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A Business Analysis of Innovations in Aquaculture: Evidence from Israeli Sturgeon Caviar Farm

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Abstract: The background of this study is related to the tendencies in caviar production and prices in the world. The objective of the study is to evaluate and compare the profitability of different sturgeon sex determination methods for the conditions of aquaculture farms in northern Israel. We present the economic valuation of the technological innovation of early sex determination in this aquaculture industry. The production of sturgeon biomass exceeded the fishery harvest during the 1970–1980s by more than four times. There was a significant decline in world caviar prices the last time. The aquafarming business has a high potential economic value in the region of northern Israel. Based on the empirical data of the Caviar Galilee farm in this region, we examine the economic benefits of the innovation in sturgeon sex determination, including the case of a possible decrease in caviar price. Using the bio-economic model for a sturgeon caviar farm in two versions (for each of the considered sex determination methods, the endoscopy method and the early sex determination method), we show the economic advantages of this innovation of 9–34% for different financial highlights compared to the traditional method of sturgeon sex determination. The study empirically illustrates the economic advantages of the cooperation between aquaculture farming and research institutes. Our study suggests that additional directions in research should be sought in order to increase the profitability of sturgeon farms, especially when the world caviar prices decline. Further research can be conducted for additional regions and data.

Keywords: aquaculture; sex determination; economic valuation; sturgeon; caviar

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1. Introduction

The region of northern Israel has unique conditions for developing aquaculture farming businesses. Through this subtropical area, the Jordan River flows, one of the inflows of which is the Dan Stream. The Jordan River, in turn, flows into Lake Kinneret, which is the most important freshwater resource in Israel. Available high-quality water and suitable climatic conditions in the region allow the development of innovative aquaculture farming and to gain profit in this industry in today's often volatile market. The aquafarming business has a high potential economic value in the region of northern Israel [1]. The research question of this study is as follows: How large can the economic benefits of innovations in aquaculture farming be when world market prices can drop significantly? For this purpose, we analyze and compare a possible technology innovation in the project of sturgeon and caviar production evaluated for the conditions of northern Israel.

A unique branch of Russian sturgeon (*Acipenser gueldenstaedtii*) was developed in Kibbutz Dan (in the name of the Dan Stream) for fish and caviar production. For this purpose, the ponds with a total volume of 12,000 cubic meters were built at the beginning of the 2000s in the Dan Fish Farm (Caviar Galilee, Kiryat Shmona, Israel) [2].

The objective of the current study is to evaluate and compare the profitability of different sturgeon sex determination methods for the conditions of the aquaculture farm in northern Israel. The use of specific methods of sex determination is important for the business analysis of sturgeon aqua farms. The endoscopic methods for determining sex can only be used once the gonads differentiate, at the age of 3 years or later.

Recently, the economic problems of the sturgeon aquaculture farms that follow from the late maturity of fish, leading to a long payback period for sturgeon farms, were described in an article [3]. In that article, the innovation of ESD was evaluated using an economic model of a sturgeon farm. In the present study, we confirm the findings of that article and present the updated model and more detailed novel data of: (a) number of fish in the Caviar Galilee farm, (b) caviar productivity by fish age, and (c) world tendencies in sturgeon caviar production and prices. The important feature of the updated economic model of the present research is that it can be used in the economic evaluation of other innovations in sturgeon caviar farms.

The rest of the paper is structured as follows: In Section 2, we discuss recent tendencies in the sturgeon/caviar world market, key data of the researched innovation, and describe the developed bio-economic model, which was used as the main method of the study. In Section 3, we present the results obtained using the bio-economic model, while Section 4 discusses them and compares them with the results obtained in previous studies, and Section 5 concludes.

2. Materials and Methods

The data on the world and Israel sturgeon catch and sturgeon and caviar production were collected using FishStatJ. This application can be downloaded from the site [4]. This site enables access to fisheries and aquaculture statistics of the Food and Aquaculture Organization of the United Nations [5]. The caviar prices (export and import) for the EU and USA were taken from EUMOFA (European Market Observatory for Fisheries and Aquaculture) [6].

2.1. Literature Review

Various biological aspects related to the adaptation of the species of Russian sturgeon in aquaculture farming under Israeli conditions were studied in cooperation between the MIGAL Research Institute (Kiryat Shmona, Israel) and the Caviar Galilee aquaculture farm [7]. Many aspects of aquaculture, fish nutrition, and hormone control reproduction were studied in the research [8,9] on sturgeon sexing, and of sex determination in the articles [10,11].

