	**30 026**	**1 552**	**1 973**	**1 779**	**92 491**
16/04/1st year	01/10/1st year	1 700	2 100	1 900	22	26	24	557	503	527	592	566	578	30 055	1 585	1 832	1 718	89 338
23/04/1st year	01/10/1st year	1 800	1 900	1 850	21	27	24	510	554	532	598	544	568	29 549	1 712	1 680	1 694	88 078
30/04/1st year	08/10/1st year	1 800	2 000	1 900	21	27	24	511	530	521	600	548	571	29 686	1 732	1 600	1 658	86 239
07/05/1st year	15/10/1st year	1 800	2 000	1 900	21	27	24	511	518	515	600	536	564	29 339	1 728	1 465	1 581	82 231
14/05/1st year	22/10/1st year	1 900	2 100	2 000	21	27	24	510	501	505	632	544	583	30 304	1 812	1 406	1 586	82 473
21/05/1st year	29/10/1st year	2 100	2 000	2 050	21	27	24	502	511	506	687	528	599	31 132	1 961	1 375	1 634	84 977
28/05/1st year	05/11/1st year	2 000	1 900	1 950	21	27	24	529	507	518	690	498	583	30 310	2 017	1 247	1 588	82 566
04/06/1st year	12/11/1st year	1 900	1 700	1 800	21	27	24	559	512	537	693	450	558	28 999	2 059	1 114	1 532	79 667
11/06/1st year	19/11/1st year	1 800	1 700	1 750	21	27	24	584	503	544	685	442	550	28 576	2 109	1 057	1 522	79 158
18/06/1st year	**19/11/1st year**	**2 000**	**1 600**	**1 800**	**20**	**28**	**24**	**530**	**532**	**531**	**723**	**426**	**551**	**28 678**	**2 268**	**941**	**1 503**	**78 137**
25/06/1st year	10/12/1st year	1 500	1 500	1 500	22	26	24	702	505	603	658	405	522	27 147	2 132	1 047	1 547	80 469
02/07/1st year	17/12/1st year	1 500	1 600	1 550	22	26	24	708	504	602	664	432	539	28 013	2 160	1 074	1 575	81 902
09/07/1st year	24/12/1st year	1 500	1 600	1 550	22	26	24	705	518	609	661	444	544	28 301	2 214	1 078	1 602	83 311
16/07/1st year	08/01/2nd year	1 500	1 600	1 550	23	25	24	706	522	611	636	464	547	28 421	2 144	1 156	1 631	84 802
23/07/1st year	22/01/2nd year	1 500	1 600	1 550	24	24	24	707	529	615	612	488	550	28 600	2 086	1 220	1 653	85 958
30/07/1st year	22/01/2nd year	1 600	1 400	1 500	23	25	24	663	591	630	637	460	545	28 329	2 283	1 129	1 684	87 580
06/08/1st year	22/01/2nd year	1 700	1 300	1 500	22	26	24	619	648	632	657	451	547	28 418	2 450	1 078	1 711	88 990
13/08/1st year	05/03/2nd year	1 500	1 700	1 600	27	21	24	706	512	603	548	567	556	28 938	1 843	1 577	1 725	89 724
20/08/1st year	19/02/2nd year	1 700	1 300	1 500	24	24	24	625	650	636	613	488	550	28 617	2 279	1 228	1 753	91 172
27/08/1st year	19/02/2nd year	1 900	1 200	1 550	23	25	24	558	693	611	637	462	546	28 396	2 428	1 098	1 738	90 352
03/09/1st year	12/03/2nd year	1 900	1 400	1 650	25	23	24	560	606	580	591	509	552	28 699	2 167	1 286	1 744	90 666
10/09/1st year	19/03/2nd year	2 000	1 400	1 700	25	23	24	533	620	569	592	521	558	29 025	2 125	1 333	1 744	90 686
17/09/1st year	02/04/2nd year	1 900	1 600	1 750	26	22	24	557	564	561	567	564	566	29 431	1 972	1 502	1 755	91 270
24/09/1st year	09/04/2nd year	2 000	1 700	1 850	26	22	24	530	554	541	568	588	577	30 026	1 973	1 552	1 779	92 491
01/10/1st year	16/04/2nd year	2 100	1 700	1 900	26	22	24	503	557	527	566	592	578	30 055	1 832	1 585	1 718	89 338
08/10/1st year	30/04/2nd year	2 000	1 800	1 900	27	21	24	530	511	521	548	600	571	29 686	1 600	1 732	1 658	86 239
15/10/1st year	07/05/2nd year	2 000	1 800	1 900	27	21	24	518	511	515	536	600	564	29 339	1 465	1 728	1 581	82 231
22/10/1st year	14/05/2nd year	2 100	1 900	2 000	27	21	24	501	510	505	544	632	583	30 304	1 406	1 812	1 586	82 473
29/10/1st year	21/05/2nd year	2 000	2 100	2 050	27	21	24	511	502	506	528	687	599	31 132	1 375	1 961	1 634	84 977
05/11/1st year	28/05/2nd year	1 900	2 000	1 950	27	21	24	507	529	518	498	690	583	30 310	1 247	2 017	1 588	82 566
12/11/1st year	04/06/2nd year	1 700	1 900	1 800	27	21	24	512	559	537	450	693	558	28 999	1 114	2 059	1 532	79 667
19/11/1st year	11/06/2nd year	1 700	1 800	1 750	27	21	24	503	584	544	442	685	550	28 576	1 057	2 109	1 522	79 158
26/11/1st year	25/06/2nd year	1 600	1 900	1 750	28	20	24	533	556	546	426	720	551	28 644	957	2 303	1 526	79 356
03/12/1st year	09/07/2nd year	1 400	2 000	1 700	29	19	24	589	530	554	399	757	544	28 276	870	2 594	1 566	81 451
10/12/1st year	16/07/2nd year	1 400	1 900	1 650	29	19	24	600	549	571	406	745	543	28 241	873	2 600	1 570	81 651
17/12/1st year	09/07/2nd year	1 600	1 600	1 600	27	21	24	526	663	594	435	692	549	28 528	1 003	2 330	1 590	82 662
24/12/1st year	30/07/2nd year	1 200	1 900	1 550	29	19	24	676	549	598	393	746	535	27 825	845	2 759	1 618	84 137

are: 22 January and 6 August; 19 February and 20 August; 12 March and 3 September; 19 March and 10 September; 2 April and 17 September; 9 April and 24 September; 16 April and 1 October; 30 April and 18 October; 7 May and 15 October; 14 May and 22 October; 21 May and 29 October; 28 May and 5 November; 4 June and 12 November; and 11 June and 19 November (Table 8 and Figure 24).

Stocking timing

Arrangements with one crop starting in February, March or early April and the other one starting in August or September would tend to have relatively high profitability, generally above CNY 90 000/ha per year, whereas those with one crop starting in June and the other in November would have relatively low profitability, generally below CNY 70 000/ha per year.

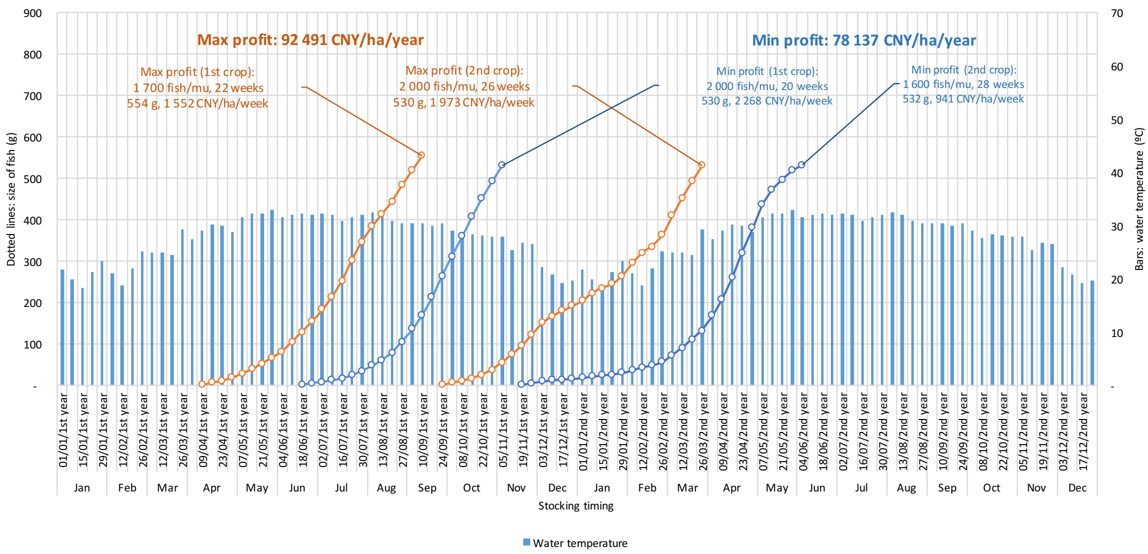
The most profitable arrangement is to start one crop on 9 April and the other crop on 24 September; the overall profitability would be CNY 92 491/ha per year. The least profitable starting time is 28 June, which would yield only CNY 78 137/ha per year (Table 8; Figure 24).

In terms of profitability for an individual crop, 18 June is actually a much better stocking timing than 9 April. The highest profitability for stocking on 18 June is CNY 2 275/ha per week under 1 900 fish/mu stocking density and 19-week growing period, whereas that for stocking on 9 April would only be CNY 1 630/ha per week under 1 700 fish/mu and 17 weeks.

However, while the first-crop profitability (CNY 2 268/ha per week) of the least profitable 1-year-2-crop arrangement is CNY 716/ha per week higher than the CNY 1 552/ha per week first-crop profitability of the most profitable 1-year-2-crop arrangement, its second-crop profitability (CNY 941/ha per week) would be CNY 1 031/ha per week less than that of the most profitable arrangement (CNY 1 973/ha per week). In addition, the CNY 2 268/ha per week high profitability is only for 20 weeks, whereas the CNY 941/ha per week low profitability is for 28 weeks (Figure 25). Therefore, the overall profitability of the least profitable arrangement (CNY 78 137/ha per year) is 16 percent lower than that of the most profitable arrangement (CNY 92 491/ha per year).

As indicated in Figure 25, starting the first crop on 18 June would force the second crop to start at the beginning of the cold season, which would take a long time for the fish to reach market size and result in low profitability. Generally speaking, the initial

FIGURE 25
Most versus least profitable arrangements under 1 year 2 crops (1 g fingerlings)



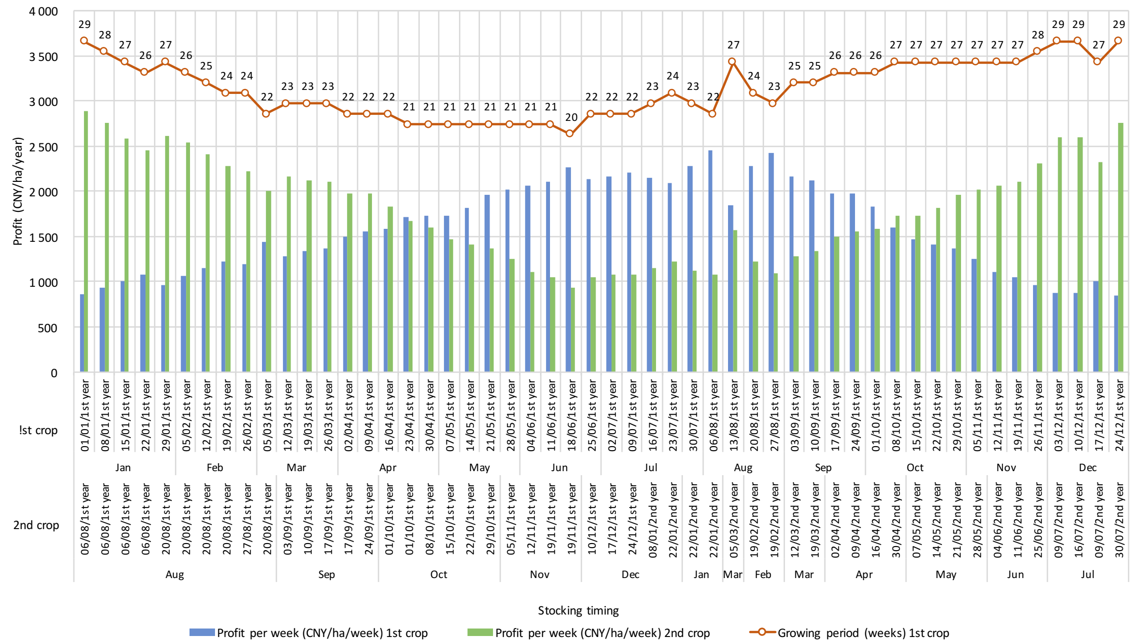
stocking timing should not be selected based on the maximization of the profitability of the first crop, which may force the next crop to start at a bad timing and result in low overall profitability. Importantly, stocking small-size fingerlings for outgrowing at the beginning of the cold season tends to result in low profitability and hence should be avoided.

Growing period and harvest timing

The 52 initial weekly stocking timings in Table 8 correspond to only 38 unique harvest timings, which means that that there are 14 cases of identical harvest timings. This indicates that optimal farming arrangements require the adjustment of the growing period under different climate conditions.

For example, when starting on 1 January, the optimal 1-year-2-crop arrangement is to stock 1 200 fish/mu and harvest the fish after 29 weeks, followed by a second stocking of 2 000 fish/mu on 6 August and harvesting after 19 weeks;[18] the profitability of the first and second crop and the overall profitability are CNY 866/ha per week, CNY 2 887/ha per week, and CNY 87 469/ha per year, respectively. When starting one week later on 8 January, the first crop should be shortened by one week so that the second crop can still start on 6 August and its growing period increased by one week with the harvest time postponed for one week. The profitability gain in the first crop would outweigh the profitability loss in the second crop and hence the overall profitability would increase. Similar growing period adjustments apply to nearly all stocking timings from January to early March (Figure 26). Indeed, for 10 initial stocking timings during this period, the optimal stocking timings for the second crop are all in August, including four cases on 6 August and five cases on 20 August (Table 8; Figure 26).

