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Published in:
Aquaculture

Link to article, DOI:
10.1016/j.aquaculture.2021.737530

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Fernández-Sánchez, J. L., Breton, A. L., Brun, E., Vendramin, N., Spiliopoulos, G., Furones, D., & Basurco, B. (2022). Assessing the economic impact of diseases in Mediterranean grow-out farms culturing European sea bass. *Aquaculture*, *547*, Article 737530. https://doi.org/10.1016/j.aquaculture.2021.737530

Aquaculture 547 (2022) 737530

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Assessing the economic impact of diseases in Mediterranean grow-out farms culturing European sea bass

José L. Fernández Sánchez [a,*], Alain Le Breton [b], Edgar Brun [c], Niccolò Vendramin [d], Georgios Spiliopoulos [e], Dolors Furones [f], Bernardo Basurco [g]

[a] IDES Research Group, University of Cantabria, Santander, Spain
[b] Vet'eau, Grenade sur Garonne, France
[c] Norwegian Veterinary Institute, Oslo, Norway.
[d] National Institute of Aquatic Resources (DTU Aqua), Lyngby, Denmark
[e] Kefalonia Fisheries S.A., Athens, Greece
[f] Institute of Agrifood Research and Technology IRTA, Sant Carles de la Ràpita, Tarragona, Spain
[g] Mediterranean Agronomic Institute of Zaragoza (CIHEAM Zaragoza), Zaragoza, Spain

ARTICLE INFO

Keywords:
Disease outbreak
Disease cost
Mediterranean aquaculture
Nodavirus
Vibriosis

ABSTRACT

The aim of this work is to propose a novel and formal approach to evaluate the direct costs of diseases caused by different pathogens as well as their economic impact on typical Mediterranean grow-out farms culturing European sea bass under different scenarios of production related to the biomass produced (farm size) and the size of the fish produced (production strategy). We employ a deterministic static model to simulate the annual income statement of those facilities to evaluate the direct costs caused by different diseases as well as, through a partial budget and sensitivity analyses, the economic impact of them. An important conclusion of this work is that the profitability and economic viability of sea bass grow-out farms suffering recurrent outbreaks of diseases caused by different pathogens depend on the farm typology (farm size) as well as the decisions taken by owners/investors about the size of the fish produced and sold in the market. Our estimations show that as the larger is the farm and the size of the fish produced, the larger are the direct cost of a disease outbreak. However, the economic impact on the net operating profit is significantly worse as smaller is the farm and smaller the fish produced. The conclusions of this research stress the need for small producers to pay attention and devote resources to prevent and treat disease outbreaks.

1. Introduction

Infectious diseases represent a bottleneck for the development of the aquaculture industry. Thus, disease outbreaks are associated with an increase of mortality, a feed conversion worsening, and a decline in animal welfare, hampering the farms' production and their economic viability (Lama et al., 2020). Clinical disease outbreaks are the output of multiple factors related to the production process (e.g., rearing conditions, stocking density, water quality, diet, oxygen availability, handling, seasonality), the host susceptibility, and the specific pathogen's virulence (Firmino et al., 2019). Consequently, disease prevention and control are pivotal for the development of a sustainable aquaculture industry, and this has to be implemented with the collaboration of farmers and the animal health authorities.

One of the most important infectious diseases in Mediterranean aquaculture is viral encephalopathy and retinopathy (VER), previously described as viral nervous necrosis (VNN). The causative agent of this disease is the nervous necrosis virus (NNV) or betanodavirus (Bellance and Gallet de Saint-Aurin, 1988; Glazebrook et al., 1990; Breuil et al., 1991). Due to its virulence and rapid spreading, VER outbreaks are associated with growth reduction and high mortality of fish, affecting mostly juveniles (Vendramin et al., 2016; Lama et al., 2020; Muniesa et al., 2020). As regards bacterial disease vibriosis, photobacteriosis and tenacibaculum spp., their infections are considered among the most important diseases for European sea bass (Zrnčić and Pavlinec, 2020). Classical vibriosis, caused by *Vibrio anguillarum*, is considered the most

* Corresponding author at: Faculty of Economics and Business Administration, University of Cantabria, Avda. de los Castros 56, 39005 Santander, Spain.
E-mail addresses: jluis.fernandez@unican.es (J.L. Fernández Sánchez), alain.lebreton@veteau.com (A. Le Breton), edgar.brun@vetinst.no (E. Brun), niven@aqua.dtu.dk (N. Vendramin), g.spiliopoulos@kefish.gr (G. Spiliopoulos), Dolors.Furones@irta.cat (D. Furones), basurco@iamz.ciheam.org (B. Basurco).

https://doi.org/10.1016/j.aquaculture.2021.737530
Received 19 July 2021; Received in revised form 22 September 2021; Accepted 24 September 2021
Available online 27 September 2021
0044-8486/

common bacterial disease, affecting all fish stages throughout the production cycle (Rucker, 1959; Sørensen and Larsen, 1986). Vibriosis outbreaks exhibit a clear seasonal trend, as VER, with increasing prevalence at temperatures above 20 °C, which could lead to co-infection by other pathogens. This prevalence is expected to increase in the future due to climate change (Firmino et al., 2019). Outbreaks due to bacteria may result on higher or lower mortality depending on their pathogenicity, but also on treatment and prevention measures. Frequently, they can become chronic. Additionally, a disease outbreak is not necessarily caused by a single bacterial species, but it may involve synergistic interactions between two or more taxa (Zrnčić and Pavlinec, 2020). Moreover, diseases caused by parasites, for which no vaccine are available and very few treatments are licensed, have been recognized as the third cause of mortality affecting mainly in the on-growing stage (Vendramin et al., 2016; Fioravanti et al., 2020).