A monosex population of farmed fishes can considerably enhance the economic benefits of aquaculture farms [12]. As a result, sexing is based on endoscopy or ultrasound examination of the gonads at the age of 4–5 years at the earliest, with ~70–90% accuracy [13]. Transcriptome studies of the gonads have been conducted in the Russian sturgeon [14]. As sexual maturation is earlier in males than in females, the gonad and fin transcription profiles of 29 known and sex-related genes of males (4 years old) and females (7 years old) have been compared. In non-gonadal tissues of Russian sturgeon, the expression of these genes is similar among the sexes at 4 years old [8].

Relatively few studies examine the variation between genes expiration variation in the gonad of Russian sturgeon after sex differentiation [9] in order to find the genes that control sex differentiation to ovary or testis. Early sex determination (ESD) is taken at juvenile fish might using a molecular method based on a DNA variation between sex [10]. As this is described in [11], different gene expiration of AllWSEX2 between sex might use as the sex marker for Russian sturgeon and sex differentiation a few months after hatching from the eggs.

2.2. Recent Tendencies in Sturgeon World Market

From the period 1990–2018, the catch of the commercial species of sturgeons has undergone a sharp decline. Only in 2019 did the size of the catch stop declining and even slightly increase (Figure 1).

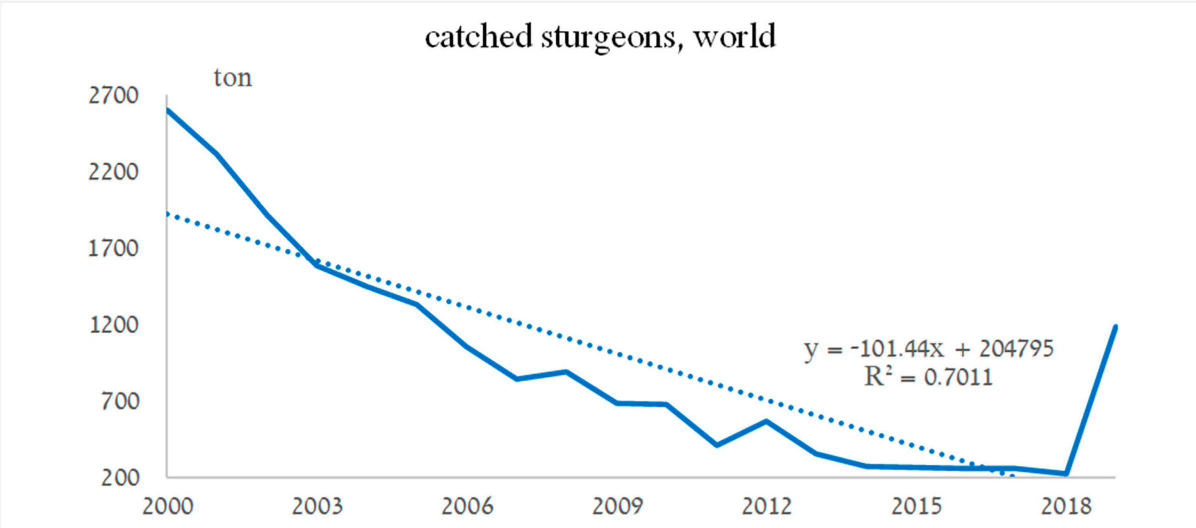

Figure 1. Sturgeons caught in the world, 2000–2019. Source: [5].

Due to the latest achievements of sturgeon aquaculture and the expansion of the caviar market, particularly among middle-class consumers, there remains vast potential to reshape caviar consumption [15]. Because of this, the need for aquaculture production of sturgeons has greatly increased, and as a result, sturgeon farms began to substitute fishery production. A total of 2329 commercial sturgeon farms worked in 2017 in the world. Their production of sturgeon biomass exceeded the fishery harvest during the 1970–1980s by more than four times. In Figure 2, the production of sturgeons in the aquaculture farms in the world (2000–2019) and in Israel (from 2005) is shown. There was a significant positive tendency in the world sturgeon production during this period. Since the year 2009, the production of sturgeons in Israel (Caviar Galilee farm) has been stabilized at the level of 30 tons, the maximal capacity of the farm.

