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ORIGINAL RESEARCH

Assessing the economic impacts of severe skeletal anomalies in Mediterranean hatcheries culturing seabream and seabass

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Abstract

The economic impact of skeletal anomalies in aquaculture farming is a significant issue for the industry, as deformed fish are frequently discarded because of their low survival rate and a variety of other disadvantages, including increased costs, consumer distrust of aquaculture products, and ethical concerns. The goal of this article is to propose a method for calculating the direct costs of severe skeletal anomalies in typical Mediterranean seabream and seabass aquaculture hatcheries using a deterministic static model programmed in MATLAB that simulates their annual operation. Our findings suggest that larger hatcheries experience higher direct costs associated with severe skeletal anomalies but have better financial stability and significantly higher expected profits. Mean results indicate that the annual economic losses of severe skeletal anomalies for seabream and seabass Mediterranean aquaculture are 22.88 million euros per year for a scenario of low severe skeletal anomalies, 65.34 million euros per year for a scenario of medium severe skeletal anomalies, and 115.98 million euros per year for a scenario of high severe skeletal anomalies. Furthermore, some options for increasing the financial stability of the hatcheries are to increase the sale price of fingerlings, reduce the feed conversion ratio, and reduce the feed unit cost.

KEYWORDS
aquaculture farming, economic impact, European sea bass, gilthead sea bream, Mediterranean hatcheries, severe skeletal anomalies

1 | INTRODUCTION

Over the last 60 years, global fish consumption has risen dramatically, from 9 kg/capita in 1961 to 20 kg/capita in 2016, more than doubling the population's average annual growth rate in the same period (FAO, 2018). Similarly, aquaculture farming has grown from around 10 million tons per year in the late 1980s to 80 million tons in 2016, making it the fastest growing food production sector; meanwhile, capture fishery production has remained relatively stable at around 90 million tons since the late 1980s (FAO, 2018).

Despite the significant expansion of aquaculture farming, there are still some issues that need to be addressed. One of these is the problem of skeletal anomalies in fish, which lowers their physiological ability to develop normally, as they grow slower, die more easily, and have a lower level of animal welfare (Berillis, 2017). Furthermore, deformed fish necessitate manual classification, increasing the costs of human labor, while also lowering the performance of the fish in areas such as swimming ability, conversion rate, growth rate, survival, stress susceptibility, pathogens, and bacteria (Boglione et al., 2001). Prestinicola et al. (2013) also suggested that the presence of anomalies in fish could cause consumers to lose faith in aquaculture products, lowering their commercial value.

Berillis (2017) categorized skeletal anomalies into three different types: (1) Vertebral and spinal malformations such as kyphosis, lordosis, scoliosis, platyspondyly, and vertebrae fusion; (2) neck bend, compressed snout, bent jaw, harelip, or front and downwards protuberance of the jaw; and (3) reduction of the lower jaw, short operculum, and reduced or asymmetric fins.

Skeletal anomalies have a significant economic impact on the aquaculture industry, as deformed fish are typically discarded because of their low survival rate and a variety of other drawbacks (Boglione et al., 2001). Boglione et al. (2001) reported that academic researcher P. Divanach found evidence that the rate of seabream fish discarded for being deformed ranged from 15% to 50% depending on the farm and country. In addition, Georgakopoulou et al. (2010) reported that results from case studies of quality control in marine hatcheries over the last 15 years show that skeletal deformities affect 7%–20% of produced juveniles on average, with occasional incidences as high as 45%–100%. Moreover, Theodorou et al. (2016) determined that in an average hatchery producing around 22,000,000 seabream fry, the average cost per fry nearly doubles when 60% of the total production is lost because of mortalities or skeletal deformities.