Several studies about the economic impact of fish diseases have been published recently, (Lafferty et al., 2015; Abolofia et al., 2017; Nor et al., 2019; Peterman and Posadas, 2019), although none of these studies are focused on Mediterranean aquaculture. European sea bass (*Dicentrarchus labrax*) is along with the gilthead sea bream (*Sparus aurata*) one of the most important species in the Mediterranean aquaculture, representing the first a 20% (€579 million) of the total value of the European aquaculture in the year 2018 (STECF, 2021). Currently the largest share of sea bass production takes place in sea cages either inshore or offshore, being the intensification of production a risk factor for the occurrence of disease outbreaks. The aim of this work is to propose an approach to evaluate the direct costs of diseases caused by different pathogens as well as their economic impact on a typical European grow-out farm culturing sea bass in the Mediterranean under different scenarios of production related to the biomass produced (farm size) and the size of the fish produced (production strategy). This work presents a novel and formal approach to estimate farm losses associated with disease outbreaks in the Mediterranean aquaculture. According to Costello (2009), this type of research is very important because it may be the 'best metric' for prioritizing resources as, for example, how much to expend in disease prevention and treatments (i.e., in vaccination, biosecurity, or veterinarian services).

The structure of this work is as follows. Firstly, we explain the model proposed for our analysis together with the work assumptions. Secondly, we set up the scenarios of production and the parameter values employed to obtain the baseline or reference values of each scenario. Thirdly, we present the results obtained with our model applying the partial budget and sensitivity analyses. Finally, in the last section, we present the main conclusions of our work.

2. Methodology

We have designed a deterministic static model programmed with the spreadsheet Excel (version 16.0) to simulate the annual income statement of a typical grow-out farm producing European sea bass in the Mediterranean Sea. This model, which is based on the work of previous researchers as Rizzo and Spagnolo (1996), Cacho (1997), Gasca-Leyva et al. (2002), Pomeroy et al. (2008), Di Trapani et al. (2014), Janssen et al. (2017) or Arru et al. (2019), is composed of two sub-models

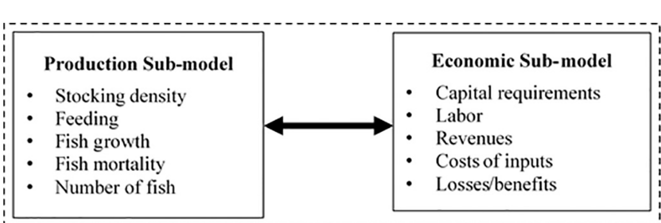

Fig. 1. Model framework to simulate the economic performance of sea bass production.

(Fig. 1): a production sub-model with different parameters and variables related to the production process (e.g., stocking density, feeding, fish growth, fish mortality, number of fish, etc.), and an economic sub-model with parameters and variables related to the economic issues of operating an aquaculture farm (e.g., capital requirements, labor, revenues, costs of inputs, and so on). The model, however, does not include biological or environmental sub-models as other more complex models do (e.g., bio-economic or system dynamic models) as they would not relate to the purpose of this work.

2.1. Model description and assumptions

Our aim was to build a model to simulate the operations of a typical grow-out farm during a regular year to estimate its annual net operating profit. This facility employs the production system based on cages in the sea and we assume that the production process is continuous with multiple batches (i.e., the fry stocking and fish harvest are repeated with similar frequency), so that the distribution of the economic variables (prices and costs) and production variables (stocking, feeding, and harvesting) are assumed constant during repeated production cycles. We also assume that limiting factors of production are specific of farming conditions (e.g., water temperature or mortality rates) and practices (e.g., selection of fingerling size, stocking density, feed composition or feeding regime), and they are considered fixed and appropriate (optimal) along the production process, so that fry stocking and fish harvesting are unaffected by them.

Therefore, the annual net operating profit (π) of a sea bass grow-out facility with a continuous production system can be obtained by subtracting the annual total operating costs (*TC*) from the annual operating revenues (*TR*) obtained from the fish sales, such as:

$$\pi\ (€/\text{year}) = \text{TR}\ (€/\text{year}) - \text{TC}\ (€/\text{year}) \tag{1}$$

The annual operating revenues from fish sales can be calculated as follows:

$$TR = p \times Q \tag{2}$$

where *TR* is the annual operating revenues (€/year); *p* is the unit sales price of fish (€/kg); and *Q* equals the annual biomass of fish produced (kg/year).[1] Moreover, the annual biomass of fish produced in each facility can be calculated in the following way:

$$Q = N \times \left(\frac{s}{100}\right) \times \left(\frac{w_1}{1000}\right) \tag{3}$$

where *N* is the annual quantity of cultured fish (# units/year); *s* is the fish survival rate (%); and w_1 is the fish final weight (g/unit). The annual quantity of cultured fish can be obtained using the following expression:

$$N = d \times c \times \frac{12}{T} \tag{4}$$

where *d* is the fish density per cage (# units/cage); *c* is the total cages in the facility (# cages); and *T* equals the production period (# months). This production period has been obtained as follows:

$$T = \frac{w_1 - w_0}{g} \tag{5}$$

where w_1 is the fish final weight (g/unit); w_0 is the fish initial weight (g/unit); and *g* is the fish absolute growth rate (g/month).

On the other hand, the total operating cost per year of a grow-out farm is given by the sum of its variable and fixed costs in the period. Fingerling and feed costs are considered variable costs, assuming that these costs are proportional to sea bass production, whereas it is

[1] We assume that the harvested fish exhibit homogeneous genetic behavior and weight distribution (no malformations), as well as the harvested biomasses can be sold to a price *p* independent on the supplied biomass.