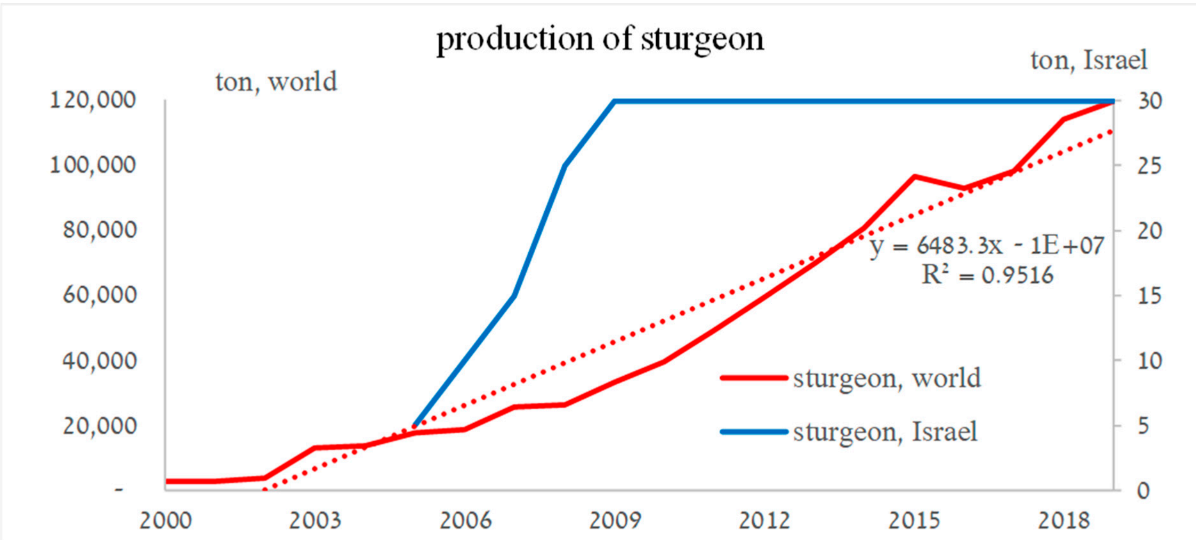

Figure 2. Sturgeons produced in aquaculture farms in the world and in Israel, 2000–2019. Source: [5].

2.3. Recent Tendencies in Caviar World Market

With a delay of a few years after starting intensive sturgeon farming, farmed caviar entered the market on a large scale. The forecasts for caviar production show that the trends of the demand are lower than those of the supply [16]. In Israel, the Caviar Galilee farm began to produce Sturgeon Osetra caviar at the beginning of the 2000s. In 2005 the Farm began to export caviar to the USA. In the database [6], the first data on caviar production in the Caviar Galilee farm appeared in 2012. In Figure 3, the tendency of caviar production in the Caviar Galilee farm is compared with the tendency of the world production by years. There was a significant positive tendency in the world caviar production during this period. The caviar production in Israel was rather stable from the year 2013 when the Caviar Galilee farm reached its full production capacity.