FIGURE 26
Growing period under 1 year 2 crops (1 g fingerlings)



[18] Although the 29-week crop length is not profit maximizing for the first crop – shortening it by four weeks would increase the profitability from CNY 866/ha per week to CNY 1 032/ha per week, it is the arrangement that maximizes the overall profitability.

Stocking density

For the 52 arrangements in Table 8, the stocking density ranges from 1 200 fish/mu to 2 100 fish/mu in both the first and second crops (Figure 27). The stocking density is positively correlated with the water temperature (Figure 28) and negatively correlated with harvest size (Figure 29).

FIGURE 27
Stocking density and stocking timing under 1 year 2 crops

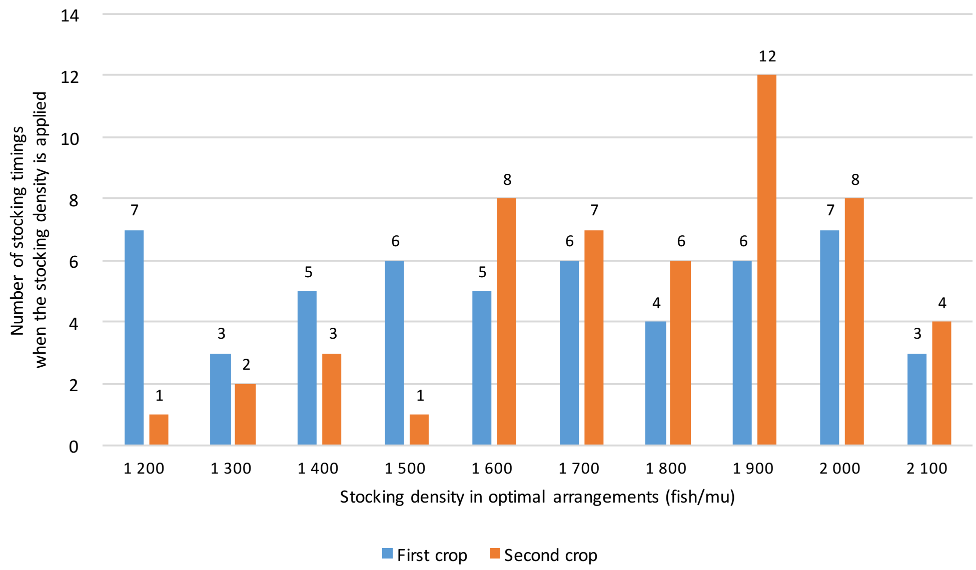
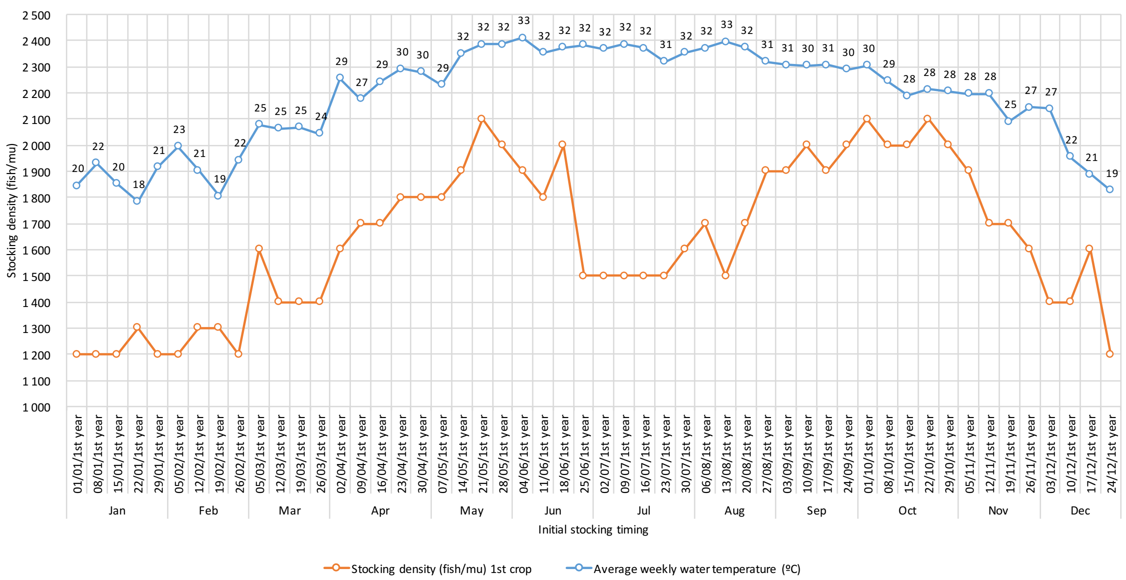
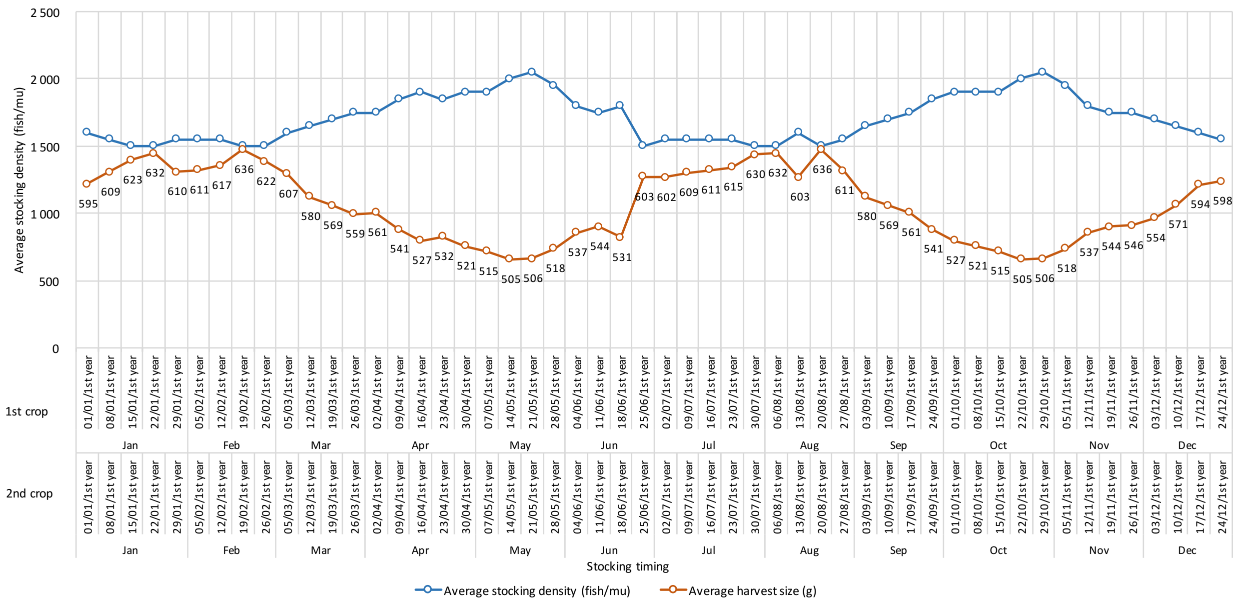


FIGURE 28
Stocking density and water temperature under 1 year 2 crops



These results indicate that there is no single stocking density that is optimal under all situations. Given the fingerling size, stocking density needs to be adjusted according to stocking timing and growing period. For example, when starting on 26 March, the optimal arrangement for the first crop is to stock 1 400 fish/mu and harvest after 23 weeks and then stock 2 100 fish/mu and harvest after 25 weeks, which would yield

FIGURE 29
Stocking density and harvest size under 1 year 2 crops



CNY 91 004/ha per year of profit (CNY 1 368/ha per week and CNY 2 104/ha per week for the first and second crop, respectively). When the starting date is moved forward by one week to 2 April, if the same arrangements of stocking density and growing period are used, the overall profit would be CNY 60 268/ha per year only (CNY 1 419/ha per week and CNY 918/ha per week for the first and second crop, respectively). The much lower profitability of the second crop is due to fish weighing under 500 g at harvest size and hence the lower farmgate price. In order to allow the second crop to produce fish with a desirable size, the farmer can reduce the stocking density and/or increase the growing period of the second crop.

Suppose the farmer reduces the stocking density for the second crop to 1 800 fish/mu, yet keeps the growing period the same at 25 weeks, the overall profitability would be increased to CNY 81 491/ha per year (CNY 1 419/ha per week and CNY 1 705/ha per week for the first and second crop, respectively).

Suppose the first crop is shortened by one week to 22 weeks and the second increased to 26 weeks; accordingly, the stocking density in the second crop would need to be reduced to 1 900 fish/mu in order to keep the fish biomass within the 16 000 kg/ha limit. Under this situation, the overall profitability would be increased to CNY 90 920/ha per year (CNY 1 488/ha per week and CNY 1 972/ha per week for the first and second crop, respectively). It should be noted that shortening the growing period of the first crop would increase its profitability from CNY 1 419 to CNY 1 488/ha per week.

However, the CNY 90 920/ha per year overall profit is still not the maximum profitability when starting on 2 April. Because of the shortened growing period, the stocking density for the first crop can be increased from 1 400 to 1 600 fish/mu, which would increase the first crop profitability to CNY 1 502/ha per week and the overall profitability to CNY 91 270/ha per year.

For a crop starting in the low temperature season (from December to February), the stocking density tends to be relatively low with a relatively long growing period and large harvest size under the optimal arrangement (Figure 28). For example, when stocking on 5 February, the first crop arrangement that would maximize the overall profitability is to stock 1 200 fish/mu and harvest 698 g fish after 26 weeks (Table 8). The profitability of this first crop arrangement would generate a profit of

CNY 1 058/ha per week, which is lower than the maximum first crop profitability (CNY 1 375/ha per week) achievable by stocking 1 400 fish/mu and harvesting 503 g fish after 21 weeks. However, having a 26-week first crop would allow the second crop to have more opportune stocking timing and growing period, and the profitability gain in the second crop would exceed the profitability loss in the first crop. Given the 26-week growing period, 1 400 fish/mu is not optimal; it would be better to lower it to 1 200 fish/mu so as to mitigate the inefficiency caused by the overly long growing period.

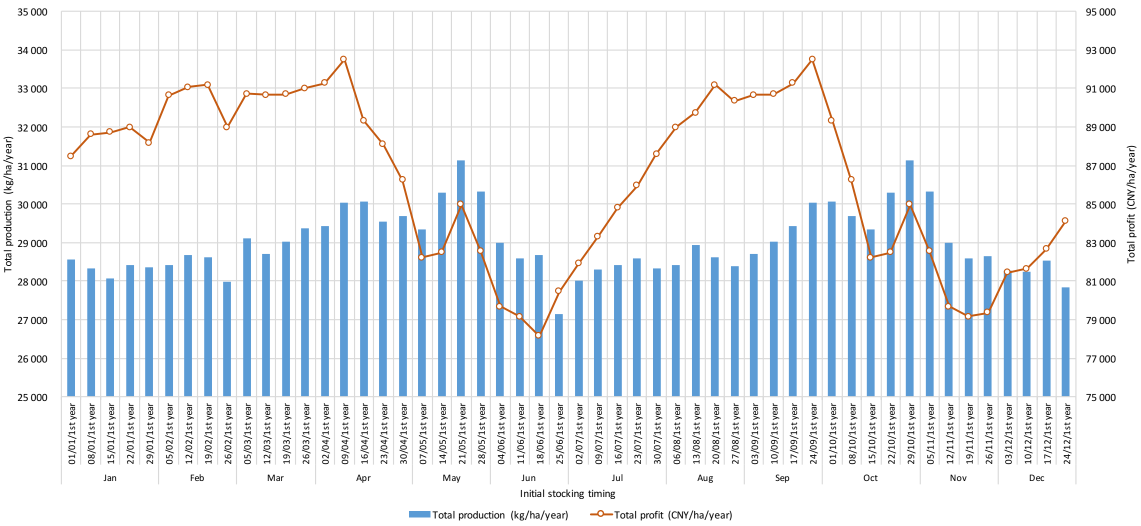
Productivity

With the fish biomass limit imposed in the model, the largest productivity allowed is 16 000 kg/ha per crop, which means 32 000 kg/ha per year under a 1-year-2-crop arrangement. For the 52 initial stocking timings, the overall productivity ranges from 27 147 kg/ha per year (stocking on 25 June) to 31 132 kg/ha per year (stocking on 21 May), with most of them below 30 000 kg/ha per year (Figure 30). This means that the fish biomass upper bound (16 000 kg/ha per crop) is not binding under many occasions. As indicated in Figure 31, for nearly all of the 52 initial stocking timings, the 16 000 fish biomass limit is binding in one crop but not in the other.

For example, when starting on 9 April, the optimal first crop arrangement under 1 year 2 crops is to stock 1 700 fish/mu and harvest 554 g fish after 22 weeks (Table 8). The first crop production is 14 132 kg/ha/crop. Increasing the stocking density from 1 700 fish/mu to 2 000 fish/mu would reduce the harvest size to 507 g (still a desirable size) yet increase the yield to 15 217 kg/ha per crop. The profit of the first crop, however, would be reduced from CNY 1 552/ha per week to CNY 1 519/ha per week.

On the other hand, the optimal arrangement for the second crop, which is to stock 2 000 fish/mu on 24 September and harvest 530 g fish after 26 weeks, would have the production (15 903 kg/ha per crop) bound by the fish biomass limit. That is, increasing the stocking density to 2 100 fish/mu is not possible in the model because the fish biomass at harvest would exceed the 16 000 fish/mu upper bound.