Table 1
Annual operating costs of a grow-out farm.[a]

Operating costs		Formula	Definitions
Variable costs	Fingerling cost	$p_j \times N$	p_j = Fingerling unit cost (€/unit)N = Annual quantity of cultured fish (# units/year)
	Feed cost	$p_f \times W = p_f \times \left[N \times \left(\frac{1+\frac{s}{100}}{2}\right) \times \left(\frac{w_1 - w_0}{1000}\right) \times r\right]$	p_f = Feed unit cost (€/kg) W = Annual feed weight (kg/year)[b]N = Annual quantity of cultured fish (# units/year) s = Fish survival rate (%) w_1 = Fish final weight (g/unit) w_0 = Fish initial weight (g/unit) r = Feed conversion ratio (FCR)[c]
Fixed costs	Labor cost	$l \times e \times c$	l = Annual labor cost per employee (€/employee × year) e = Employees per cage (# employees/cage) c = Total cages in the facility (# cages)
	Energy cost	$n \times c$	n = Annual energy cost per cage (€/cage × year) c = Total cages in the facility (# cages)
	Veterinarian and medicine cost	$v \times c$	v = Annual veterinarian-medicine cost per cage (€/cage × year) c = Total cages in the facility (# cages)
	Other operating cost	$m \times c$	m = Annual other operating cost per cage (€/cage × year) c = Total cages in the facility (# cages)
	Depreciation cost	$a \times i \times c$	a = Annual depreciation rate (%) i = Annual capital investment per cage (€/cage × year) c = Total cages in the facility (# cages)

[a] Model parameters are in lowercase letters and model variables are in uppercase letters.
[b] The annual feed weight is calculated using the average stock of cultured fish.
[c] The FCR measures the efficiency of conversion of feed to fish.

Table 2
Parameter values assumed for each farm size.

Concept	Unit	Micro farm	Small farm	Medium-Large farm
Farm annual production	tons/year	180	540	2250
Number of cages	# cages	12	18	40
Cage size (volume capacity)	m^3/cage	1000	2000	3750
Biomass density	kg/m^3	15	15	15
Annual wage per employee	€/employee × year	16,440	16,440	16,440
Number of employees per cage	# employees/cage	0.8	0.8	0.8
Annual energy cost per cage	€/cage × year	3124	3124	3124
Annual veterinarian cost per cage[a]	€/cage × year	0	0	0
Annual other operating costs per cage	€/cage × year	3411	3411	3411
Annual depreciation rate	%	10	10	10
Annual capital investment per cage	€/cage × year	151,265	151,265	151,265

[a] Assuming that there is not any disease outbreak during the production period.

Table 3
Parameter values assumed for each production strategy.

Concept	Unit	Strategy 1	Strategy 2	Strategy 3
Cultured species	name	European seabass	European seabass	European seabass
Unit sales price[a]	€/kg	5.80	8.72	11.46
Fish weight at harvest	grams/unit	450	1000	2000
Fish initial weight	grams/unit	2	2	2
Baseline mortality[b]	%	10	15	20
Absolute growth rate (AGR)	grams/month	18	27	33
Cost of fingerlings	€/unit	0.20	0.20	0.20
Average feed cost	€/kg	1.05	1.05	1.05
Feed conversion ratio (FCR)	ratio	2.4	2.4	2.4

[a] The unit sales price of seabass was calculated by using the Spanish retail prices and discounting the added value over the ex-farm price (EUMOFA, 2019).
[b] Baseline mortality is estimated with losses produced by non-pathogenic reasons (e.g. management stress, environment, non-infectious or parasitic diseases, etc.), assuming that there are no significant escapee events.

supposed that the remaining operating costs are fixed (see Table 1).[2] In this model, however, we have not included the financial costs (cost of capital) and the corporate taxes to the operating costs in order to avoid the problems arising from the use of different financial and taxation policies followed in different geographical areas.

Dividing the annual net operating profit (π) and the total operating cost (TC) between the annual biomass of fish produced in the period (Q), we obtain respectively the average net operating profit ($\overline{\pi}$) as well as the average operating cost (AC) of producing and selling a kilogram of fish.

2.2. Scenarios of production and model parameter values

Once the model had been designed, the next stage to conduct the simulation analysis is to set up the different scenarios of production and the model parameter values that we employed to obtain the baseline values of each scenario. To estimate suitable parameter values, we have selected data of a sample of ten grow-out facilities from a representative group of European firms producing sea bass in the Mediterranean Sea (five from Croatia, three from Spain, one from Italy, and one from Cyprus), that were gathered through an extensive regional survey

[2] According to Janssen (2019), trends in the increase in productivity per person support the assumption that labor should be treated more as a fixed cost than a variable cost. Moreover, energy costs are to a larger extent determined by the farm layout than by the realized production and, even though the costs of medicines may vary, veterinary costs are likely to be fixed per farm whereby they can be also considered as fixed costs in our model. Other operating costs include a set of miscellaneous expenses from different external services (rents, fees, repairs, transports, etc.).

Table 4
Impact of defined disease outbreaks by production strategy.

Disease	Impact on	Strategy 1 (450-g fish)	Strategy 2 (One-kg fish)	Strategy 3 (Two-kg fish)
VER	Mortality rate[a]	+42%	+45%	+50%
	Growth rate[b]	+2 months	+2 months	+2 months
	Feed conversion ratio (FCR)	+0.02	+0.02	+0.02
Chronic disease	Mortality rate[a]	+5%	+10%	+15%
	Growth rate[b]	+2 weeks	+3 weeks	+5 weeks
	Feed conversion ratio (FCR)	+0.20	+0.20	+0.20

[a] Cumulated mortality over the baseline mortality rate.
[b] Time delay in production.