Furthermore, the presence of malformed fish raises ethical concerns and impacts firms' profits, as fish with a deformed mouth, fins, or vertebral axis have poorer feeding and swimming abilities compared with healthy non-deformed individuals, resulting in higher feed conversion ratios (FCRs), slower growth rates, and a higher vulnerability to stress and pathogens, putting them in an unsuitable welfare condition (Boglione, Gavaia, et al., 2013, p. 1). It is evident that the lower feeding and growth rates implicate higher feed costs for firms. Similarly, higher vulnerability to stress and pathogens increases the probability of higher death rates for fish, affecting the revenue function. Thus, fish malformations are either translated into higher costs, lower revenues, or both, which imply fewer profits for the firms.

Boglione et al. (2001) reported that there is a substantial amount of literature related to anomalies in farmed fish, which suggests that temperature, light, salinity, pH, low oxygen concentrations, inadequate hydrodynamic conditions, feed quality, and parasites are the main sources of malformations. Moreover, excluding pollutants and pathogens, which are well controlled under rearing conditions, the literature indicates that unfavorable abiotic conditions, improper nutrition, and genetic factors are the most likely causes of skeletal anomalies in reared fish (Boglione, Gisbert, et al., 2013, p. 2).

Accordingly, some measures could be considered to reduce the incidence of skeletal anomalies. For example, Prestinicola et al. (2013) discovered that the semi-intensive breeding techniques they used (large volumes and mesocosm) could improve the morphological quality of juvenile seabream fish when compared with other intensively reared techniques. The higher quality juveniles have a higher commercial value if properly raised. As a result, it is not surprising to find extensive literature analyzing proper diets to reduce the incidence of skeletal anomalies as many studies suggest that certain nutrients (such as lipids, amino acids, vitamins, and minerals) are responsible for the appearance of skeletal anomalies when their level and form of supply in the diet are insufficient or unbalanced (Boglione, Gisbert, et al., 2013, p. 2).

Until now, no studies have examined the economic impact of severe skeletal anomalies in any fish species. However, a number of recent studies have examined the economic impact of fish diseases (Abolofia et al., 2017; Fernández Sánchez et al., 2021, 2022; Lafferty et al., 2015; Nor et al., 2019; Peterman & Posadas, 2019). Furthermore, only the investigations of Fernández Sánchez et al. (2021, 2022) focused on Mediterranean aquaculture, taking into account European seabass, *Dicentrarchus labrax*, and gilthead seabream, *Sparus aurata*. Seabream and seabass are the second and third most important species in Mediterranean aquaculture (Spain, France, Italy, Croatia, Cyprus, Greece, and Turkey), accounting for 30.3% and 28.2% of total farmed fish production in these countries, respectively, while trout is first with 36.6% (FEAP, 2020). Given their importance, this is the first attempt to quantify the impact of severe skeletal anomalies in Mediterranean aquaculture hatcheries that raise gilthead seabream and European seabass.

The article aims to propose a method for calculating the direct costs of severe skeletal anomalies in typical Mediterranean aquaculture hatcheries of seabream and seabass. In Costello's (2009) words, “the economic cost of a problem may be the best metric for prioritizing research and management resources (p. 115).” Thus, separate evaluations for different types of aquaculture hatcheries based on their size (micro, small, and medium) and different incidence rates of severe skeletal anomalies are presented in the study. The study ends by providing the overall impact of severe skeletal anomalies for different Mediterranean countries based on their production volume.

The remainder of the article presents a description of the methodology and the model used for the analysis; general results, the impacts of skeletal anomalies and a sensitivity analysis taking into account variations in some model parameters; a discussion of the main implications of the findings; and finally, some conclusions.

2 | METHODOLOGY

We used a deterministic static model programmed in MATLAB using as a basis the models of Fernández Sánchez et al. (2021, 2022). At the same time, the previous authors claim that their models are based on the work of Arru et al. (2019), Cacho (1997), Di Trapani et al. (2014), Gasca-Leyva et al. (2002), Janssen et al. (2017), Pomeroy et al. (2008), and Rizzo and Spagnolo (1996). Similarly to Fernández Sánchez et al. (2021, 2022), our model consists of two sub-models: production and economic (see Figure 1). The production sub-model includes variables associated with the production process, such as stocking density, feeding, fish growth, fish with severe skeletal anomalies, fish without swim bladder, fish mortality because of other reasons, and the number of fish. Meanwhile, the economic sub-model consists of the variables that affect the economics of an aquaculture hatchery, such as revenues, input costs, labor, capital requirements, and losses/benefits.