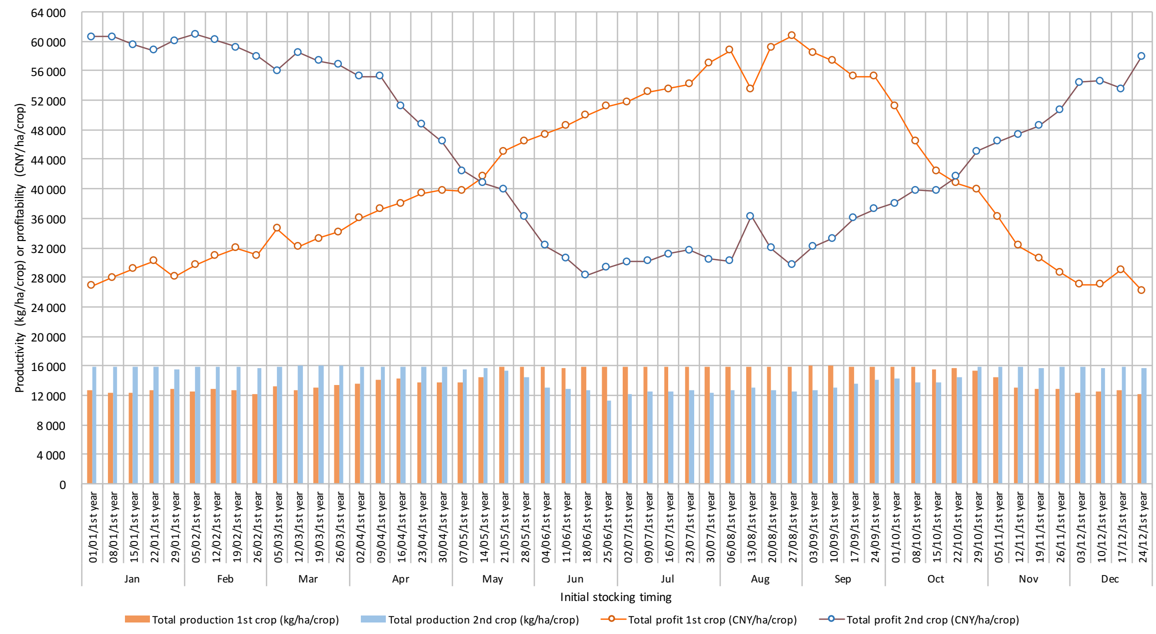
FIGURE 30
Overall productivity and profitability under 1 year 2 crops



More general 1-year-2-crop arrangements

Under a 1-year-2-crop arrangement, the crop length of the two crops (including the time for pond preparation) needs to add up to 52 weeks. This could force the farmer to adopt an inefficient arrangement in one or another or both crops.

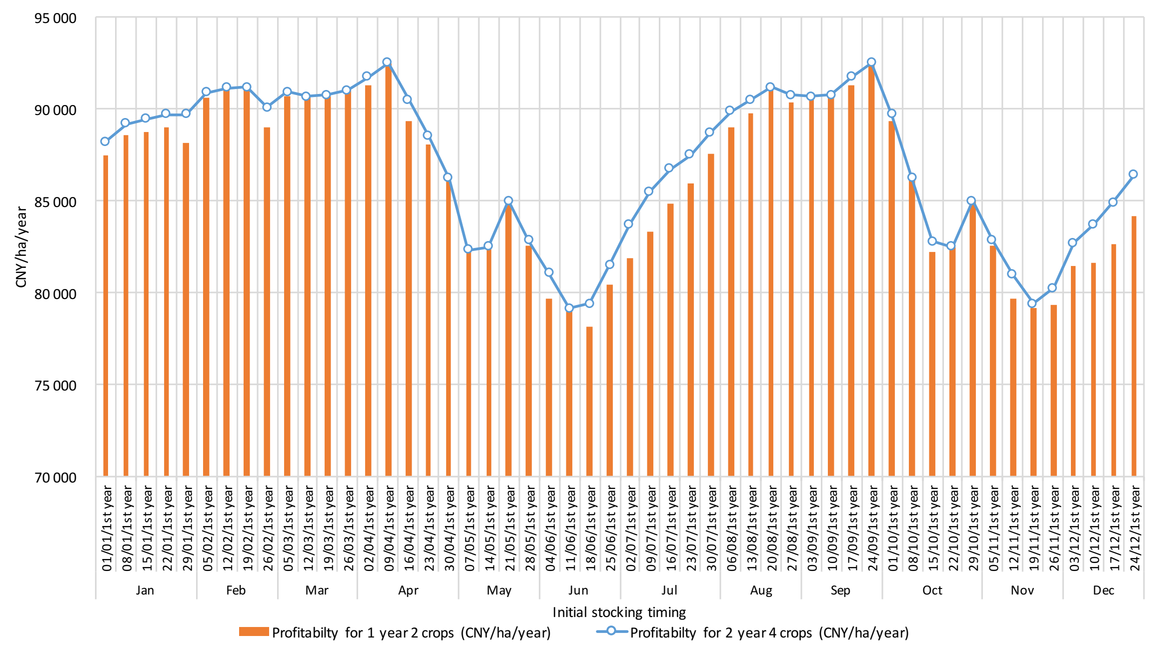
FIGURE 31
Productivity and profitability by crop under 1 year 2 crops



In order to relax the constraint, arrangements of 2 years 4 crops are simulated. A 2-year-4-crop arrangement is on average one year and two crops, but the total crop length of any two of the four crops does not need to add up to 52 weeks, even though the total crop length of the four crops would need to add up to 104 weeks.

The results indicate that 2 years 4 crops would have slightly better profitability for some initial stocking timing, yet the same profitability for other initial stocking timing (Figure 32). For example, when starting on 18 June, the profitability for 2 years 4 crops would be CNY 79 412/ha per year, greater than the CNY 78 137/ha per year profitability under 1 year 2 crops. On the other hand, when starting on 9 April, the

FIGURE 32
Profitability – 2 years 4 crops versus 1 year 2 crops



profitability for 2 years 4 crops would be the same as that for 1 year 2 crops, which means that the optimal arrangement for 2 years 4 crops would be a replicate of that for 1 year 2 crops.

Summary

The results in Table 8 are optimal arrangements that give the maximum profitability under 1-year-2-crop arrangements for different initial stocking timings. When farmers have freedom to select the initial stocking timing, they should choose an initial stocking timing (e.g. 9 April) that gives relatively high profitability and follow the arrangements described in Table 8 to realize the high profitability.

However, when farmers have to start on a less opportune stocking timing, they should not follow the arrangement for the stocking timing described in Table 8, which would keep the operation trapped in a low-profit arrangement. Instead, farmers should arrange initial crops in such a way as to allow the selection of a more opportune stocking timing.

For example, suppose that for some reason (e.g. the availability of fingerlings or other materials or financial resources) a farmer has to postpone the initial stocking timing to 23 April (two weeks later than the optimal stocking timing on 9 April), it is not advisable to follow the corresponding arrangement described in Table 8 (i.e. a 1 800 fish/mu, 21-week first crop and a 1 900 fish/mu, 27-week second crop) because it would result in a profitability of CNY 88 078/ha per year. Instead, the farmer can adopt a 50-week cycle (i.e. a 1 500 fish/mu, 20-week first crop and a 2 000 fish/mu, 26-week second crop), which would generate CNY 91 375 of total profit and allow the next cycle to start on the optimal stocking timing on 9 April.

4.3 HARVESTING SMALLER SIZE FISH

In China, tilapia below 500 g are usually considered small-size fish sold at a discounted price. However, consumers in some countries (the Philippines, for example) prefer smaller tilapia, around 250 g. Experts from the industry and academics suggest that farming relatively small-size tilapia could improve profitability,[19] especially when there is not much price discrepancy between small- and large-size fish.

It is argued that farming relatively small-size fish could shorten the production cycle and hence allow farmers to profit from more crops. Also, the FCR tends to be lower during the early stages of farming. However, farming small-size fish tends to be inefficient in the use of fingerlings. Additionally, harvesting at a small size may miss the fast growing part of the tilapia cycle. This especially matters for GIFT strains, which tend to show advantages at the later stages. In light of this background, the advanced bioeconomic model is used to examine whether it would be more profitable to farm relatively small-size fish.

Premium price for large-size fish

The harvest size in all situations in Table 8 is more than 500 g. This indicates that when, as is the case in most places in China, there is a price premium for 500–1 000 g fish (CNY 9.89/kg) compared with 250–500 g fish (CNY 7.95/kg), harvesting fish below 500 g would be suboptimal in a 1-year-2-crop arrangement.

No price discrepancy between small- and large-size fish

What if there were no price discrepancy between small- and large-size fish? Indeed, small-size fish may be preferred for various reasons. In the Philippines, for instance,

[19] See, for example, the article *Could aquaculture solve Africa's fishing crisis?*, published by *The Guardian* on 5 June 2013. Available at: https://www.theguardian.com/global-development-professionals-network/2013/jun/05/aquaculture-africa-fishing-crisis-marine.

many households prefer buying 250–300 g tilapia so that each family member can be served one whole fish at dinner. In Yunnan province, in China, restaurants like to use 250–300 g tilapia to prepare grilled fish, as they are easier to season and have more tender flesh than larger fish. In many places in Africa, 250 g and smaller fish are often sold in pieces by which the equivalent price in weight could be higher than larger fish.

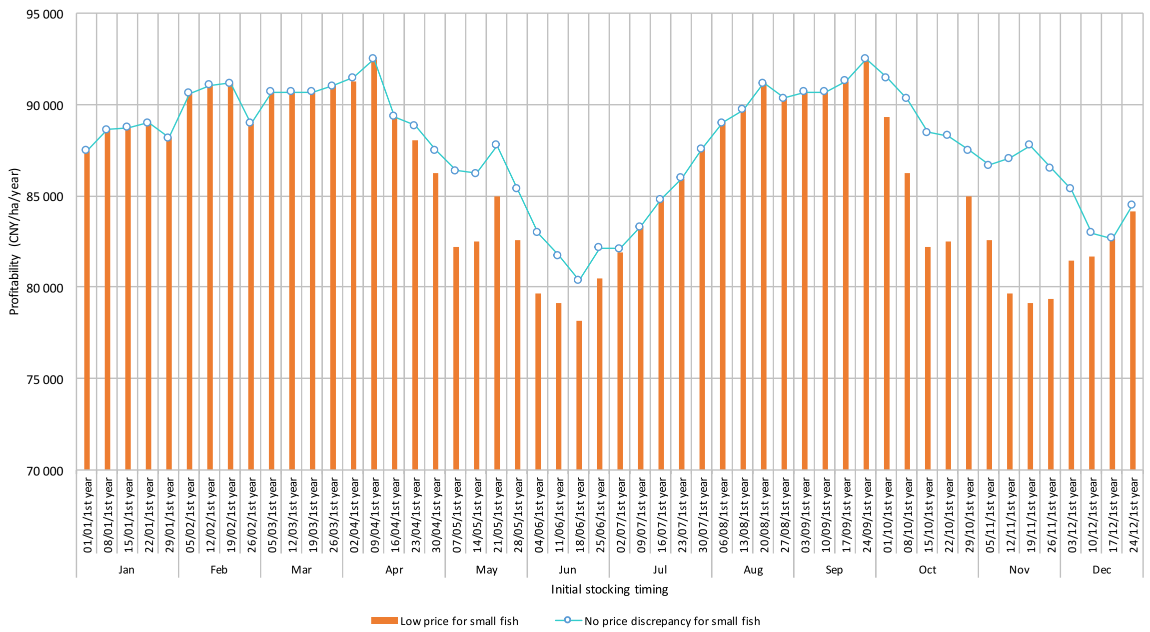
In order to examine optimal farming arrangements under no price discrepancy between small- and large-size fish, the baseline assumption is modified to let the price of 250–500 g fish be the same as that of 500–1 000 g fish (i.e. CNY 9.89/kg). Under this situation, the simulation results indicate that harvesting small-size fish could be more profitable.

1 year 2 crops

As indicated in Figure 33, the overall profitability of 1 year 2 crops could be improved by farming smaller fish. For example, under the baseline situation where the price for 250–500 g fish is lower than that of 500–1 000 g, when stocking on 19 November the optimal arrangement for the first crop is to stock 1 700 fish/mu and harvest 503 g fish after 27 weeks for CNY 1 057/ha per week profitability. The 27-week growing period is necessary – harvesting small-size fish at 483 g after 26 weeks would render a much lower first crop profitability (CNY 310/ha per week). When there is no price discrepancy for small fish, farmers could choose to stock 3 100 fish/mu and harvest 343 g fish after 24 weeks for a profit of CNY 1 685/ha per week, which is much higher than the baseline case. The overall profit would be CNY 87 762/ha per year compared with CNY 79 158/ha per year in the baseline case (Figure 33).

However, for many stocking timings (including those that give relatively high overall profit), the overall profitability is the same with or without price discrepancy for small fish (Figure 33). This implies that when the initial stocking timing allows a conducive growing period for both crops, harvesting small-size fish would not improve profitability under 1 year 2 crops. For example, when starting on 9 April, the optimal first crop arrangement would be to stock 1 700 fish/mu and harvest 554 g fish after 22 weeks for a production of 14 123 kg/ha per crop and a profit of CNY 1 552/ha per week. The farmer can increase the production to 15 889 kg/ha per crop by increasing

FIGURE 33
Overall profitability of 1 year 2 crops under no price discrepancy for small fish



the stocking density to 2 200 fish/mu and harvesting 482 g fish after 22 weeks. The profit would nevertheless be reduced to CNY 1 492/ha per week, even with no price discrepancy between 250–500 g and 500–1 000 g fish.

In summary, under a 1-year-2-crop arrangement with no price discrepancy between small- and large-size fish, harvesting small fish could increase the profit when it would take an inefficiently long growing period to grow fish above 500 g; however, harvesting smaller fish under higher stocking density could be technically efficient (i.e. increasing productivity) yet economically inefficient (i.e. reducing profitability).