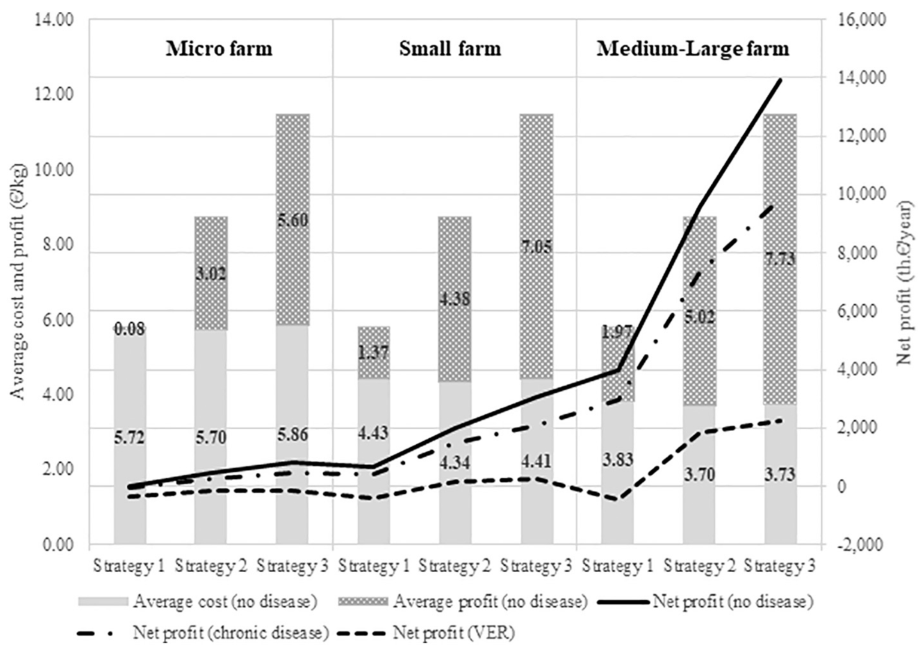

Fig. 2. Economic baseline values (production with no disease) and economic impact of diseases (VER and chronic disease) on the net operating profit under different scenarios of production.

conducted by MedAID H2020 project (Cidad et al., 2018). The data employed to estimate the parameter values were collected between 2015 and 2017.

For our analysis, we have considered three different farm sizes, or typologies, depending on the annual biomass produced (Table 2) and three production strategies depending on the size of the fish produced (Table 3), so that we have contemplated nine different scenarios of production. Looking at Table 2, we have assumed an annual production for a micro-sized farm of around 180 tons obtained with the use of 12 cages of 1000 m^3 (each cage would have approximately 15 m of diameter and 4 m deep) and a biomass density of 15 kg/m^3 in each one. Regarding the small-sized farm, we have assumed an annual production of around 540 tons obtained with the use of 18 cages of 2000 m^3 (each cage being approximately of 22 m diameter and 6 m deep) and a biomass density of 15 kg/m^3. Finally, we have assumed an annual production for a medium-large-sized farm of around 2250 tons obtained with the use of 40 cages of 3750 m^3 (each cage being approximately of 25 m diameter and 8 m deep) and a biomass density of 15 kg/m^3. To facilitate the comparison, we have assumed that all operating costs per cage were the same for all facilities (average values obtained from our sample of farms). Thus, the labor cost per employee would be 16,440 €/year and the number of employees employed in each facility of 0.8 workers per installed cage. We have also assumed that these farms do not expend for disease treatments and prevention, so that the veterinarian and medicine costs per cage were fixed at zero euros. The other operating costs per cage would be around 6411 €/year and the annual depreciation rate would be a 10% with a capital investment of 151,265 €/year per cage.

Table 3 shows the different production strategies that can be employed in the former farms. Thus, each of the former farms can choose to produce and sell different sizes of fish (specifically European sea bass). Strategy 1 is to produce a sea bass of 450 g with a sales price of 5.80 €/kg. The average survival rate during the whole period of production (almost two years) was assumed to reach 90%.[3] On the other hand, strategy 2 is to produce a one-kg sea bass with a sales price of 8.72 €/kg. In this case, the average survival rate during the whole period of production (three years) was assumed to reach 85%. Finally, strategy 3 is to produce a two-kg sea bass with a sales price of 11.46 €/kg. In this case, the average survival rate during the whole period of production (five years) was assumed to reach 80%. In addition, we have assumed in all cases, that the initial weight of fingerlings was 2 g/unit, which were

[3] The baseline survival rates of this research are based on a range of values observed in a sample of farms culturing European sea bass in the Mediterranean (Cidad et al., 2018; Muniesa et al., 2020).

Table 5
Estimation of annual direct costs by diseases in a Mediterranean grow-out farm culturing European sea bass.[a]

Disease	Concept	Micro farm (180 tons/year)			Small farm (540 tons/year)			Medium-Large farm (2250 tons/year)		
		Strategy 1 (450-g fish)	Strategy 2 (One-kg fish)	Strategy 3 (Two-kg fish)	Strategy 1 (450-g fish)	Strategy 2 (One-kg fish)	Strategy 3 (Two-kg fish)	Strategy 1 (450-g fish)	Strategy 2 (One-kg fish)	Strategy 3 (Two-kg fish)
VER	Loss of dead fish	343,647	604,464	918,113	1,030,942	1,813,392	2,754,340	4,295,592	7,555,802	11,476,418
	Loss due to growth retardation	6467	14,114	9794	19,402	42,341	29,383	80,840	176,421	122,429
	Loss due to FCR degradation	2578	2505	2376	7733	7515	7128	32,220	31,314	29,701
	Output losses (foregone revenues)	*352,692*	*621,083*	*930,284*	*1,058,077*	*1,863,249*	*2,790,851*	*4,408,652*	*7,763,537*	*11,628,547*
	Collection of mortalities/ waste	3000	3000	3000	3000	3000	3000	3000	3000	3000
	Disposal of dead fish	1386	996	675	4158	2989	2025	17,325	12,454	8438
	Diagnostics	1700	1700	1700	1700	1700	1700	1700	1700	1700
	Expenditures (foregone incomes)	*6086*	*5696*	*5375*	*8858*	*7689*	*6725*	*22,025*	*17,154*	*13,138*
	Disease direct costs (€/year)	358,778	626,779	935,659	1,066,935	1,870,938	2,797,576	4,430,677	7,780,691	11,641,685
	Increase in the average operating cost (€/kg)	4.40	5.43	8.07	3.04	3.70	5.46	2.41	2.89	4.25
Chronic disease	Loss of dead fish	40,910	134,325	275,434	122,731	402,976	826,302	511,380	1,679,067	3,442,925
	Loss due to growth retardation	7674	13,848	18,443	23,023	41,545	55,329	95,929	173,103	230,537
	Loss due to FCR degradation	34,124	32,395	30,548	102,372	97,186	91,645	426,551	404,942	381,854
	Output losses (foregone revenues)	*82,709*	*180,569*	*324,425*	*248,126*	*541,707*	*973,276*	*1,033,860*	*2,257,112*	*4,055,317*
	Collection of mortalities/ waste	700	700	700	700	700	700	700	700	700
	Disposal of dead fish	165	221	203	495	664	608	2063	2768	2531
	Diagnostics	1700	1700	1700	1700	1700	1700	1700	1700	1700
	Expenditures (foregone incomes)	*2565*	*2621*	*2603*	*2895*	*3064*	*3008*	*4463*	*5168*	*4931*
	Disease direct costs (€/year)	85,274	183,190	327,028	251,021	544,771	976,284	1,038,322	2,262,279	4,060,248
	Increase in the average operating cost (€/kg)	0.56	0.92	1.42	0.45	0.69	1.04	0.40	0.59	0.86