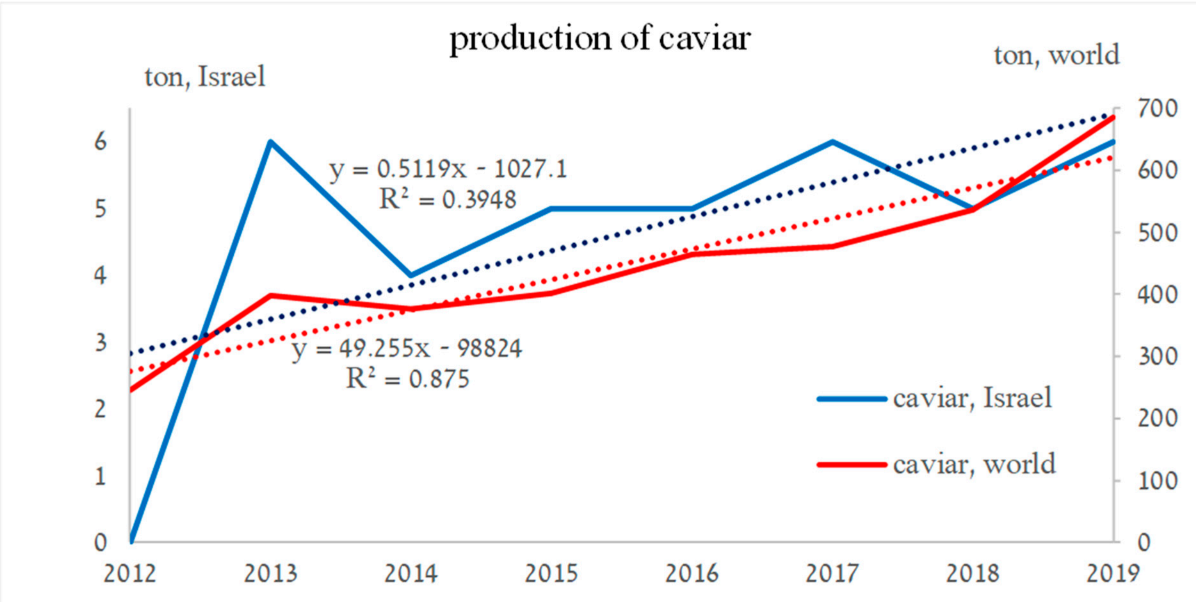

Figure 3. Production of caviar in Israel compared to world production. Source: [5].

The average caviar prices of intra-EU trade and U.S. import experienced a significant negative trend in 2014–2020, as shown in Figure 4.

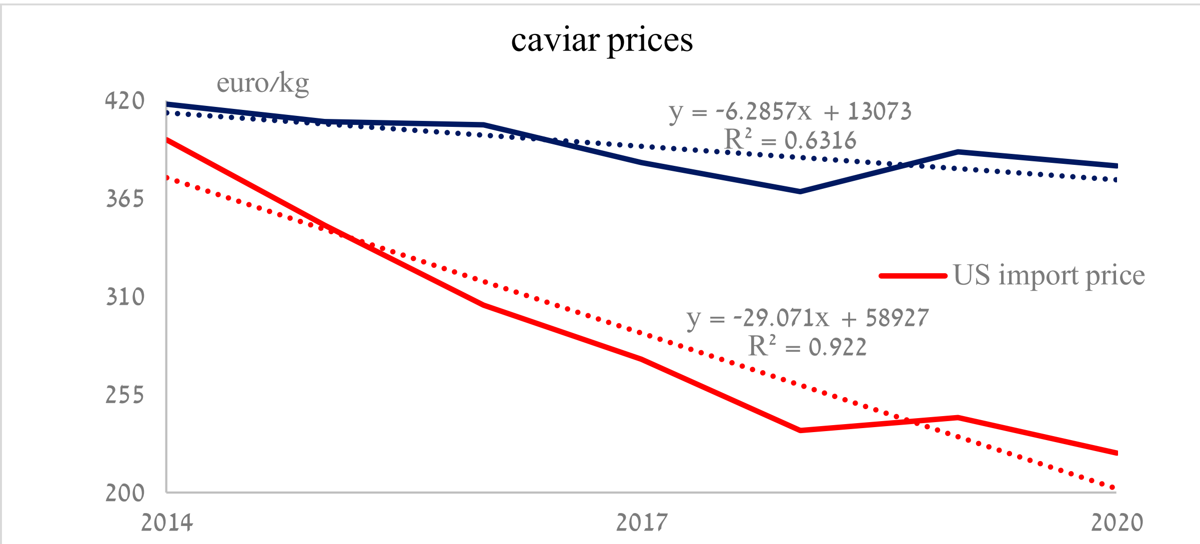

Figure 4. The average caviar prices of intra-EU trade and U.S. import. Source: [6].

One of the practical solutions to the problem of a negative trend in caviar prices lies in the ESD of the aquacultured sturgeons. This could lead to a possible reduction in the caviar production cost and thereby to the continued high profitability of the caviar farms [3].

2.4. Key Data of the Innovation and the Background of the Economic Model

The original data were collected in the *Caviar Galilee* farm in the last 5 years, including research that was conducted in cooperation between MIGAL and the Caviar Galilee farm [4,6]. Specifically, the important data of caviar output in kg per female fish in the Caviar Galilee farm were collected. For Russian sturgeons, a female begins to produce caviar from age 7, and at age 10, the amount of caviar arrives at the maximum of 2.75 kg per female. From age 7, the farm begins to sell fish of the market size of 13.5 kg (Table 1). Additionally, the data on the investment needed for the farm establishment, financing data, current expenses, sturgeon weight, and fish and caviar prices were collected on the Caviar Galilee farm.