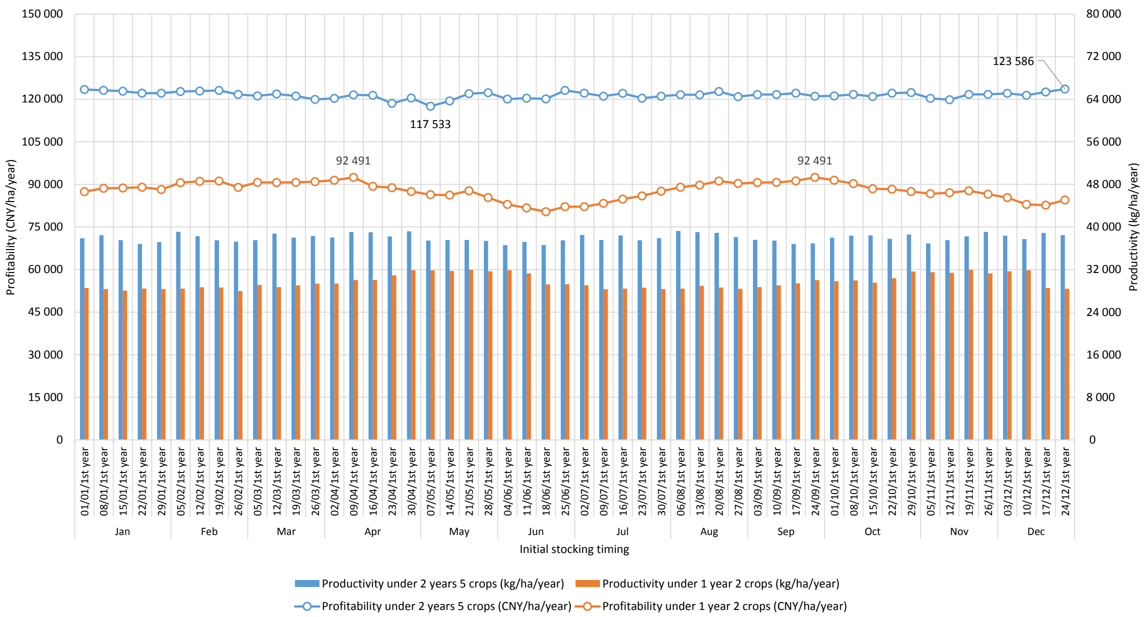
1 year 3 crops

Given no price discrepancy between small- and large-size fish, farmers can shorten the growing period and harvest small-size fish for more than two crops a year. However, when 1 g fingerlings are stocked, it is not possible to grow fish above 250 g in all the three crops under a 1-year-3-crop arrangement. Allowing for six weeks that is needed for pond preparation (two weeks per crop), a 1-year-3-crop arrangement would have an average duration of 15 weeks. Though it is possible to grow fish over 250 g in 15 weeks when the temperature is favourable, the growth during the low temperature season would take about 20 weeks.

2 years 5 crops

When examining 2-year-5-crop arrangements, all the 2-year-5-crop arrangements that maximize the overall profitability for the first two crops are identified, and then among these arrangements finding the cases that maximize the overall profitability for all the five crops. Although the arrangements identified as such (Table 9A and 9B) may not be the optimal 2-year-5-crop arrangements that maximize the overall profitability for each of the 52 stocking timings,[20] they are sufficient to show that given no price discrepancy between small- and large-size fish, harvesting small-size fish (250–500 g) through 2 years 5 crops would be more profitable than harvesting large-size fish (over 500 g) through 1 year 2 crops (Figure 34).

FIGURE 34
Profitability and productivity – 2 years 5 crops versus 1 year 2 crops



[20] It is difficult to simulate the large number of all the feasible 2-year-5-crop arrangements comprehensively.

TABLE 9A
2-year-5-crop arrangements under 1 g fingerlings and no price discrepancy between small and large fish

Starting time		Stocking density (fish/mu)						Growing period (weeks)						Harvest size (g)					
		1st crop	2nd crop	3rd crop	4th crop	5th crop	Average	1st crop	2nd crop	3rd crop	4th crop	5th crop	Average	1st crop	2nd crop	3rd crop	4th crop	5th crop	Average
Jan	01/01/1st year	3 700	4 000	2 300	4 000	2 200	3 240	19	16	25	16	18	18.8	250	252	456	251	484	312
	08/01/1st year	3 800	4 100	3 100	3 900	1 900	3 360	19	16	23	16	20	18.8	251	260	342	254	559	305
	15/01/1st year	3 500	4 100	3 100	2 700	2 200	3 120	18	16	23	18	19	18.8	253	260	342	345	484	321
	22/01/1st year	3 400	4 100	2 700	1 700	3 900	3 160	17	16	24	21	16	18.8	251	260	386	520	272	311
	29/01/1st year	3 600	3 900	3 200	1 700	3 700	3 220	17	16	23	21	17	18.8	251	270	328	520	288	308
Feb	05/02/1st year	3 800	4 200	3 900	3 800	1 900	3 520	18	15	22	17	22	18.8	263	253	272	272	557	296
	12/02/1st year	3 900	4 200	3 900	1 700	4 000	3 540	17	15	22	22	18	18.8	251	253	272	554	265	288
	19/02/1st year	3 700	4 200	3 900	1 700	3 000	3 300	16	15	22	21	20	18.8	251	253	272	520	354	303
	26/02/1st year	3 400	4 200	3 900	2 200	2 400	3 220	15	15	22	20	22	18.8	251	253	272	424	440	308
Mar	05/03/1st year	3 400	3 900	4 100	2 400	2 700	3 300	15	15	22	20	22	18.8	251	270	260	409	390	303
	12/03/1st year	3 800	4 200	4 200	2 600	3 000	3 560	16	14	22	20	22	18.8	256	251	251	395	352	290
	19/03/1st year	3 500	4 200	4 200	2 600	2 700	3 440	15	14	22	20	23	18.8	250	251	251	395	391	295
	26/03/1st year	3 500	4 100	2 700	3 900	2 900	3 420	15	14	25	17	23	18.8	250	259	388	272	365	299
Apr	02/04/1st year	3 300	3 900	3 100	3 900	2 600	3 360	15	14	24	17	24	18.8	250	270	343	272	409	302
	09/04/1st year	4 000	4 100	4 200	4 100	2 000	3 680	16	13	22	17	26	18.8	251	251	253	257	530	283
	16/04/1st year	3 800	4 200	4 100	2 100	4 100	3 660	16	13	22	21	22	18.8	251	253	260	502	260	284
	23/04/1st year	3 400	4 200	4 000	2 000	4 200	3 560	16	13	22	21	22	18.8	252	252	267	529	251	286
	30/04/1st year	4 000	4 000	4 200	2 500	3 100	3 560	17	14	20	19	24	18.8	251	262	250	424	342	294
May	07/05/1st year	3 200	4 000	4 200	1 600	4 200	3 440	16	14	20	22	22	18.8	251	262	250	648	251	290
	14/05/1st year	3 400	3 900	3 900	1 600	4 200	3 400	16	16	18	22	22	18.8	252	272	251	657	253	295
	21/05/1st year	3 700	4 000	2 600	2 000	4 100	3 280	16	18	19	19	22	18.8	252	265	343	530	260	305
	28/05/1st year	4 000	4 200	1 500	2 400	4 000	3 220	16	19	22	17	20	18.8	252	251	570	444	251	310
Jun	04/06/1st year	3 400	4 200	1 500	2 200	4 200	3 100	15	19	22	18	20	18.8	251	251	570	484	250	315
	11/06/1st year	3 600	4 000	2 100	2 200	4 000	3 180	15	21	20	19	19	18.8	251	265	439	484	252	312
	18/06/1st year	3 900	4 200	2 200	1 900	3 500	3 140	15	21	19	22	17	18.8	251	252	411	557	252	311
	25/06/1st year	4 200	3 900	1 700	3 000	3 700	3 300	15	22	21	20	16	18.8	253	272	520	354	251	303
Jul	02/07/1st year	3 900	4 100	2 400	3 000	3 600	3 400	15	22	20	20	17	18.8	270	260	409	354	271	302
	09/07/1st year	3 900	4 100	2 400	3 000	2 900	3 260	14	22	20	20	18	18.8	251	260	409	354	318	307
	16/07/1st year	4 200	4 200	3 200	3 000	2 400	3 400	14	22	19	20	19	18.8	251	251	330	354	372	301
	23/07/1st year	4 100	4 000	3 300	3 000	2 100	3 300	14	22	18	20	20	18.8	259	251	302	354	416	303
	30/07/1st year	3 900	4 200	4 100	3 000	1 800	3 400	14	22	17	20	21	18.8	270	251	251	354	474	297
Aug	06/08/1st year	3 800	4 200	3 500	2 600	3 900	3 600	14	22	18	24	16	18.8	278	253	303	409	254	291
	13/08/1st year	4 100	4 200	4 100	2 000	4 000	3 680	13	22	17	26	16	18.8	251	253	257	530	251	283
	20/08/1st year	4 200	4 100	3 900	2 600	2 700	3 500	13	22	17	24	18	18.8	253	260	272	409	345	296
	27/08/1st year	4 200	3 900	3 900	2 600	2 400	3 400	13	21	17	24	19	18.8	252	252	272	409	380	299
Sep	03/09/1st year	3 400	3 700	3 700	3 100	2 100	3 200	15	19	17	23	20	18.8	313	250	287	342	427	313
	10/09/1st year	4 000	3 700	3 700	3 100	1 800	3 260	14	19	17	23	21	18.8	262	250	287	342	497	306
	17/09/1st year	3 900	3 400	4 100	2 700	1 700	3 160	16	17	16	24	21	18.8	272	251	260	386	520	311
	24/09/1st year	4 000	3 200	3 700	3 900	1 700	3 300	18	16	16	22	22	18.8	265	251	286	272	554	298
Oct	01/10/1st year	4 200	3 400	1 600	4 100	3 900	3 440	19	15	21	22	17	18.8	251	251	645	260	272	295
	08/10/1st year	4 000	3 500	2 200	4 100	3 300	3 420	21	15	18	22	18	18.8	265	250	479	260	321	299
	15/10/1st year	4 200	3 500	2 500	4 100	2 900	3 440	21	15	17	22	19	18.8	252	250	421	260	368	298
	22/10/1st year	3 900	3 300	2 000	4 200	2 800	3 240	22	15	19	20	18	18.8	272	252	531	250	369	311
	29/10/1st year	4 100	3 800	2 200	4 000	2 800	3 380	22	16	19	19	18	18.8	260	251	484	252	378	304
Nov	05/11/1st year	4 200	3 400	1 900	2 400	4 200	3 220	22	16	23	19	14	18.8	251	252	558	372	251	306
	12/11/1st year	4 000	4 000	2 500	2 400	3 500	3 280	22	17	21	19	15	18.8	251	251	420	372	302	305
	19/11/1st year	4 200	4 100	3 000	2 400	3 000	3 340	22	17	20	19	16	18,8	251	251	354	372	355	305
	26/11/1st year	4 200	4 100	4 000	3 900	1 900	3 620	22	17	18	17	20	18,8	253	257	265	251	556	288
Dec	03/12/1st year	4 100	3 700	2 000	4 000	3 600	3 480	22	16	26	16	14	18,8	260	252	530	251	292	294
	10/12/1st year	3 900	3 700	2 000	4 000	3 100	3 340	21	16	26	16	15	18,8	252	252	530	251	340	301
	17/12/1st year	4 200	4 000	2 300	4 000	2 700	3 440	21	16	25	16	16	18,8	252	252	456	251	394	301
	24/12/1st year	4 000	4 000	2 300	4 000	2 400	3 340	20	16	25	16	17	18.8	251	252	456	251	444	307

TABLE 9B
Productivity and profitability for the 2-year-5-crop arrangements in Table 9A