[a] Disease outbreak without any vaccination and/or treatment.

bought from an external facility, at the unit price of 0.20 €/unit.[4] The average feed cost was fixed at 1.05 €/kg, whereas the feed conversion ratio (FCR) was 2.4.

To validate our model, parameters and results were revised by some experts in sea bass production, who verified that these values were mostly realistic. In addition, we have also compared the relative values of the different operating costs obtained from our model with those from other previous studies. In this work, the relative values obtained with our model were very similar to the values found by other researchers (Bozoglu and Ceyhan, 2009; Hadelan et al., 2012; Di Trapani et al., 2014; Arru et al., 2019), so that our typical farm presented a variable operating cost between the 50% and 70% of the farm's total operating costs and the feed cost was the most important operating cost.

In addition, we have also set up the parameter values to evaluate the economic cost of different disease outbreaks. To facilitate this analysis, two disease categories were selected as outbreak actors. VER was selected as a first outbreak actor for being considered a major constraint to the Mediterranean and worldwide aquaculture, which is associated with high mortalities in juvenile fish (Bandín and Souto, 2020). As a second outbreak actor, we have estimated the impact of pathogens with a chronic course and different mortality cumulative rates, which we have named as 'chronic disease.' This category can encompass the impact of many bacteria (e.g., *vibriosis*, *photobacteriosis*, *tenicibaculosis*, etc.) or parasites (e.g., *amyloodimium*, *dactylogyrus*, *sparicotyle*, etc.).

According to McInerney et al. (1992), the total economic cost of a disease can be explained in terms of the 'output losses following disease occurrence' (foregone revenues) as well as the 'expenditures made to treat disease or prevent its occurrence' (foregone incomes). To estimate the economic losses caused by disease outbreaks, we have hypothesized their impact on the production process, specifically in the mortality rate, growth rate, and feed conversion ratio (FCR).[5] These assumptions are presented in Table 4 while the mathematical formulas employed to calculate these economic losses are presented in an appendix at the end of this paper. These values were defined by the authors, contrasted with fish health experts, and supported by other studies as well (e.g., Azeredo et al., 2015; Fioravanti et al., 2020; Muniesa et al., 2020). In the case of a VER outbreak, we have assumed that most of the mortality occurs during the first six months of production and can reach 42% for production strategy 1, with recurrent smaller mortality events in the following years, so that the cumulative mortality can reach up to 45% and 50% for strategy 2 and 3 respectively. We have also assumed some impact, due to diseases, on the growth performance with an average delay of 2 months in the production period, and an increase in the FCR of 0.02 points for all production strategies. In the case of a chronic disease outbreak, we have

[4] Intensively reared sea bass may be transferred from the hatchery to open sea cages at different sizes. For example, the transfer of 2-g fingerlings is the common practice in Eastern Mediterranean farms, whereas the fingerling transfer, of 15 g (following land based pre-growing) is a common practice in the Western Mediterranean production systems.

[5] The mortality caused by the different disease outbreaks is added to the baseline mortality values previously described that are attributed to other causes (e.g. management stress, environment, unknown diseases, etc.).