Table 1. Caviar production and marketed fish in the Caviar Galilee farm.

Age of Female Fish	Caviar Production, kg per Fish	Marketed Fish, Thousand, 13.5 kg Fish Market Size
Year 7	1.93	0.8
Year 8	2.20	6.1
Year 9	2.48	6.8
Year 10 and forth	2.75	7.6

The traditional *y* methods of sturgeon sex determination enable to leave only female fish on the farm from the year 3–4 of their life. Using molecular DNA markers for sturgeon enables ESD at the age of 0.5 years. This innovative method is important for increasing the profitability of sturgeon farms due to early male separation and thus growing more females and producing more caviar for the same farm area. This method enables higher profitability of the sturgeon caviar farm because the price of the caviar is much higher than the price of the sturgeon meat [3].

Because of the great importance of sex determination in the Russian and other sturgeon species, there was an intensive study of the theoretical and practical aspects of this problem [13]. The reproductive cycle of white sturgeon was researched in [17]. Basic research has been carried out on the differences between fish sex, and subsequently, practical methods were developed that enabled sex determination in farm sturgeons. The first method was an endoscopy, where a difference between males and females is determined at the fish age of about 3 years when genitals are developed enough in the Russian sturgeon [18]. The genomic state of sturgeons is not very clear [19,20]. Recently, after finding molecular markers in the genome, it became possible to determine sex in the Russian sturgeon at a much earlier age. Molecular methods enable us to find the sex difference at the fish age of six months and perhaps even less [17,19,21] and sex-related genes [12]. A molecular method was tested on the Caviar Galilee farm. In the current study, both sturgeon sex determination technologies: (a) using molecular DNA markers for ESD at the age of 0.5 years old and (b) using endoscopy methods at the age of 3.5 years, are examined and compared from an economic point of view.

For the sturgeons farmed in the northern Israel region, males are separated at the age of 3.5 years and sold for meat (the producer price of meat is relatively low compared to the producer price of caviar). Females continue to grow and produce caviar at the age of 7–10 years. Endoscopy methods for sex determination are currently used in the Caviar Galilee farm, as on many other sturgeon farms around the world [18].

Several studies showed that there is a genetic difference between males and females in the Russian sturgeon [14,22]. In the Russian sturgeon, it was eventually possible to isolate a segment of DNA that also serves as a genetic marker for the Russian sturgeon. The genetic marker AllWSEX2 examined in PCR is different between males and females as it was found by endoscopy, and a suitable correlation to female Russian sturgeon was found in the Caviar Galilee farm [23]. The ESD of fish using molecular DNA markers at the age of 0.5 years old is important for increasing the profitability of sturgeon farms due to early male separation, thus enabling growing more females and producing more caviar for the same farm area. Using the data of Table 1 and the projected flow of sturgeon females for the two methods of sex determination, the caviar production in the Caviar Galilee farm was calculated (Table 2).

Table 2. Number of females, thousand, caviar and sturgeon production, in the Caviar Galilee farm.

Year of the Farm Establishment	Endoscopy Method of Sex Determination			Method of Early Sex Determination		
	Number of Females, Age 7–10 Year	Caviar Sale, Ton	Sold Fish, Ton	Number of Females, Age 7–10 Year	Caviar Sale, Ton	Sold Fish, Ton
7	6.3			7.6		
8	10.6	1.2	8.4	12.9	1.5	10.2
9	11.3	10.8	67.5	13.6	13.1	81.7
10	11.9	12.4	75.9	14.4	15.0	91.9
11 and forth	11.9	14.1	84.4	14.4	17.1	102.1

As is presented in Table 2, the caviar production and sold fish for the method of ESD is significantly higher than for the endoscopy method (21–25%) for the same farm area and other characteristics. For both methods, it was assumed that the establishment of the farm where the number of fish reaches 70 thousand in 10 years after the start of the fish stocking was an investment of 14 million U.S. $ (this needs to be verified in further research).