Starting time		Productivity							Profitability						
		Weekly (kg/ha/week)						Annual (kg/ha/year)	Weekly (CNY/ha/week)						Annual (CNY/ha/year)
		1st crop	2nd crop	3rd crop	4th crop	5th crop	Overall		1st crop	2nd crop	3rd crop	4th crop	5th crop	Overall	
Jan	01/01/1st year	662	839	583	836	798	729	37 883	1 976	2 550	2 042	2 362	3 089	2 373	123 421
	08/01/1st year	680	888	636	825	724	740	38 480	1 916	2 634	2 252	2 321	2 754	2 368	123 148
	15/01/1st year	663	888	636	698	760	722	37 541	1 979	2 634	2 252	1 972	2 997	2 362	122 831
	22/01/1st year	674	888	602	577	884	708	36 806	2 082	2 634	2 114	1 630	3 603	2 349	122 142
	29/01/1st year	713	877	629	577	842	715	37 158	2 091	2 612	2 208	1 630	3 413	2 349	122 139
Feb	05/02/1st year	749	938	663	816	661	752	39 105	1 920	2 922	2 331	2 130	2 541	2 360	122 745
	12/02/1st year	772	938	663	588	794	736	38 259	2 077	2 922	2 331	1 552	3 171	2 363	122 870
	19/02/1st year	775	938	663	577	724	721	37 504	2 225	2 922	2 331	1 630	2 867	2 368	123 118
	26/02/1st year	753	938	663	635	660	716	37 236	2 356	2 922	2 331	1 698	2 515	2 340	121 698
Mar	05/03/1st year	754	929	665	669	658	722	37 536	2 363	3 024	2 169	1 772	2 487	2 330	121 153
	12/03/1st year	811	990	660	700	659	745	38 744	2 236	3 353	2 082	1 837	2 477	2 343	121 857
	19/03/1st year	774	990	660	700	633	731	38 021	2 392	3 353	2 082	1 837	2 301	2 329	121 103
	26/03/1st year	773	996	582	837	635	736	38 294	2 358	3 420	1 575	2 405	2 275	2 307	119 962
Apr	02/04/1st year	728	989	614	837	614	731	38 016	2 315	3 458	1 685	2 405	2 172	2 314	120 326
	09/04/1st year	836	1 028	664	832	568	751	39 055	2 362	3 694	1 870	2 368	1 973	2 337	121 524
	16/04/1st year	794	1 064	667	687	665	750	39 009	2 320	3 905	1 887	1 961	2 169	2 335	121 396
	23/04/1st year	713	1 060	666	690	660	735	38 211	2 175	3 938	1 772	2 017	2 082	2 280	118 552
	30/04/1st year	792	984	717	758	612	754	39 190	2 180	3 943	1 868	2 267	1 833	2 316	120 435
May	07/05/1st year	669	984	717	648	658	720	37 435	2 146	3 943	1 868	1 945	1 899	2 260	117 533
	14/05/1st year	714	884	733	657	664	722	37 559	2 290	3 603	1 994	2 000	1 870	2 297	119 420
	21/05/1st year	777	794	637	757	667	722	37 563	2 439	3 171	1 757	2 594	1 887	2 346	121 997
	28/05/1st year	839	753	534	841	683	719	37 379	2 550	2 862	1 458	3 195	1 950	2 352	122 301
Jun	04/06/1st year	753	753	534	798	717	703	36 581	2 478	2 862	1 458	3 089	1 868	2 309	120 049
	11/06/1st year	798	692	629	760	719	715	37 179	2 605	2 490	1 686	2 997	1 866	2 315	120 392
	18/06/1st year	862	691	646	661	697	704	36 627	2 730	2 463	1 818	2 541	1 999	2 310	120 101
	25/06/1st year	938	663	577	724	775	721	37 504	2 922	2 331	1 630	2 867	2 225	2 368	123 118
Jul	02/07/1st year	929	665	669	724	769	741	38 513	3 024	2 169	1 772	2 867	2 037	2 348	122 116
	09/07/1st year	917	665	669	724	692	723	37 571	3 144	2 169	1 772	2 867	1 885	2 328	121 067
	16/07/1st year	990	660	755	724	637	739	38 420	3 353	2 082	1 922	2 867	1 768	2 348	122 083
	23/07/1st year	996	627	748	724	596	721	37 493	3 420	1 896	2 090	2 867	1 621	2 315	120 383
	30/07/1st year	989	658	813	724	556	729	37 891	3 458	1 899	2 289	2 867	1 505	2 328	121 041
Aug	06/08/1st year	992	664	794	614	825	755	39 241	3 469	1 870	2 231	2 172	2 321	2 339	121 626
	13/08/1st year	1 028	664	832	568	836	751	39 055	3 694	1 870	2 368	1 973	2 362	2 337	121 524
	20/08/1st year	1 064	667	837	614	698	748	38 891	3 905	1 887	2 405	2 172	1 972	2 360	122 746
	27/08/1st year	1 060	640	837	614	652	732	38 087	3 938	1 886	2 405	2 172	1 769	2 325	120 894
Sep	03/09/1st year	938	662	840	636	612	723	37 586	3 735	1 976	2 430	2 252	1 627	2 339	121 630
	10/09/1st year	984	662	840	636	583	720	37 458	3 943	1 976	2 430	2 252	1 575	2 339	121 633
	17/09/1st year	884	674	888	602	577	708	36 806	3 603	2 082	2 634	2 114	1 630	2 349	122 142
	24/09/1st year	794	670	883	663	588	710	36 927	3 171	2 057	2 692	2 331	1 552	2 328	121 045
Oct	01/10/1st year	753	753	673	667	837	731	37 994	2 862	2 356	2 228	1 887	2 405	2 331	121 193
	08/10/1st year	692	774	790	667	794	738	38 368	2 490	2 392	2 753	1 887	2 255	2 340	121 687
	15/10/1st year	691	773	831	667	761	739	38 411	2 463	2 358	2 932	1 887	2 101	2 326	120 933
	22/10/1st year	663	734	759	717	776	727	37 795	2 331	2 379	2 887	1 868	2 310	2 349	122 161
	29/10/1st year	665	794	760	719	794	742	38 590	2 169	2 320	2 997	1 866	2 437	2 353	122 348
Nov	05/11/1st year	660	713	637	637	990	710	36 896	2 082	2 175	2 428	1 768	3 353	2 313	120 290
	12/11/1st year	627	792	684	637	932	722	37 533	1 896	2 180	2 679	1 768	3 175	2 304	119 829
	19/11/1st year	658	813	724	637	887	736	38 250	1 899	2 289	2 867	1 768	3 009	2 341	121 714
	26/11/1st year	664	832	794	772	720	751	39 065	1 870	2 368	3 171	2 077	2 303	2 340	121 702
Dec	03/12/1st year	667	777	568	836	986	738	38 357	1 887	2 439	1 973	2 362	3 577	2 348	122 100
	10/12/1st year	640	777	568	836	931	726	37 743	1 886	2 439	1 973	2 362	3 395	2 334	121 383
	17/12/1st year	691	839	583	836	886	747	38 866	1 882	2 550	2 042	2 362	3 237	2 357	122 558
	24/12/1st year	683	839	583	836	841	740	38 458	1 950	2 550	2 042	2 362	3 195	2 377	123 586

Indeed, the lowest profitability among the 2-year-5-crop arrangements in Table 9B (CNY 117 533/ha per year) is 27 percent (or CNY 25 042/ha per year) higher than the maximum profitability under 1 year 2 crops (CNY 92 491/ha per year); the highest profitability in Table 9B (CNY 123 586/ha per year) is 34 percent (or CNY 31 095/ha per year) higher than the maximum overall profit under 1 year 2 crops (Figure 34).

The average stocking density for the 2-year-5-crop arrangements in Table 9A ranges from 3 100 to 3 680 fish/mu for the 52 initial stocking timings. It is about double the average stocking density under the 1 year 2 crops (ranging from 1 500 to 2 050 fish/mu; Table 8). The stocking density for individual crops under the 2 years 5 crops arrangements ranges from 1 500 to 4 200 fish/mu (Table 9A) compared with the range from 1 200 to 2 100 fish/mu under the 1-year-2-crop arrangements (Table 8).

The average growing period under 2 years 5 crops is 18.8 weeks[21] irrespective of the stocking timing. It is shorter than the average growing period (24 weeks) under 1 year 2 crops. The growing period for individual crops under the 2-year-5-crop arrangements in Table 9A ranges from 13 to 26 weeks, whereas the range under 1 year 2 crops is from 19 to 29 weeks (Table 8).

The average harvest size for the 2-year-5-crop arrangements in Table 9A ranges from 283 to 321 g, which is only about half of the average size under 1 year 2 crops (ranging from 505 to 636 fish/mu; Table 8). The harvest size for individual crops under the 2-year-5-crop arrangements in Table 9A ranges from 250 to 657 g, whereas the range under 1 year 2 crops is from 501 to 712 g (Table 8).

For the arrangements of the first and second crops which maximize the overall profitability of the first two crops, the stocking density ranges from 3 200 to 4 200 fish/mu, the growing period from 13 to 22 weeks, and the harvest size from 250 to 313 g. These results indicate that given no price discrepancy between small- and large-size fish, it is more profitable to harvest small-size fish stocked in high density and farmed in a shorter growing period.

Summary

The higher overall profitability of 2 years 5 crops reflects its higher productivity compared with 1 year 2 crops (Figure 34). By stocking in higher density, a shorter crop with a smaller harvest size could produce as much fish biomass as a longer crop with lower stocking density and larger harvest size. Therefore, the productivity of 2 years 5 crops (average 1 year 2.5 crops) is at the proximity of the 40 000 kg/ha per year upper bound for 2.5 crops (16 000 kg/ha per year for each crop), whereas the productivity of 1 year 2 crops is at the proximity of the 32 000 kg/ha per year upper bound for 2 crops (Figure 34).

Although harvesting small fish could increase productivity and profitability by more efficient use of the pond area through a higher stocking density and shorter growing period, it may sacrifice technical efficiency by missing the fast growing stage of the fish growth cycle, especially for GIFT strains. As indicated in Table 1, it takes 14 weeks for GIFT tilapia to grow over 250 g, whereas it takes an additional four weeks to grow over 500 g. In addition, farming small-size fish, being more technically efficient notwithstanding, may not be economically viable when small fish is sold at discounted prices in the market.

A multi-tiered farming system, which is essentially to allow the use of large-size fingerlings, could increase efficiency in pond utilization while at the same time capture the technical and economic advantages in harvesting large-size fish. This arrangement will be examined in the next section.

[21] The 104 weeks in two years minus 10 weeks needed for pond preparation (two weeks for each of the five crops) is equal to 94 weeks, which implies an average of 18.8 weeks per crop (94 divided by 5).

4.4 MULTI-TIER FARMING SYSTEMS

Under the 1-year-2-crop arrangement where the targeted harvest size is above 500 g, the average stocking density (1 g fingerling) is mostly less than 2 000 fish/mu (Table 8). The stocking density cannot be made higher because doing so would result in the fish biomass exceeding the capacity limit at harvest. However, during the growing period when the fish are below the targeted harvest size, the fish biomass in the pond would be well under the capacity limit, which results in inefficient use of the pond area. Thus, stocking at a higher density for a smaller harvest size could increase productivity by utilizing the pond area more efficiently.

Another way to improve the efficiency in the utilization of the pond area is to adjust the stocking density according to fish size so as to maintain the fish biomass at high levels. For example, in Hainan province, in China, tilapia farmers often stock 3–4 cm fingerlings in nursery ponds at 5 000–10 000 fish/mu and grow them for 50–60 days until they reach 13–17 cm (100–150 g); they then stock the large-size fingerlings at 1 800–2 000 fish/mu in outgrowing ponds and raise them to the targeted harvest size. Such a two-tier farming system enhances the efficiency in utilizing pond areas. Some farmers even add an additional tier by nursing 1 cm fry into 3–4 cm fingerlings in ponds or hapas at 30 000–50 000 fish/mu density (Yang, 2015, p. 51).

In this section, the advanced bioeconomic model is used to examine the technical and economic performance of a two-tier tilapia farming system and compare it to the 1-year-2-crop benchmark. To simplify the model set-up, the production costs of large fingerlings of different size are estimated first and then the costs are used as the shadow prices of the fingerlings to estimate the profitability of farming arrangements that allow farmers to stock fingerlings of different sizes.

Production costs of large fingerlings

The advanced bioeconomic model is used to estimate the production costs of large fingerlings (50 g, 100 g or 150 g). Based on the economic parameters specified in Table 3 and the technical parameters specified in Table 10, nearly 230 000 cases of fingerling nursing arrangements (52 different stocking timings, 218 different stocking density and 20 different nursing periods) are simulated in the advanced model.

TABLE 10
Technical parameters used in the simulation of the production of large fingerlings

Parameters	Specification
Initial fingerling size	1 g
Stocking timing	52 weekly stocking timings – see Table 8
Stocking density	1 500–110 000 fish/mu with 500 fish/mu increments (e.g. 1 500 fish/mu, 2 000 fish/mu, 2 500 fish/mu, and so on)
Nursing period	1 to 20 weeks, which is enough time for 1 g fingerlings to grow up to 150 g in all seasons

Among them, the cases that produce 40–60 g fingerlings are used to estimate the production costs of 50 g fingerling. As the size of the fingerling harvested is usually not equal to 50 g exactly, the actual production cost of the fingerling would need to be normalized into a cost for a 50 g fingerling. For example, suppose in an arrangement the cost of producing 45 g fingerlings is CNY 0.36/fish, then the normalized cost for producing 50 g fingerlings under that arrangement would be CNY 0.4/fish (equal to CNY 0.36/fish ÷ 45 g × 50 g). For a harvest date, there may be different normalized production costs of 50 g fingerlings because more than one arrangement harvests fingerlings within the size range on that date. Under this situation, the lowest normalized cost is deemed the production cost of 50 g fingerlings for the harvest date. The range of 40–60 g is selected to ensure that for each of the 52 weekly harvest date there is at least one arrangement that produces fingerlings at a size within the range – this may not be the case for a narrower range (e.g. 45–55 g).

The production costs of 100 g and 150 g fingerlings are estimated in a similar way.[22] The results indicate that the production costs of 50 g, 100 g and 150 g fingerlings are at the range of CNY 0.34–0.39/fish (average CNY 0.36/fish), CNY 0.59–0.68/fish (average CNY 0.63/fish), and CNY 0.87–1.00/fish (average CNY 0.93/fish), respectively (Table 11; Figures 35 and 36).

The production costs of large fingerlings in terms of weight are CNY 7.10/kg, CNY 6.28/kg and CNY 6.20/kg for 50 g, 100 g and 150 g fingerlings, respectively (Figure 36). The costs are much lower than those shown in Figure 9, where the stocking density is 1 200 fish/mu. This indicates that nursing fingerlings in higher stocking density before stocking the large-size fingerlings in outgrowing ponds is more efficient than stocking small-size fingerlings directly in outgrowing ponds and growing them to harvest size.

Stocking large-size fingerlings – 1 year 3 crops

When large-sized fingerlings are used, it is possible to produce three crops within a year. The advanced model is used to simulate the arrangements of 1 year 3 crops and compare its technical and economic performance to the 1-year-2-crop arrangements.

The technical and economic parameters used in the simulation is mostly the same as those used in the 1-year-2-crop simulation. A key difference is that, as opposed to 1 g fingerlings being used in the 1-year-2-crop simulation, the farmer under the 1-year-3-crop set-up has options to use fingerlings of four different sizes (1 g, 50 g, 100 g or 150 g) at the costs specified in Table 11 and that in Table 3 for 1 g fingerlings.

The resulting 1-year-3-crop arrangements that maximize the overall profit for the 52 weekly stocking timings are presented in Tables 12A and 12B. The comparison between 1 year 3 crops and the other two crop arrangements is summarized in Table 13.

The results indicate that for all the 52 initial stocking timings, the profitability of 1 year 3 crops under the two-tier system would be substantially higher than that under the 1 year 2 crops (Figure 37).

- The average profitability across the 52 initial stocking timings is nearly CNY 150 000/ha per year, which is higher than that under 1 years 2 crops (Table 13).
- The average growing period under 1 year 3 crops is about 15 weeks, shorter than that under 1 year 2 crops (Table 13).
- The average stocking density under 1 year 3 crops is close to 1 900 fish/mu, which is slightly higher than that under 1 year 2 crops (Table 13).
- The average harvest size under 1 year 3 crops is 535 g, which is slightly smaller than that under 1 year 2 crops (Table 13).
- The average productivity under 1 year 3 crops is 45 000 kg/ha per year, which is higher than that under 1 year 2 crops (Table 13).