2.1 | Model description

The model attempts to replicate the annual routine of a Mediterranean hatchery of seabream/seabass using Recirculating Aquaculture System RAS. It is assumed that the fish are raised in tanks indoors in a continuous production system with multiple batches, in which stocking and harvesting occur at a consistent rate. The model also

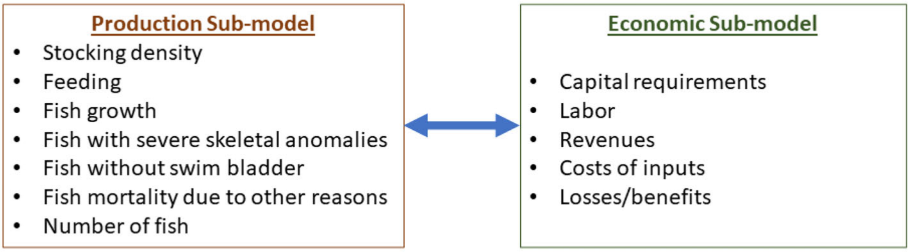


FIGURE 1 Model framework.

assumes that the economic variables related to prices and costs, and production variables, are constant during repeated production cycles. In addition, we do not include the costs of operations during larval development in the rearing unit in the model. For this reason, we do only consider the costs of operations of the larvae in the weaning unit when the diet is entirely artificial feed. As a result, we contemplate the survival rate in relation to the proportion of fish ready for sale versus those who survive after weaning in our model.

The annual operating profit *OP* (€/year) is calculated by subtracting the hatchery's annual operating costs *OC* (€/year) from the annual operating revenues *OR* (€/year) generated by juvenile sales, as indicated in Equation (1). The *OR* can be calculated by multiplying the fingerlings' unit sales price *fiusp* (€/fingerling) by the annual fingerling harvested production *N* (fingerlings/year) (see Equation (2)). The annual supply of fingerlings *B* indicates the number of fingerlings per year that must be stocked at the beginning of weaning in the farms to reach the expected production *N* given the expected survival rate *s*. Equation (3) shows how to calculate the annual supply of fingerlings *B* (fingerlings/year) by multiplying the annual harvested production of fingerlings *N* (fingerlings/year) by 100 and dividing by the survival fish rate *s* (%).

$$OP = OR - OC \tag{1}$$

$$OR = N \times fiusp \tag{2}$$

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

The survival rate *s* is calculated by subtracting the rate of total dead fish *Mo* (%) (see Equation (4)). The rate of total dead fish *Mo* is a sum of the rate of dead fish because of severe skeletal anomalies *MoSA* (%), the rate of fish without swim bladder *MoSB* (%), and the rate of fish dead because of other reasons *MoOR* (%) (see Equation (5)). However, it is important to note that the model assumes no significant escapee events or disease outbreaks.

$$s = 100 - Mo \tag{4}$$

$$Mo = MoSA + MoSB + MoOR \tag{5}$$

Furthermore, the density of fingerlings per tank *d* (fingerlings/tank) is calculated as a function of the annual supply of fingerlings *B*, the number of tanks used in the production *t* (tanks), and the culturing period *T* (months), as shown in Equation (6). The culturing period *T* is calculated using the fingerlings' initial and final weights (*w*0 and *w*1, respectively) in grams per fingerling, as well as their absolute growth rate *g* (g/month) (see Equation (7)).