2.5. Model

In the recent survey on the use of bio-economic models in fisheries and aquaculture (a total of 1100 articles from many countries were surveyed), it was shown the growing popularity of the application of bio-economic models in various areas of fisheries and aquaculture [24]. The results in [25] indicate an increasing contribution of using population models within the general field of sturgeon research. These models are used to analyze the impacts of fisheries and aquafarms and genetic innovations and to conduct sensitivity analyses. Based on the findings of these studies, in the current research, the bio-economic model for the valuation of the ESD innovation in a sturgeon caviar farm was developed in Excel and included the following modules: technological assumptions (including feed consumption, fish growth by sex, age, and weight), investment and loans, labor and other current expenses, cash flows and calculation of financial highlights, and sensitivity to caviar prices.

The module of technological assumptions enabled us to run the model in two versions: For each of the considered sex determination *methods, the* endoscopy method and ESD. Every module included the following variables: HOG (head-on-gutted) fish, cost in $, for year 1, 2, . . . , 25 for the evaluation period, and caviar, cost in $, for year 1, 2, . . . , 25 for the evaluation period, a total 50 variables in the model. The data presented in Table 2 were used for describing these variables.

The module of sensitivity enabled us to decide that the ESD method was more profitable than the endoscopy method, also in the case of further decline of caviar world prices. The module of cash flows enabled us to link the financial calculations with changing technological assumptions in the two versions of the model for various production and sale of fish and caviar depending on the used sex determination method (Tables 1 and 2).

To evaluate and compare the profitability of the Caviar Galilee farm for both methods of sex determination, the traditional endoscopy method and the innovative ESD, the following economic criteria were used:

- IRR (internal rate of return) of the project for estimating the profitability of the investment in the farm;
- Cumulative net profit and cumulative cash flow for the evaluation period of 25 years;

- Payback period, nominal (not discounted), including the investment period;
- Revenue and net profit of the farm in year 11 (when the fish stock and cash flows become stable).

The investment with the highest IRR is considered the best. In our case, this is the investment of the same sum of money (14 million U.S. $) but for two different methods of sex determinations that lead to different revenue and expenses.

The Excel built-in IRR function was used in this module for the calculation of the project IRR. The cash flow proforma was calculated in this module, as well, to evaluate the project IRR and other financial highlights (net profit, return on investment). The approach is based on using two versions of the economic model of the farm, with and without applying the technological innovation, which enables a clear evaluation of the innovation profitability.

3. Results

The above financial criteria for the Caviar Galilee farm were evaluated and compared for both considered methods of sex determination. The innovative method of ESD was found to be significantly better than the traditional endoscopy method for all compared economic criteria, including the case when *world prices of caviar drop significantly*:

(a) For the IRR criterion, 2.6 percentage points (17.7% and 15.1% for ESD and the endoscopy method, respectively);
(b) For the cumulative net profit, 34% (175 and 130 million U.S. $, respectively);
(c) For the cumulative cash flow, 31% (184 and 141 million U.S. $, respectively);
(d) For the payback period, 10 months (10 years and 7 months, and 11 years and 5 months, respectively);
(e) For the revenue in year 11, 21% (18.1 and 14.9 million U.S. $, respectively);
(f) For the net profit in year 11, 9% (11.4 and 10.5 million U.S. $, respectively).

To summarize, for the model version, when the method of ESD is used, the farm is evaluated as a more profitable one and the payback period of this farm is shorter than for the version when the endoscopy method is used. To answer the research question of the study (how large can the economic benefits of innovations in aquaculture farming be when world market prices can drop significantly?), we note that in the case of a possible decrease of 10% for caviar producer price, the advantage of ESD, in terms of IRR, for example, even a little greater (Table 3).

Table 3. Financial highlights of the Caviar Galilee farm for various methods of sex determination.

Criterion	Endoscopy Method of Sex Determination	Method of Early Sex Determination	Advantage of Early Sex Determination
Cumulative net profit, U.S. $M	130	175	34%
Cumulative cash flow, U.S. $M	141	184	31%
Payback period	11 years 5 months	10 years 7 months	10 months
Revenue in year 11, U.S. $M	14.9	18.1	21%
Net profit in year 11, U.S. $M	10.5	11.4	9%
Project IRR	15.1%	17.7%	2.6 percentage points
Project IRR when caviar producer price decreases by 10%	13.9%	16.6%	2.7 percentage points

4. Discussion

The world aquaculture sturgeon production reaches 120 thousand tons of sturgeon meat and 700 tons of caviar. This aquaculture industry is also important for countries with limited water resources like Israel. So far, many studies have been carried out on various aspects of Russian sturgeon farming in Israel. They include adaptation to growing conditions in Israel, food demand and lighting conditions for fish [25], egg development and caviar formation [17], hormonal control over Russian sturgeon growth and egg development, the differences between the genes that monitor sex, and more [13,21]. At the same time, relatively little research has been conducted hitherto on the economic valuation of caviar production in the aquaculture farms for the case of applying ESD to Russian sturgeon [12].