It seems that the higher profitability is primarily due to the higher productivity under 1 year 3 crops, where the use of large fingerlings shortens the growing period and hence allows an extra crop compared to 1 year 2 crops. It should be noted, however, that the use of large fingerlings per se may not improve profitability; it is the efficiency gain from nursing fingerlings at higher stocking density that leads to higher profitability.

The two-tier, 1-year-3-crop arrangement that gives the highest overall profitability is as follows (Table 14).[23]

[22] The size range for estimating the cost of 100 g and 150 g fingerlings is 85–115 g and 135–165 g, respectively.

[23] The sequence of the first, second and third crop is arbitrarily specified.

TABLE 11
Production of large-size fingerlings

Large-size fingerlings harvested on:	50 g fingerlings				100 g fingerlings				150 g fingerlings			
	1 g fingerlings stocked on:	Stocking density (fish/mu)	Nursing period (weeks)	Normalized fingerling production cost (CNY/fish)	1 g fingerlings stocked on:	Stocking density (fish/mu)	Nursing period (weeks)	Normalized fingerling production cost (CNY/fish)	1 g fingerlings stocked on:	Stocking density (fish/mu)	Nursing period (weeks)	Normalized fingerling production cost (CNY/fish)
01/01/year t	29/10/year t-1	11 000	9	0.35	15/10/year t-1	10 500	11	0.60	01/10/year t-1	6 500	13	0.88
08/01/year t	05/11/year t-1	11 000	9	0.39	15/10/year t-1	10 000	12	0.59	08/10/year t-1	7 500	13	0.87
15/01/year t	05/11/year t-1	11 000	10	0.37	22/10/year t-1	11 000	12	0.60	08/10/year t-1	7 000	14	0.88
22/01/year t	05/11/year t-1	11 000	11	0.37	22/10/year t-1	11 000	13	0.60	08/10/year t-1	6 500	15	0.89
29/01/year t	05/11/year t-1	11 000	12	0.35	22/10/year t-1	10 000	14	0.59	15/10/year t-1	7 500	15	0.88
05/02/year t	12/11/year t-1	11 000	12	0.38	29/10/year t-1	11 000	14	0.61	15/10/year t-1	6 500	16	0.90
12/02/year t	12/11/year t-1	11 000	13	0.36	29/10/year t-1	10 500	15	0.61	22/10/year t-1	4 500	16	1.00
19/02/year t	19/11/year t-1	11 000	13	0.39	29/10/year t-1	9 500	16	0.62	22/10/year t-1	7 500	17	0.91
26/02/year t	19/11/year t-1	11 000	14	0.37	05/11/year t-1	11 000	16	0.63	22/10/year t-1	6 500	18	0.92
05/03/year t	26/11/year t-1	11 000	14	0.38	05/11/year t-1	9 500	17	0.63	29/10/year t-1	7 000	18	0.94
12/03/year t	03/12/year t-1	11 000	14	0.38	12/11/year t-1	9 000	17	0.64	05/11/year t-1	7 000	18	0.95
19/03/year t	10/12/year t-1	11 000	14	0.37	19/11/year t-1	8 500	17	0.65	05/11/year t-1	6 500	19	0.94
26/03/year t	24/12/year t-1	11 000	13	0.36	26/11/year t-1	10 000	17	0.65	12/11/year t-1	7 000	19	0.95
02/04/year t	08/01/year t	11 000	12	0.36	03/12/year t-1	9 500	17	0.68	19/11/year t-1	7 000	19	0.98
09/04/year t	05/02/year t	10 000	9	0.36	10/12/year t-1	8 000	17	0.68	26/11/year t-1	6 500	19	1.00
16/04/year t	19/02/year t	9 500	8	0.35	22/01/year t	7 000	12	0.66	17/12/year t-1	5 500	17	1.00
23/04/year t	05/03/year t	9 000	7	0.35	29/01/year t	6 000	12	0.65	15/01/year t	4 500	14	0.99
30/04/year t	12/03/year t	10 500	7	0.34	26/02/year t	5 500	9	0.64	05/02/year t	4 500	12	0.96
07/05/year t	26/03/year t	8 500	6	0.34	05/03/year t	5 500	9	0.62	26/02/year t	4 500	10	0.93
14/05/year t	02/04/year t	8 500	6	0.35	12/03/year t	5 500	9	0.63	05/03/year t	4 500	10	0.93
21/05/year t	09/04/year t	10 000	6	0.35	19/03/year t	5 500	9	0.63	12/03/year t	4 500	10	0.94
28/05/year t	09/04/year t	10 500	7	0.34	26/03/year t	5 500	9	0.62	19/03/year t	4 500	10	0.93
04/06/year t	16/04/year t	9 000	7	0.35	02/04/year t	5 500	9	0.63	26/03/year t	4 500	10	0.93
11/06/year t	23/04/year t	10 500	7	0.36	09/04/year t	6 000	9	0.63	26/03/year t	4 000	11	0.93
18/06/year t	30/04/year t	10 000	7	0.37	09/04/year t	6 500	10	0.64	02/04/year t	4 500	11	0.94
25/06/year t	30/04/year t	9 000	8	0.35	16/04/year t	5 500	10	0.64	09/04/year t	4 000	11	0.94
02/07/year t	07/05/year t	9 000	8	0.35	23/04/year t	6 000	10	0.64	16/04/year t	4 500	11	0.95
09/07/year t	14/05/year t	9 500	8	0.36	30/04/year t	6 000	10	0.65	16/04/year t	4 000	12	0.95
16/07/year t	21/05/year t	9 500	8	0.36	30/04/year t	6 000	11	0.65	23/04/year t	4 000	12	0.95
23/07/year t	28/05/year t	9 500	8	0.35	07/05/year t	5 500	11	0.64	30/04/year t	4 500	12	0.95
30/07/year t	04/06/year t	9 500	8	0.35	14/05/year t	5 500	11	0.65	07/05/year t	4 500	12	0.96
06/08/year t	11/06/year t	9 000	8	0.35	21/05/year t	5 500	11	0.64	14/05/year t	4 500	12	0.96
13/08/year t	18/06/year t	8 000	8	0.35	28/05/year t	5 500	11	0.64	21/05/year t	4 500	12	0.96
20/08/year t	25/06/year t	9 000	8	0.35	04/06/year t	6 000	11	0.65	28/05/year t	4 500	12	0.96
27/08/year t	02/07/year t	10 000	8	0.35	11/06/year t	6 500	11	0.65	04/06/year t	4 500	12	0.95
03/09/year t	16/07/year t	9 000	7	0.36	25/06/year t	5 500	10	0.64	11/06/year t	4 500	12	0.95
10/09/year t	23/07/year t	9 500	7	0.35	02/07/year t	5 000	10	0.64	25/06/year t	4 500	11	0.95
17/09/year t	30/07/year t	8 500	7	0.35	16/07/year t	5 500	9	0.64	02/07/year t	4 500	11	0.94
24/09/year t	06/08/year t	10 000	7	0.34	23/07/year t	5 500	9	0.64	09/07/year t	4 000	11	0.94
01/10/year t	20/08/year t	8 500	6	0.35	30/07/year t	5 500	9	0.63	16/07/year t	4 500	11	0.94
08/10/year t	27/08/year t	8 500	6	0.34	06/08/year t	5 500	9	0.62	30/07/year t	4 500	10	0.93
15/10/year t	03/09/year t	9 500	6	0.34	20/08/year t	5 500	8	0.61	06/08/year t	4 500	10	0.91
22/10/year t	10/09/year t	10 000	6	0.34	27/08/year t	6 000	8	0.61	13/08/year t	4 500	10	0.90
29/10/year t	17/09/year t	9 500	6	0.34	03/09/year t	6 000	8	0.62	20/08/year t	4 500	10	0.90
05/11/year t	24/09/year t	9 500	6	0.34	10/09/year t	6 500	8	0.62	27/08/year t	4 500	10	0.90
12/11/year t	01/10/year t	10 000	6	0.35	17/09/year t	6 000	8	0.61	03/09/year t	4 500	10	0.90
19/11/year t	08/10/year t	11 000	6	0.35	17/09/year t	7 500	9	0.61	10/09/year t	5 000	10	0.89
26/11/year t	15/10/year t	11 000	6	0.36	24/09/year t	7 000	9	0.60	17/09/year t	5 500	10	0.89
03/12/year t	22/10/year t	11 000	6	0.36	01/10/year t	6 500	9	0.60	24/09/year t	5 500	10	0.89
10/12/year t	22/10/year t	11 000	7	0.34	01/10/year t	9 000	10	0.60	24/09/year t	6 000	11	0.88
17/12/year t	29/10/year t	11 000	7	0.37	08/10/year t	8 000	10	0.60	01/10/year t	7 000	11	0.88
24/12/year t	29/10/year t	11 000	8	0.36	08/10/year t	8 500	11	0.59	01/10/year t	7 500	12	0.88

TABLE 12A

1-year-3-crop arrangements that maximize the overall profit for each of the 52 initial stocking timings

Stocking timing			Stocking size (g)				Stocking density (fish/mu)				Growing period (weeks)				Harvest size (g)			
1st crop	2nd crop	3rd crop	1st crop	2nd crop	3rd crop	Average	1st crop	2nd crop	3rd crop	Average	1st crop	2nd crop	3rd crop	Average	1st crop	2nd crop	3rd crop	Average
01/01/1st year	23/04/1st year	01/10/1st year	150	1	100	86	2 000	1 800	1 900	1 900	14	21	11	15.33	530	510	554	532
08/01/1st year	23/04/1st year	01/10/1st year	150	1	100	87	2 100	1 800	1 800	1 900	13	21	12	15.33	502	510	583	530
15/01/1st year	30/04/1st year	08/10/1st year	150	1	100	86	2 000	1 800	1 900	1 900	13	21	12	15.33	531	511	539	528
22/01/1st year	30/04/1st year	15/10/1st year	150	1	100	83	2 000	2 100	2 100	2 067	12	22	12	15.33	523	504	506	511
29/01/1st year	21/05/1st year	29/10/1st year	100	1	150	83	1 900	2 100	2 100	2 033	14	21	11	15.33	551	502	502	517
05/02/1st year	21/05/1st year	29/10/1st year	100	1	150	82	2 000	2 100	2 000	2 033	13	21	12	15.33	519	502	518	513
12/02/1st year	21/05/1st year	29/10/1st year	100	1	150	81	2 000	2 100	1 900	2 000	12	21	13	15.33	505	502	548	517
19/02/1st year	21/05/1st year	29/10/1st year	100	1	150	80	1 900	2 100	1 800	1 933	11	21	14	15.33	506	502	587	530
26/02/1st year	21/05/1st year	29/10/1st year	150	1	150	95	1 900	2 100	1 700	1 900	10	21	15	15.33	549	502	611	550
05/03/1st year	21/05/1st year	05/11/1st year	150	1	150	103	2 000	1 800	1 900	1 900	9	22	15	15.33	509	580	559	548
12/03/1st year	21/05/1st year	05/11/1st year	150	1	150	100	1 800	1 800	1 800	1 800	8	22	16	15.33	504	580	592	559
19/03/1st year	28/05/1st year	05/11/1st year	150	1	100	80	1 700	2 000	2 000	1 900	8	21	17	15.33	512	529	522	521
26/03/1st year	06/08/1st year	19/11/1st year	50	50	150	89	1 100	1 900	1 900	1 633	17	13	16	15.33	730	549	559	593
02/04/1st year	16/07/1st year	29/10/1st year	50	50	50	50	1 500	2 000	2 000	1 833	13	13	20	15.33	514	505	533	518
09/04/1st year	20/08/1st year	03/12/1st year	50	50	150	90	1 200	1 800	2 000	1 667	17	13	16	15.33	689	592	530	590
16/04/1st year	17/09/1st year	24/12/1st year	1	50	150	73	1 600	2 100	2 100	1 933	20	12	14	15.33	500	507	500	503
23/04/1st year	01/10/1st year	08/01/2nd year	1	100	150	87	1 800	1 800	2 100	1 900	21	12	13	15.33	510	583	502	530
30/04/1st year	15/10/1st year	22/01/2nd year	1	100	150	83	2 100	2 100	2 000	2 067	22	12	12	15.33	504	506	523	511
07/05/1st year	29/10/1st year	29/01/2nd year	1	150	150	104	1 800	2 100	1 900	1 933	23	11	12	15.33	589	502	546	543
14/05/1st year	29/10/1st year	29/01/2nd year	1	150	100	86	1 900	2 100	2 000	2 000	22	11	13	15.33	549	502	502	517
21/05/1st year	29/10/1st year	29/01/2nd year	1	150	100	83	2 100	2 100	1 900	2 033	21	11	14	15.33	502	502	551	517
28/05/1st year	05/11/1st year	19/02/2nd year	1	150	100	84	2 000	2 000	2 100	2 033	21	13	12	15.33	529	518	502	516
04/06/1st year	05/11/1st year	05/03/2nd year	1	150	100	82	2 000	1 900	1 800	1 900	20	15	11	15.33	509	559	508	525
11/06/1st year	12/11/1st year	12/03/2nd year	1	150	100	81	2 100	2 000	1 600	1 900	20	15	11	15.33	506	523	529	519
18/06/1st year	19/11/1st year	26/03/2nd year	1	150	100	81	2 000	1 900	1 500	1 800	20	16	10	15.33	530	559	512	535
25/06/1st year	19/11/1st year	26/03/2nd year	1	150	100	81	2 000	1 900	1 600	1 833	19	16	11	15.33	505	559	528	530
02/07/1st year	03/12/1st year	09/04/2nd year	1	150	100	85	1 800	2 000	1 500	1 767	20	16	10	15.33	583	530	502	540
09/07/1st year	03/12/1st year	09/04/2nd year	1	150	100	82	2 000	2 000	1 500	1 833	19	16	11	15.33	530	530	528	529
16/07/1st year	24/12/1st year	16/04/2nd year	1	150	100	90	1 600	2 100	1 600	1 767	21	14	11	15.33	659	500	504	549
23/07/1st year	24/12/1st year	16/04/2nd year	1	150	100	88	1 700	2 100	1 500	1 767	20	14	12	15.33	610	500	542	547
30/07/1st year	24/12/1st year	16/04/2nd year	1	150	50	72	1 900	2 100	1 400	1 800	19	14	13	15.33	549	500	509	520
06/08/1st year	08/01/2nd year	23/04/2nd year	1	150	100	85	1 900	2 100	1 400	1 800	20	13	13	15.33	559	502	587	544
13/08/1st year	08/01/2nd year	23/04/2nd year	1	150	50	70	2 000	2 100	1 600	1 900	19	13	14	15.33	517	502	510	509
20/08/1st year	22/01/2nd year	30/04/2nd year	1	150	50	69	2 000	2 000	1 500	1 833	20	12	14	15.33	522	523	514	520
27/08/1st year	03/12/1st year	09/04/2nd year	50	150	50	89	2 000	2 000	1 100	1 700	12	16	18	15.33	528	530	736	574
03/09/1st year	24/12/1st year	16/04/2nd year	50	150	50	94	1 600	2 100	1 100	1 600	14	14	18	15.33	648	500	726	601
10/09/1st year	01/01/2nd year	23/04/2nd year	50	150	50	91	1 700	2 000	1 200	1 633	14	14	18	15.33	618	530	700	602
17/09/1st year	24/12/1st year	16/04/2nd year	50	150	1	73	2 100	2 100	1 600	1 933	12	14	20	15.33	507	500	500	503
24/09/1st year	08/01/2nd year	23/04/2nd year	50	150	1	74	2 100	2 100	1 500	1 900	13	13	20	15.33	506	502	512	506
01/10/1st year	08/01/2nd year	23/04/2nd year	100	150	1	87	1 800	2 100	1 800	1 900	12	13	21	15.33	583	502	510	530
08/10/1st year	08/01/2nd year	23/04/2nd year	100	150	1	86	2 000	2 100	1 900	2 000	11	13	22	15.33	515	502	530	515
15/10/1st year	22/01/2nd year	30/04/2nd year	100	150	1	83	2 100	2 000	2 100	2 067	12	12	22	15.33	506	523	504	511
22/10/1st year	22/01/2nd year	30/04/2nd year	150	150	1	103	1 900	2 000	1 800	1 900	11	12	23	15.33	550	523	581	550
29/10/1st year	29/01/2nd year	21/05/2nd year	150	100	1	83	2 100	1 900	2 100	2 033	11	14	21	15.33	502	551	502	517
05/11/1st year	19/02/2nd year	21/05/2nd year	150	100	1	86	2 000	1 900	1 800	1 900	13	11	22	15.33	518	506	580	534
12/11/1st year	12/03/2nd year	21/05/2nd year	150	150	1	106	2 000	1 800	1 600	1 800	15	8	23	15.33	523	504	653	555
19/11/1st year	09/04/2nd year	13/08/2nd year	100	50	50	68	1 900	1 300	2 100	1 767	18	16	12	15.33	544	640	500	550
26/11/1st year	09/04/2nd year	13/08/2nd year	150	50	50	87	1 800	1 300	1 800	1 633	17	16	13	15.33	591	640	578	599
03/12/1st year	09/04/2nd year	20/08/2nd year	150	50	50	90	2 000	1 200	1 800	1 667	16	17	13	15.33	530	689	592	590
10/12/1st year	09/04/2nd year	17/09/2nd year	150	1	100	88	2 000	1 700	2 000	1 900	15	21	10	15.33	504	520	531	518
17/12/1st year	16/04/2nd year	24/09/2nd year	150	1	100	87	2 000	1 800	2 000	1 933	15	21	10	15.33	521	508	529	520
24/12/1st year	16/04/2nd year	17/09/2nd year	150	1	50	73	2 100	1 600	2 100	1 933	14	20	12	15.33	500	500	507	503