$$d=\frac{B}{t}\times\frac{T}{12} \tag{6}$$

$$T=\frac{w1-w0}{g} \tag{7}$$

The annual operating costs *OC* are calculated by adding the year's variable and fixed costs. The costs associated with feed *FEC*, energy *EC*, veterinary and medicine *VEC*, oxygen *OXC*, and water *WC* are included in the variable costs *VC* (€/year). Meanwhile, the fixed costs *FC* (€/year) include labor costs *LC*, other operating costs *OPC*, and depreciation costs *DC*. As a result, the *OC* is calculated using Equation (8). It is important to clarify that labor costs were considered fixed for modeling purposes because it is assumed that a fixed annual production for each type of hatchery exists. As a result, these costs only vary between the different types of hatcheries according to the number of employees considered for each of them.

$$OC=FEC+EC+VEC+OXC+WC+LC+OPC+DC \tag{8}$$

Table 1 shows how to calculate each of the previous operating costs. In this table, we hypothesized that there is a one-third reduction in the feed unit cost *f* per fish removed because of severe skeletal anomalies, lack of swim bladder, or mortality, based on the fact that these fish are usually not removed from the process until a certain point, which implies that they still consume some feed resources, but not as much as harvested fish. It is also worth noting that, like Fernández Sánchez et al. (2021, 2022), we do not include financial costs and corporate taxes in the operating costs because they are dependent on policies specific to the geographic area where the hatchery is located.

2.2 | Model parameter values

Most of the parameters are based on those employed by Fernández Sánchez et al. (2021). Fernández Sánchez et al. (2021) obtained their data from the MedAID (Mediterranean Aquaculture Integrated Development) project survey (Deliverable 1.2) (Cidad et al., 2018) and partners. Although the MedAID project survey obtained responses from around 27 farms, not all of these were hatcheries and not all provided economic data. There were 11 observations from hatcheries, 5 related to seabass, 2 for seabream, and 4 for both. From the previous information, Fernández Sánchez et al. (2021) just used 10 observations: 5 of them corresponded to micro hatcheries (production of fewer than 5 million fingerlings), 3 to small hatcheries (production between 5 and 25 million fingerlings), and 2 to medium hatcheries (production between 25 and 100 million fingerlings). These observations were also the final data used for our models (see Table 2). It is important to clarify that the data from Fernández Sánchez et al. (2021) do not include observations from big hatcheries, categorized by the same authors as those hatcheries that exceed the production of 100 million fingerlings. As a result, the present research would just also account for the impacts on micro, small, and medium hatcheries. Moreover, the findings of Theodorou et al. (2016) were used to parametrize the mortality rates because of other reasons and the rate of fish without swim bladders; while the findings of Cidad et al. (2018) (MedAID project), Theodorou et al. (2016) and Georgakopoulou et al. (2010) were considered to build the scenarios of severe skeletal anomalies.

We considered triangular distributions for most of the parameters (see Table 2). As a result, each parameter distributes triangularly according to *a*, *b*, and *c*, with *b* representing the average value and *a* and *c* indicating the smallest and largest possible values, respectively. In the majority of the cases, the value of *a* is calculated as a 10% reduction in the average value and the value of *c* is calculated as a 10% increase in the average value, except for the variables related to fish dead because of other reasons, fish without swim bladder, and fish with severe skeletal anomalies, whose values *a* and *c* were considered based on the findings of the source of the information. Thus, triangular random numbers were generated according to *a*, *b*, and *c* for each parameter, to account for possible variations in the

TABLE 1 Operating costs.