The decrease in fish catch in nature is compensated more and more by the development of aquaculture production using biotechnological technologies. The establishment of an aquafarm is a costly business. From the results of our study, it seems that implementing technological innovations in a sturgeon farm, such as ESD, is a suitable way to increase the profitability of the farm. Specifically, for the region of northern Israel, our study confirms the conclusion about the high economic potential of the sturgeon aquaculture in this region [1].

Due to the latest achievements of sturgeon aquaculture and the expansion of the caviar market, particularly among middle-class consumers, there remains vast potential to reshape caviar consumption. Our study, which is a predominantly economic valuation, suggests that additional directions in research should be sought in order to increase the profitability of sturgeon caviar farms, especially when the world caviar prices decline. This is in line with the conclusion that from the productive point of view, the principal difference from the past caviar production is the definitive shift from wild to farmed caviar [15].

The amount of water and its cost is the limiting factor of the aquaculture business in Israel. In many other countries around the world, greater and cheaper water resources are available, and more caviar production can be created. The results of our study show explicitly that the production of caviar in the world is on the rise, while in Israel, the increase is moderate compared to the world's tendencies. However, even when water resources are limited, biotechnological innovations such as ESD can significantly increase the profitability of caviar production, as follows from our study.

Our results confirm the conclusion of the previous research [26] that the cooperation between a sturgeon caviar farm (Caviar Galilee farm) and a scientific research institute (MIGAL) can enable lower production costs, greater production, and higher profitability in this important aquaculture industry due to biotechnological innovations. This is consistent with the conclusion of the interdisciplinary nature of modern aquaculture innovations and knowledge in light of the contributions of academic research to industrial performance [24,27].

5. Conclusions

The technological innovation of sturgeon early sex determination instead of the traditional endoscopic methods for determining the sex of sturgeons is important for this fast-growing aquaculture industry. For many species, a monosex population of farmed fishes can considerably enhance the economic benefits of aquaculture farms [28], but it needs sex determination. Endoscopy methods are used for this purpose [11]. For Russian sturgeon, sexual maturation is earlier in males than in females, and this can be determined genetically [13]. Early sex determination can be performed using a molecular method based on a DNA variation between sex. For Russian sturgeon, it is possible several months after hatching from the eggs, and not several years as in the endoscopy method [14,21]. However, the research on this topic is limited in the literature.

In this study, the bio-economic model was developed and implied for the evaluation of these two sex determination methods in a sturgeon caviar farm. The data of the Caviar-Galilee farm from the northern Israel region were used for running the model.

The yearly flows of sturgeon females and of sturgeon and caviar production were calculated in this study on the base of the bio-economic model for each of the two methods of sex determination. The results demonstrate a clear economic advantage of the ESD method, including the case of a possible decrease in caviar producer prices.

Specifically, the results of the economic valuation show that the innovative ESD method enables the following significant improvement for all examined economic criteria of the farm performance, including profitability, internal rate of return, and payback period of the investment: the cumulative net profit can be improved by 34%, the cumulative cash flow by 31%, the payback period by 10 months, and the project IRR by 2.6 percentage points.

The presented study empirically illustrates the economic advantages of the cooperation between aquaculture farming and research institutes. This cooperation can help to answer the question of how large can be the economic benefits of innovations in aquaculture farming when world market prices and trade conditions can fluctuate significantly.

The limitations of our study arise from using the data of the only aquaculture sturgeon caviar farm from the region of northern Israel. Further research can be conducted for additional regions and data from multiple farms. Moreover, the bio-economic model that was developed in this research is presented in a yearly format. Further development of the bio-economic model in a monthly format will enable making the evaluation of the payback period and other financial highlights of the sturgeon caviar farm more accurate, as well as taking into account possible seasonal fluctuations in prices for farm products, sturgeon meat, and especially caviar.

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