TABLE 12B
Productivity and profitability for the 1-year-3-crop arrangements in Table 12A

Stocking timing			Productivity					Profitability				
			Weekly (kg/ha/week)				Annual (kg/ha/year)	Weekly (CNY/ha/week)				Annual (CNY/ha/year)
1st crop	2nd crop	3rd crop	1st crop	2nd crop	3rd crop	Overall		1st crop	2nd crop	3rd crop	Overall	
01/01/1st year	23/04/1st year	01/10/1st year	994	598	1 216	874	45 462	3 281	1 712	4 708	2 943	153 060
08/01/1st year	23/04/1st year	01/10/1st year	1 054	598	1 124	871	45 296	3 519	1 712	4 361	2 946	153 207
15/01/1st year	30/04/1st year	08/10/1st year	1 063	600	1 098	868	45 118	3 393	1 732	4 314	2 906	151 120
22/01/1st year	30/04/1st year	15/10/1st year	1 121	662	1 137	914	47 507	3 628	1 646	4 535	2 958	153 802
29/01/1st year	21/05/1st year	29/10/1st year	981	687	1 215	910	47 309	2 929	1 961	4 705	2 945	153 130
05/02/1st year	21/05/1st year	29/10/1st year	1 039	687	1 109	902	46 922	3 136	1 961	4 257	2 918	151 732
12/02/1st year	21/05/1st year	29/10/1st year	1 081	687	1 042	896	46 570	3 362	1 961	3 989	2 923	151 993
19/02/1st year	21/05/1st year	29/10/1st year	1 110	687	990	886	46 077	3 618	1 961	3 770	2 932	152 452
26/02/1st year	21/05/1st year	29/10/1st year	1 303	687	916	904	47 022	3 861	1 961	3 387	2 866	149 013
05/03/1st year	21/05/1st year	05/11/1st year	1 388	652	937	901	46 868	4 169	1 873	3 468	2 880	149 771
12/03/1st year	21/05/1st year	05/11/1st year	1 360	652	888	870	45 245	4 453	1 873	3 257	2 848	148 120
19/03/1st year	28/05/1st year	05/11/1st year	1 304	690	825	857	44 578	4 219	2 017	3 004	2 801	145 666
26/03/1st year	06/08/1st year	19/11/1st year	634	1 042	885	839	43 607	1 864	3 529	3 152	2 790	145 097
02/04/1st year	16/07/1st year	29/10/1st year	771	1 010	726	821	42 706	2 566	3 235	2 646	2 793	145 231
09/04/1st year	20/08/1st year	03/12/1st year	653	1 065	883	851	44 270	1 888	3 806	3 090	2 857	148 583
16/04/1st year	17/09/1st year	24/12/1st year	546	1 141	985	841	43 738	1 678	4 430	3 323	2 925	152 110
23/04/1st year	01/10/1st year	08/01/2nd year	598	1 124	1 054	871	45 296	1 712	4 361	3 519	2 946	153 207
30/04/1st year	15/10/1st year	22/01/2nd year	662	1 137	1 121	914	47 507	1 646	4 535	3 628	2 958	153 802
07/05/1st year	29/10/1st year	29/01/2nd year	637	1 215	1 111	909	47 269	1 677	4 705	3 415	2 902	150 898
14/05/1st year	29/10/1st year	29/01/2nd year	652	1 215	1 005	895	46 521	1 809	4 705	3 118	2 911	151 349
21/05/1st year	29/10/1st year	29/01/2nd year	687	1 215	981	910	47 309	1 961	4 705	2 929	2 945	153 130
28/05/1st year	05/11/1st year	19/02/2nd year	690	1 036	1 129	908	47 218	2 017	3 950	3 182	2 888	150 186
04/06/1st year	05/11/1st year	05/03/2nd year	694	937	1 055	864	44 926	2 132	3 468	3 175	2 830	147 138
11/06/1st year	12/11/1st year	12/03/2nd year	725	923	977	853	44 343	2 215	3 377	3 007	2 793	145 220
18/06/1st year	19/11/1st year	26/03/2nd year	723	885	960	834	43 358	2 268	3 152	3 147	2 777	144 409
25/06/1st year	19/11/1st year	26/03/2nd year	722	885	974	841	43 748	2 378	3 152	2 927	2 783	144 722
02/07/1st year	03/12/1st year	09/04/2nd year	716	883	942	826	42 944	2 410	3 090	3 123	2 810	146 115
09/07/1st year	03/12/1st year	09/04/2nd year	757	883	914	840	43 681	2 594	3 090	2 871	2 835	147 430
16/07/1st year	24/12/1st year	16/04/2nd year	688	985	930	840	43 670	2 391	3 323	2 897	2 804	145 814
23/07/1st year	24/12/1st year	16/04/2nd year	706	985	871	837	43 506	2 555	3 323	2 624	2 810	146 105
30/07/1st year	24/12/1st year	16/04/2nd year	746	985	713	810	42 116	2 759	3 323	2 478	2 851	148 268
06/08/1st year	08/01/2nd year	23/04/2nd year	724	1 054	822	847	44 065	2 754	3 519	2 495	2 900	150 807
13/08/1st year	08/01/2nd year	23/04/2nd year	738	1 054	765	837	43 549	2 871	3 519	2 474	2 936	152 668
20/08/1st year	22/01/2nd year	30/04/2nd year	712	1 121	722	825	42 907	2 790	3 628	2 411	2 899	150 742
27/08/1st year	03/12/1st year	09/04/2nd year	1 132	883	607	844	43 885	4 121	3 090	1 687	2 828	147 069
03/09/1st year	24/12/1st year	16/04/2nd year	972	985	599	833	43 303	3 642	3 323	1 704	2 799	145 526
10/09/1st year	01/01/2nd year	23/04/2nd year	985	994	630	851	44 245	3 808	3 281	1 759	2 857	148 586
17/09/1st year	24/12/1st year	16/04/2nd year	1 141	985	546	841	43 738	4 430	3 323	1 678	2 925	152 110
24/09/1st year	08/01/2nd year	23/04/2nd year	1 063	1 054	523	832	43 266	4 285	3 519	1 642	2 946	153 196
01/10/1st year	08/01/2nd year	23/04/2nd year	1 124	1 054	598	871	45 296	4 361	3 519	1 712	2 946	153 207
08/10/1st year	08/01/2nd year	23/04/2nd year	1 188	1 054	629	891	46 341	4 674	3 519	1 637	2 939	152 839
15/10/1st year	22/01/2nd year	30/04/2nd year	1 137	1 121	662	914	47 507	4 535	3 628	1 646	2 958	153 802
22/10/1st year	22/01/2nd year	30/04/2nd year	1 206	1 121	628	905	47 064	4 681	3 628	1 569	2 901	150 868
29/10/1st year	29/01/2nd year	21/05/2nd year	1 215	981	687	910	47 309	4 705	2 929	1 961	2 945	153 130
05/11/1st year	19/02/2nd year	21/05/2nd year	1 036	1 110	652	877	45 627	3 950	3 618	1 873	2 908	151 240
12/11/1st year	12/03/2nd year	21/05/2nd year	923	1 360	627	865	44 971	3 377	4 453	1 781	2 817	146 471
19/11/1st year	09/04/2nd year	13/08/2nd year	775	693	1 126	841	43 729	2 770	2 081	3 845	2 821	146 691
26/11/1st year	09/04/2nd year	13/08/2nd year	840	693	1 040	847	44 037	2 943	2 081	3 588	2 831	147 189
03/12/1st year	09/04/2nd year	20/08/2nd year	883	653	1 065	851	44 270	3 090	1 888	3 806	2 857	148 583
10/12/1st year	09/04/2nd year	17/09/2nd year	889	577	1 327	852	44 312	3 149	1 630	4 711	2 837	147 544
17/12/1st year	16/04/2nd year	24/09/2nd year	919	597	1 323	870	45 232	3 073	1 677	4 798	2 854	148 387
24/12/1st year	16/04/2nd year	17/09/2nd year	985	546	1 141	841	43 738	3 323	1 678	4 430	2 925	152 110

FIGURE 35
Costs of fingerlings of different sizes

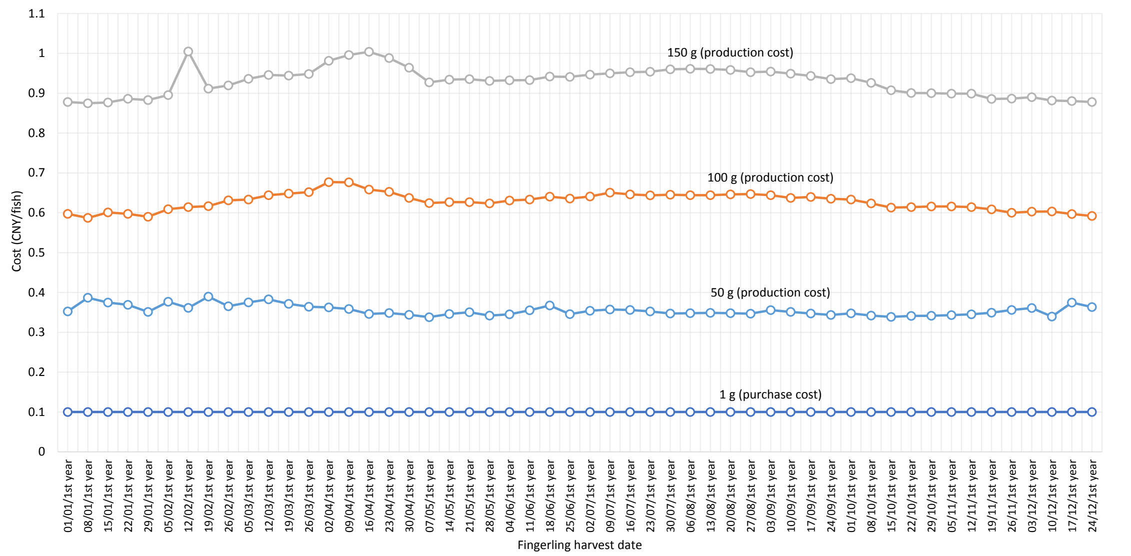
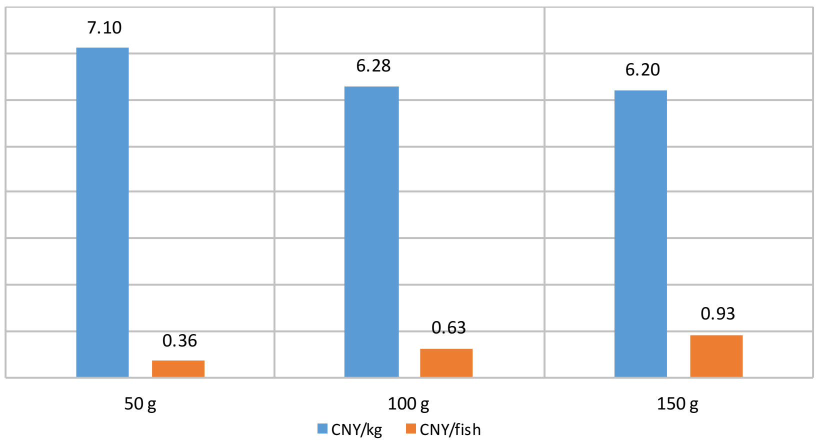


FIGURE 36
Average production cost of large fingerlings*



* Average production costs for the 52 harvest dates in Table 11.