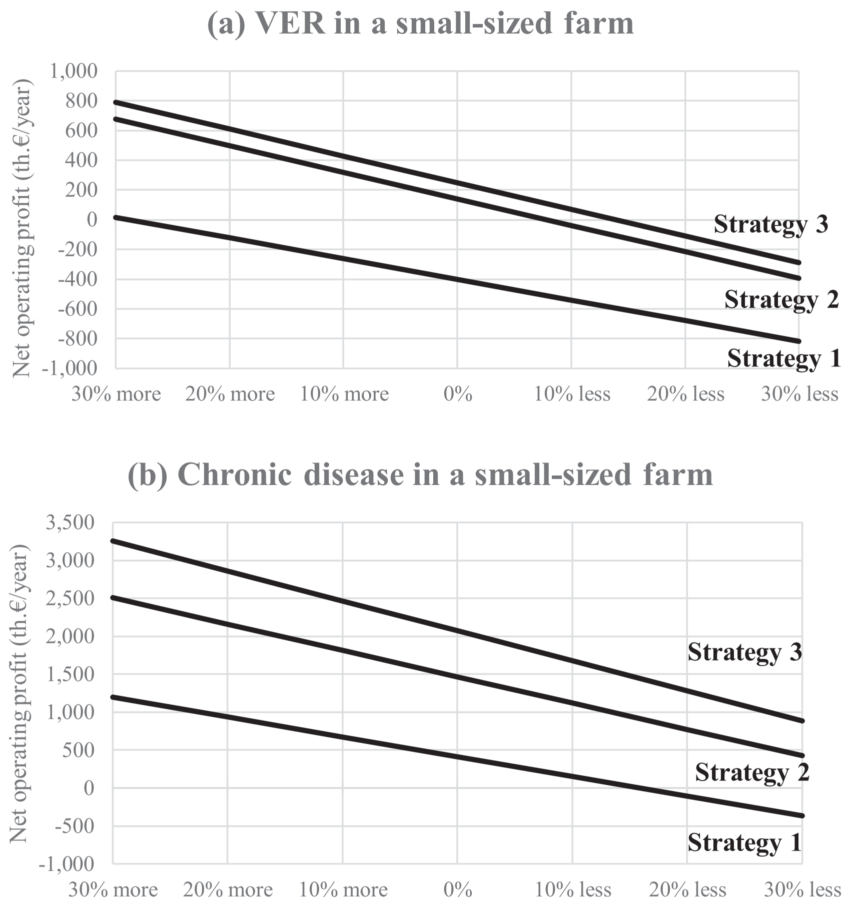

Fig. 3. Sensitivity of the net operating profit of a small-sized farm to variations in the baseline values of the unit sales price of sea bass according to different disease outbreaks: (a) VER and (b) Chronic disease.

assumed 5% of cumulated mortality for production strategy 1, with recurrent mortality events in following years leading to a cumulative mortality of 10% and 15% for strategy 2 and 3 respectively. The impact on the growth performance is higher depending on the production strategy (two weeks for strategy 1, three weeks for strategy 2, and five weeks for strategy 3), with an FCR increase of 0.20 points for all production strategies. Moreover, we have also carried out a sensitivity analysis to estimate the economic impact of higher or lower mortality rates, allowing in this way that fish health managers can estimate the extent of the impact of the different disease outbreaks in each of the nine scenarios of production defined in this work.

To estimate the expenditures of these diseases, we have considered that the cost of collecting mortalities and waste during the outbreak periods (30 days for a VER outbreak and 7 days for a chronic disease outbreak) would be around 100 €/person per day and this work could be done by one person during the whole outbreak period. Besides, we have estimated that the disposal cost would be 75 € per ton of dead fish, whereas the diagnostic work would be approximately 850 €/day to be realized in two days by an external veterinarian service.

3. Results

3.1. Estimation of direct costs and economic impact of disease outbreaks

Fig. 2 presents the baseline values of the variables employed to measure the economic performance (net operating profit, average operating cost, and average net operating profit) of the nine production scenarios proposed for this work according to the assumptions presented in Tables 3 and 4. Looking at Fig. 2, we observe that in all scenarios producers obtain positive net operating profits, although these are decreasing as smaller is the biomass produced (farm size) and the size of the fish produced (production strategy). This result can be explained because we observe economies of scale when the farm increases its size. Thus, a 450-g fish (strategy 1) may be produced in a micro-sized farm with an average operating cost of 5.72 €/kg, whereas this cost would be 4.43 €/kg in a small-sized farm and 3.83 €/kg in a medium-large-sized farm. The same effect was also obtained with the other production strategies (i.e., farms producing one-kg and two-kg fish). Moreover, we also observe that the average net operating profit is larger as the bigger is the fish produced regardless of the farm size. Thus, in a small-sized farm the average net operating profit is 1.37 €/kg for strategy 1 (450-g fish), 4.48 €/kg for strategy 2 (one-kg fish) and 7.05 €/kg for strategy 3 (two-kg fish).

Fig. 2 also presents the economic impact of diseases (VER and chronic disease) on the baseline net operating profit (production with no disease) according to the different production scenarios proposed in our work. Previously, we estimated the direct costs (output losses and expenditures) of each disease and carried out a partial budget analysis to evaluate their economic impact on the farm's net operating profit. These estimations (Table 5) show that the direct costs of both types of diseases are very significant, mostly in the case of a VER. Thus, the increase of the average operating costs ranges from 2.41 €/kg in the best scenario (medium-large farm with production strategy 1) to 8.07 €/kg in the worst scenario (micro farm with production strategy 3) in the case of VER, whereas in the case of a chronic disease, it ranges from 0.40 €/kg in the best scenario to 1.42 €/kg in the worst scenario. As in other former studies (Peterman and Posadas, 2019), our results show that the foregone revenues (output losses) significantly exceed the foregone incomes (expenditures) caused by diseases. Moreover, the largest direct cost in all scenarios is the dead fish loss (i.e., the economic value of the dead fish),

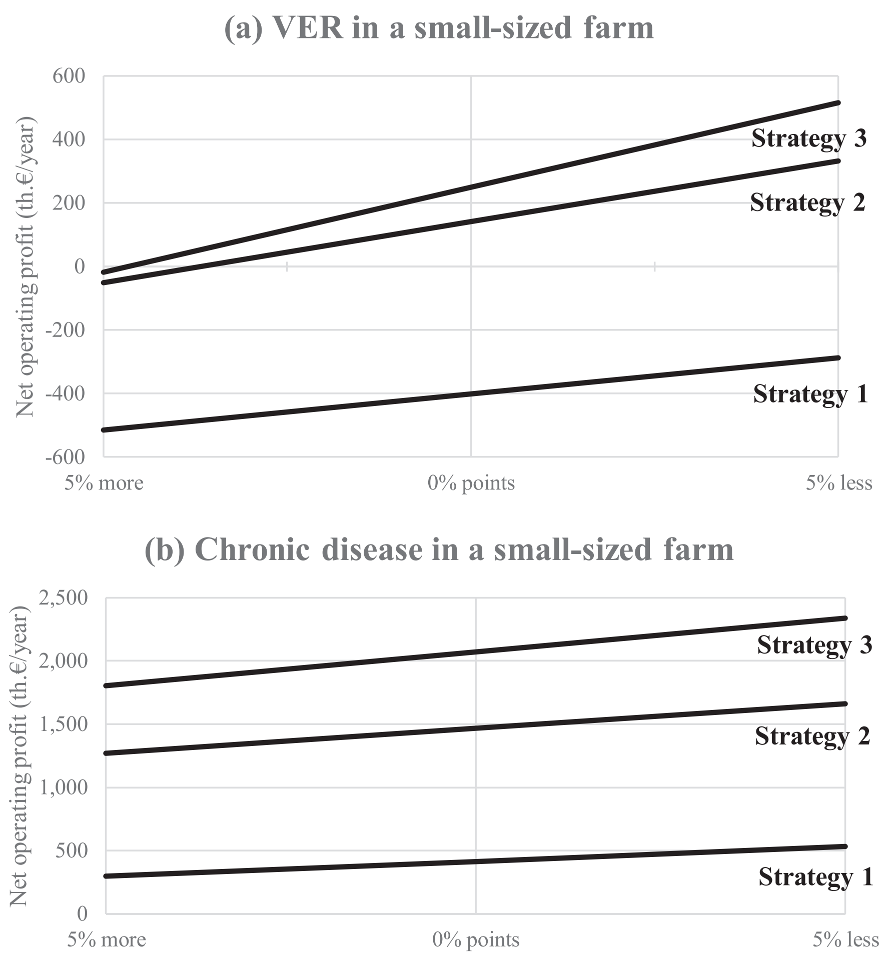

Fig. 4. Sensitivity of the net operating profit of a small-sized farm to variations in the baseline values of the disease mortality rates according to different disease outbreaks: (a) VER and (b) Chronic disease.

being very important in VER as the mortality rate is higher than in a chronic disease.

The negative impact on the annual net operating profit caused by a disease outbreak (Fig. 2) is directly proportional to the biomass produced (farm size) and the size of the fish produced (production strategy), so that this impact becomes more important as larger is the farm and bigger the fish cultured since the disease direct costs increase in that way. Nevertheless, larger farms producing bigger fish maintain positive profits despite of their larger disease direct costs because these farms can obtain higher net operating profits than smaller farms producing smaller fish. In a VER outbreak the farm operates with negative net operating profits in many of the scenarios (specifically, in five out of nine). Only in the case of small and medium-large-sized farms producing one-kg fish (strategy 2) or two-kg fish (strategy 3) that situation is not seen. On the other hand, in a chronic disease outbreak we have observed a significantly smaller negative effect since there is only one scenario with negative net operating profits, when a micro-sized farm produces 450-g fish.

3.2. Economic impact of variations in some model parameters

In this section we have performed a sensitivity analysis to evaluate the effects of variations in some model parameters such as the unit sales price of sea bass (Fig. 3) and the mortality rates for each type of disease (Fig. 4). For this analysis, we have focused on a small-sized farm for being one of the most common farm size in the Mediterranean aquaculture and has the most significant variations, whereas the economic situation of micro and medium-large-sized farms does not change significantly.[6]

Regarding the sensitivity of the net operating profit of small-sized farms to variations in the unit sales price of sea bass, we observe that the economic results obtained with production strategies 2 (one-kg fish) and 3 (two-kg fish) are sensible to reductions in the unit sales price of sea bass under a VER outbreak (Fig. 3a). Thus, strategy 2 would not be profitable with a reduction in the price of 10% and strategy 3 with a reduction of 20%. On the other hand, strategy 1 (450-g fish) would be profitable, increasing the price at 30%. In the case of a chronic disease (Fig. 3b), we observe that the economic sustainability of small-sized farms employing the production strategies 2 (one-kg fish) and 3 (two-kg fish) is not affected significantly by price variations, maintaining positive profits even with a reduction of 30% in the sales price of sea bass. However, strategy 1 (450-g fish) could be profitable with an increase in the sales price of 10%.

The sensitivity analysis also shows that, in the case of a VER outbreak (Fig. 4a), small-sized farms following the production strategies 2 (one-kg fish) and 3 (two-kg fish) are affected significantly by an increase of 5% points in the disease mortality rate assumed initially, changing the farm's net operating profit from positive to negative. On the other hand,

[6] Economic results for these farm sizes can be obtained from authors under request.

the bad economic situation of a small-sized farm producing 450-g fish (strategy 1) and suffering a VER outbreak did not change significantly despite the variation in the disease mortality rate. In the case of chronic disease (Fig. 4b), the economic situation of a small-sized farm does not change significantly in any of the production strategies analyzed in this work by an increase of 5% in the baseline disease mortality rate, maintaining positive net operating profits in all cases.

Therefore, we can conclude that, in the case of small-sized farms suffering a VER outbreak, some of our results related to strategies 2 and 3 are more sensitive to variations in the baseline values chosen for the unit sales price and the disease mortality rate. By contrast, in the case of small-sized farms suffering a chronic disease their economic sustainability is not significantly sensitive to variations of the former model parameters.

4. Conclusions

The aim of this work has been to propose a novel and formal approach to evaluate the direct costs of diseases caused by different pathogens as well as their economic impact on a typical grow-out farm with a continuous production process producing European sea bass in the Mediterranean under different scenarios of production related to the biomass produced (farm size) and the size of the fish produced (production strategy). To carry out this work, we have employed a deterministic static model to simulate the annual income statement of that facility. This model has allowed us to evaluate the direct costs caused by two types of diseases (VER and chronic disease) as well as, through a partial budget and sensitivity analyses, the economic impact of recurrent outbreaks of these diseases.