- First crop: stocking 1 g fingerlings, 2 100 fish/mu on 30 April and harvesting 504 g fish after 22 weeks, on 1 October, for 662 kg/ha per week and CNY 1 645/ha per week.
- Second crop: stocking 100 g fingerlings, 2 100 fish/mu on 15 October and harvesting 506 g fish after 12 weeks, on 8 January the next year, for 1 137 kg/ha per week and CNY 4 535/ha per week.
- Third crop: stocking 150 g fingerlings, 2 000 fish/mu on 22 January the next year and harvesting 523 g fish after 12 weeks, on 16 April the next year, for 1 121 kg/ha per week and CNY 3 628/ha per week.
- The overall productivity is 914 kg/ha per week (or 47 507 kg/ha per year).
- The overall profitability is CNY 2 958/ha per week (or CNY 153 802/ha per year), which is 66 percent higher than the maximum profitability under 1 year 2 crops.

The fingerling costs in Table 11 only account for the costs of fingerling production.[24] When the farmer purchases large-size fingerlings from commercial nurseries, the costs

[24] The production cost includes the cost of harvesting large-size fingerlings from nursery ponds.

FIGURE 37
Profitability and productivity – 1 year 3 crops versus 1 year 2 crops

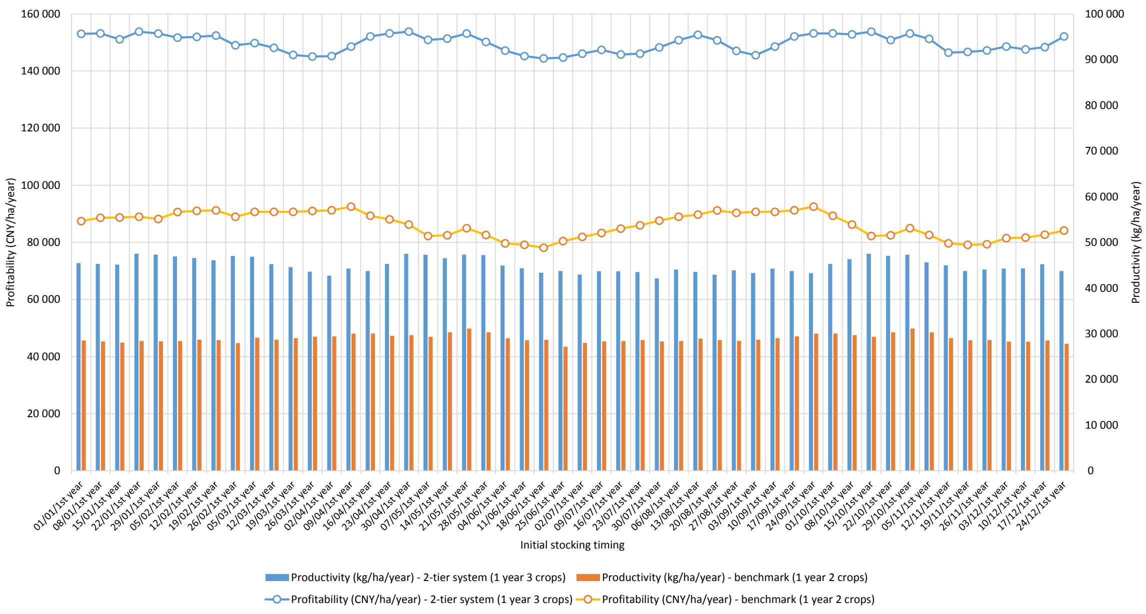


TABLE 13
Comparison of technical and economic performance of different crop arrangements

Average for 52 initial stocking timings	1 year 2 crops (premium price for fish over 500 g)	1 year 3 crops (premium price for fish over 500 g)
Fingerling size (g)	1	84
Stocking density (fish/mu)	1 708	1 873
Growing period (weeks)	24	15
Harvest size (g)	570	535
Productivity (kg/ha per year)	28 999	45 002
Profitability (CNY/ha per year)	86 322	149 705

TABLE 14
Arrangements that maximize profitability under 1 year 3 crops

Indicators		First crop	Second crop	Third crop	Overall or average
Stocking date		30 April	15 October	22 January the next year	
Harvest date		1 October	8 January the next year	16 April the next year	
Fingerling size (g)		1	100	150	82.6
Stocking density (fish/mu)		2 100	2 100	2 000	2 067
Growing period (weeks)		22	12	12	15.3
Harvest size (g)		504	506	523	511
Productivity	kg/ha/week	662	1 137	1 121	914
	kg/ha/year				47 507
Profitability	CNY/ha/week	1 645	4 535	3 628	2 958
	CNY/ha/year				153 082

could be higher because of transportation expenses, mortality during transportation, profit mark-ups, etc. For example, suppose the farmer purchases large-size fingerlings from a commercial nursery 150 km away, the transportation cost would be around

CNY 1.25/kg, which amounts to 20 percent for the production cost of 100 g and 150 g fingerlings.[25] Also suppose the commercial nursery requires 30 percent of profit margin, then the prices of the fingerlings would be 50 percent higher than the production costs in Table 11. Under this situation, the maximum overall profitability in Table 14 would be reduced from CNY 153 802/ha per year to CNY 130 857/ha per year. The reduced profitability would still be greater than that under 1 year 2 crops.

Summary

A multi-tier farming system uses nursing ponds to raise fingerlings to large size before stocking them in outgrowing ponds. Such a system could increase efficiency in pond utilization through high stocking density in nursing ponds. The simulation results in the advanced model indicate that a two-tier farming system could increase overall profitability by 59 to 87 percent (depending on different initial stocking timings) compared with the baseline 1-year-2-crop arrangement of stocking 1 g fingerlings in outgrowing ponds.

[25] A truck loaded with six oxygenated tanks for transporting live fish would cost CNY 7.5/km and CNY 1 125 for 150 km. The six tanks can hold 900 kg of live fish (150 kg each), which means the transportation cost is CNY 1.25/kg. Thus, the transportation costs for 100 g and 150 g fingerlings are CNY 0.125/fish and CNY 0.1875/fish, respectively. The costs are equal to around 20 percent of the production costs of the fingerlings (Figure 35).

5. Discussion

The technical performance of an aquaculture operation is measured by productivity, whereas the economic performance is measured by profitability. While the two are often positively correlated, farming practices and arrangements that increase productivity may not improve profitability. Therefore, farmers as well as researchers who exert constant effort to increase the yield would need to assess whether improved productivity would lead to higher profits.

Time matters. Profit (per ha) per crop is not a proper measure for comparing the profitability of crops with different growing periods; profit per unit of time (week, month or year) would be more accurate. However, it should be noted that for a crop with a length not equal to an integer number of years, profit per year is only a normalized measure of the profitability of the specific crop, but may not be a proper measure of the profitability of the operation. For example, given 1 g fingerlings and 1 200 fish/mu stocking density in the advanced model, the best single-crop profitability is CNY 1 921/ha per week, which amounts to CNY 99 879/ha per year. Yet the maximum profit of 1 year 2 crops is only CNY 92 491/ha per year because the CNY 1 921/ha per week crop occurring in the most favourable weather cannot repeat itself over time due to climate variation. Planning for an aquaculture operation should be based on arrangements that can be repeated over time, which could be multiple-crop arrangements (e.g. 1 year 2 crops, 2 years 5 crops, 1 year 3 crops, and so on).

Farming performance is jointly affected by stocking timing, fingerling size, stocking density and growing period. People often judge farming performance by how fast fish grow. Yet fish growth per se is not a good measure of technical or economic performance. Indeed, the simulation results of the advanced model indicate that given the same growing period, higher stocking density with slower fish growth often results in a higher yield than lower stocking density with faster fish growth.

Farmers as well as researchers are often interested in identifying the optimal stocking density, growing period and/or harvest size. Yet the simulation results of the advanced model indicate that under seasonal climate variation, arrangements that maximize the profitability of individual crops may not be optimal for overall profitability. Even the combination of two crops with their maximum profitability achieved may not be the optimal arrangement that maximizes the overall profitability of 1 year 2 crops – sacrificing the profitability in the first crop may render the second crop a more conducive stocking timing, and the resulting profitability gain in the second crop could outweigh the profit loss in the first crop.

The conjecture that harvesting small-size fish could be more profitable is confirmed by the simulation results – given no price discrepancy between small- and large-size fish, 2-year-5-crop arrangements with higher stocking density, a shorter growing period and smaller harvest size (around 300 g) tend to be more productive and profitable than 1-year-2-crop arrangements that harvest fish over 500 g.

The simulation results also indicate that by separating nursing and outgrowing, the two-tier farming system, which has become increasingly popular in China as well as other countries, could allow 1-year-3-crop arrangements that are more productive and profitable than the benchmark 1-year-2-crop arrangements.

It should be noted that none of the smaller harvest size, more crops or higher productivity is a sufficient condition for higher profits. Increasing stocking density and harvesting smaller fish could increase productivity but reduce profitability because the efficiency gain from having more fish biomass is outweighed by the efficiency loss from missing the fast-growing part of the fish's life cycle. Without the efficiency gain in the nursing stage through using the pond's carrying capacity more completely with higher stocking density, stocking large-size fingerlings could allow 1 year 3 crops and increase productivity accordingly, but the profitability would not be improved.

Under seasonal variation in the water temperature, a 1-year-2-crop arrangement starting at the best initial stocking timing can be nearly 20 percent more profitable than the one starting at the worse initial stocking timing, even though both arrangements are subject to the same overall weather conditions. The profitability under 2 years 5 crops could be more than 30 percent higher than the maximum profitability under 1 year 2 crops. The profitability under 1 year 3 crops could be nearly 70 percent higher than the maximum profitability under 1 year 2 crops. These results indicate that there is a great potential to improve performance through optimized business and operational planning in farming arrangements.

Farmers may be able to optimize farming arrangements gradually based on experiences accumulated over years. But experience-based business and operational planning tends to be inaccurate and less flexible in adapting to changes in environmental, technical or economic conditions. Bioeconomic models can offer help. As the optimal arrangements of the individual crops that maximize the overall profitability of a multiple-crop cycle, be it 1-year-2-crop, 2-year-5-crop or 1-year-3-crop, tend to vary in stocking density, growing period and harvest size, tailor-made bioeconomic models need to be constructed based on specific farming conditions in order to provide guidance to farmers' business and operational planning.

The bioeconomic model developed in this paper illustrates the methodology of constructing bioeconomic models for facilitating business and operational planning and shows the potential of optimal business and operational planning in improving farming performance. The model would need to be improved in many aspects in order to be more adequate for providing practical guidance to business and operational planning in the real world. Key areas for improvement include: (i) more rigorous modelling of fish growth based on more detailed, comprehensive data on tilapia growth under different conditions (water temperature, stocking density, feeding regimes, etc.); (ii) accounting for more environmental factors (water supply, climate changes, etc.); (iii) accounting for the seasonality of the availability and prices of seed, feed and other inputs as well as the fish price; (iv) accounting for the impact of water temperature on FCR; (v) allowing the farmer to adjust feeding practices according to different farming conditions; and (vi) introducing uncertainties to facilitate risk analysis.

It would take long-term, collective efforts of farmers, researchers, extension personnel and policymakers to realize the potential of bioeconomic modelling for better business and operational planning in aquaculture. The research community needs to provide more scientific data and information on tilapia growth under different farming conditions and direct more efforts towards building practical bioeconomic models for guiding business and operational planning in aquaculture. Fish farmers should embrace bioeconomic modelling as a scientific tool to help them actively seek improvement in the farming performance rather than forced to change only when the operation is losing money. The extension community should help researchers develop more practical models according to farmers' needs and facilitate farmers' use of bioeconomic modelling techniques and results in business and operational planning. Policymakers should recognize bioeconomic modelling as a knowledge-based, climate-smart innovation for improving farming performance and provide funding and coordination support to facilitate the enterprise.

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Tilapia is one of the most popular aquaculture species and is farmed in more than 120 countries and territories. A bioeconomic model on tilapia pond culture has been developed by the Food and Agriculture Organization of the United Nations (FAO) based on experiences in China, the largest tilapia farming country. The results of the model indicate that the technical and economic performance of tilapia farming can be significantly improved by optimal selection of stocking timing, fingerling size, stocking density, growing period (or crop length), harvest timing and harvest size according to technical, economic and climate factors. Bioeconomic modelling can facilitate knowledge-based innovations for increasing technical and economic benefits through more efficient use of resources. Its potential has yet to be adequately appreciated or utilized. This paper represents an effort to improve the situation.

ISBN 978-92-5-130162-3 ISSN 2070-7010

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I8442EN/1/01.18