Our estimations have shown that the direct costs caused by VER and chronic diseases are very important for sea bass producers (specially the output losses), being more significant in the case of a VER outbreak. These estimations show that as the larger is the farm and the size of the fish produced, the larger are the direct cost of a disease outbreak. However, our research shows that sea bass production in smaller farms is more vulnerable economically to the negative impact caused by diseases because their operating revenues are not sufficient to absorb the disease direct costs compared to larger farms, which may critically affect their viability. Moreover, the comparison of different production strategies shows that the production of bigger fish allows to obtain better economic results with disease outbreaks due to the larger average net operating profits of this production strategy. Therefore, the profitability and economic viability of a sea bass grow-out farm suffering recurrent outbreaks of diseases caused by different pathogens depend on the farm typology (farm size) as well as the decisions taken by owners/investors about the size of the fish produced and sold in the market. According to our findings, the economic impact on the net operating profit caused by a disease outbreak is worse as smaller is the farm and smaller the fish produced.

We must point out that the strategy of producing two-kg fish is oriented mainly to sell the product in restaurants or restauration businesses instead to the consumption market (fish mongers, supermarkets and so on). Because of it, it would be very difficult to implement and generalize this strategy in the sector to avoid the negative impact of diseases. Nevertheless, farms producing one-kg fish obtain good economic results despite a disease outbreak and the product can be sold in the consumer market.

Due to their size, small farms do not normally employ fish health managers and tend to externalize that service to respond to disease outbreaks. However, we can infer that the investment in disease control and prevention would be pivotal for the economic viability of small farms. This decision would represent a good policy for larger farms as well because they could avoid the loss of important operating revenues and maintain important net operating profits for the owners/investors. Even though this work does not make a cost-benefit analysis of vaccination, treatments, biosecurity, or other measures, it seems that there is a clear room for improvement on health management and investment, since the information we have from the field (Muniesa et al., 2020) is that current mortality rates of sea bass are significantly higher than the baseline mortality rates assumed in this work.

A comparison of our results with those from other former studies is very difficult due to significant differences among all studies, although some of our conclusions (e.g., the relative importance of output losses or the need for producers to pay attention and devote resources to prevent and treat disease outbreaks) are also pointed out in some of them (Nor et al., 2019; Peterman and Posadas, 2019). Finally, we can conclude that this work has managed to quantify the direct cost of recurrent outbreaks of diseases caused by different pathogens for sea bass farmers and has also confirmed the negative economic impact of those diseases in the Mediterranean aquaculture industry.

Declaration of Competing Interest

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

Acknowledgments

This study has been carried out with the financial support of the European Commission's Horizon 2020 research program, Grant Agreement 727315, MedAID (Mediterranean Aquaculture Integrated Development).

Appendix A

The mathematical formulas employed to calculate the different categories of losses caused by a disease (i.e., loss of dead fish, loss due to growth retardation, and loss due to FCR degradation) are presented in this appendix. The variation in the net operating profit caused by a disease outbreak ($\Delta\pi$) can be calculated as follows:

$$\Delta\pi = \Delta TR - \Delta TC = (TR - TR^{*}) - (TC - TC^{*}) \tag{A.1}$$

where TR = the baseline total operating revenues; TR^{*} = the new total operating revenues with a disease outbreak; TC = the baseline total operating costs; and TC^{*} = the new total operating costs with a disease outbreak. Next, we can substitute the former expression with the symbols used to calculate each of those variables (see Table 1) and reorder those terms according to the three categories of losses.

Loss of dead fish: this value is obtained by calculating the reduction in the annual operating revenues caused by an increase in the mortality rate of fish, which has been adjusted with the variation in the revenues caused by a change in the unit sales price of sea bass. This loss must be also adjusted with the reduction in the farm's feed cost since the average biomass is reduced by the higher mortality. Thus, the calculation of it is as follows:

$$p \times \left(\frac{w_1}{1000}\right) \times N \times \left[\frac{s}{100} - \frac{s^{*}}{100}\right] + (p - p^{*}) \times \left(\frac{w_1}{1000}\right) \times \left(\frac{N \times T}{T^{*}}\right) \times \left(\frac{s^{*}}{100}\right) - p_f \times r \times \left(\frac{w_1 - w_0}{1000}\right) \times N \times \left[\frac{\left(\frac{s}{100} - \frac{s^{*}}{100}\right)}{2}\right] \tag{A.2}$$

where s^* is equal to the survival rate of a farm suffering a disease outbreak, so that $\frac{s}{100}-\frac{s^*}{100}$ is the mortality rate of the farm caused by that disease; p^* is equal to a new unit market price of sea bass (used in the sensitivity analysis with the variations in the unit sales price of sea bass); and T^* is equal to the farms' new production period increased by the impact of a disease outbreak on the fish growth rate.

Loss due to growth retardation: this value is obtained by calculating the reduction in the annual operating revenues caused by the reduction in the fish growth rate, which increases the production period, as well as the reduction in the annual fingerling and feed costs. Consequently, we get the following formula:

$$p \times \left(\frac{w_1}{1000}\right) \times \left(\frac{N \times T}{w_1 - w_0}\right) \times \left(\frac{s^*}{100}\right) \times (g - g^*) - p_j \times \left(\frac{N \times T}{w_1 - w_0}\right) \times (g - g^*) - p_f \times r \times \left(\frac{w_1 - w_0}{1000}\right) \times \left(\frac{N \times T}{w_1 - w_0}\right) \times \left(\frac{1 + \frac{s^*}{100}}{2}\right) \times (g - g^*) \tag{A.3}$$

where g^* is equal to the new fish growth rate reduced by the fish disease.

Loss due to FCR degradation: this value is obtained by calculating the increase in the farm's annual feed cost due to the increase in the feed conversion ratio (FCR), so that we have the following expression:

$$p_f \times \left(\frac{w_1 - w_0}{1000}\right) \times \left(\frac{N \times T}{T^*}\right) \times \left(\frac{1 + \frac{s^*}{100}}{2}\right) \times (r^* - r) \tag{A.4}$$

where r^* is equal to the new FCR increased by the fish disease.

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