Operating costs		Formula	Definitions
Variable costs	Feed costs	$f \times \left(\frac{w1-w0}{1000}\right) \times r \times \left[N+(B-N)\times\left(\frac{2}{3}\right)\right]$	$f=$ Feed unit price $\left(\frac{€}{\text{kg}}\right)$ $w1=$ Fingerling final weight $\left(\frac{\text{g}}{\text{fingerling}}\right)$ $w0=$ Fingerling initial weight $\left(\frac{\text{g}}{\text{fingerling}}\right)$ $N=$ Annual harvested production $\left(\frac{\text{Fingerlings}}{\text{year}}\right)$ $B=$ Annual supply of fingerlings $\left(\frac{\text{Fingerlings}}{\text{year}}\right)$ $r=$ Feed conversion ratio (FCR)
	Energy costs	$n \times N$	$n=$ energy unit cost $\left(\frac{\text{Euro}}{\text{fingerling}}\right)$
	Veterinary and medicine costs	$v \times N$	$v=$ veterinarian unit cost $\left(\frac{\text{Euro}}{\text{fingerling}}\right)$
	Oxygen costs	$o \times N$	$o=$ oxygen unit cost $\left(\frac{\text{Euro}}{\text{fingerling}}\right)$
	Water costs	$u \times N$	$u=$ water unit cost $\left(\frac{\text{Euro}}{\text{fingerling}}\right)$
Fixed costs	Labor costs	$l \times e$	$l=$ Annual labor cost per employee (€) $e=$ Employees of the company
	Operating costs	$m \times t$	$m=$ annual operating cost per tank $t=$ Number of tanks
	Depreciation costs	$a \times i \times t$	$a=$ annual depreciation rate (%) $i=$ annual capital investment per tank $\left(\frac{€}{\text{tank}}\right)$

values for each simulation run through the algorithm. In total, 10,000 simulations were considered for the analysis of each type of hatchery. Moreover, the description of the results of the simulations is shown using as reference values the minimum (min), mean, and maximum (max), as well as the percentiles 5 (perc5), 25 (perc25), 50 (perc50), 75 (perc75), and 95 (perc95).

2.3 | The economic impact of severe skeletal anomalies

According to McInerney et al. (1992), the total economic cost of a disease is explained by "output losses following disease occurrence" (foregone revenues) and "expenditures made to treat disease or prevent its occurrence" (foregone incomes). As a result, we hypothesized the impact of severe skeletal anomalies on the production process, taking into account the mortality rate associated with severe skeletal anomalies and the associated economic losses.

Accordingly, the economic impact of severe skeletal anomalies is determined by calculating the loss of dead fish because of skeletal anomalies (*LDFSA*), which is determined by estimating the decrease in annual operating revenues caused by an increase in fish mortality rate because of severe skeletal anomalies. However, because increased mortality lowers the average number of harvested fish, this loss must be adjusted by lowering their respective variable costs. The reduction in variable costs is more noticeable in the feeding cost for a hatchery unit. To be more conservative with the results, we hypothesized that each removed fish because of severe skeletal anomalies saves around one third of the feed unit cost *f*, given that these fish are usually not removed from the process until a certain point. The number of fish lost because of severe skeletal anomalies *BSA* is calculated in Equation (9), while Equation (10) contains the formula for calculating the *LDFSA*.

$$BSA = B \times MoSA \tag{9}$$

TABLE 2 Model parameters for a hatchery facility in Europe—Average values.

Parameter	Symbol	Unit	Source	Values	Triangular parameter
Production inputs					
Annual harvested production	*N*	Fingerlings/year	MedAID	Micro: 2,500,000 Small: 8,000,000 Medium: 32,000,000	Yes
Number of employees of the company	*e*	Number of employees	MedAID	Micro: 15 Small: 18 Medium: 54	Yes
Number of tanks	*t*	Number of tanks	MedAID	Micro: 16 Small: 43 Medium: 21	Yes
Average tank size	*ats*	m^3/tank	MedAID	Micro: 57 Small: 42 Medium: 213	No
Mortality rate because of other reasons	*MoOR*	%	Theodorou et al. (2016)	Parameter (*a*, *b*, *c*): (4, 7.1, 15)	Yes
Percentage of fish without a swim bladder	*MoSB*	%	Theodorou et al. (2016)	Parameter (*a*, *b*, *c*): (2, 7.7, 12)	Yes
Percentage of fish with severe skeletal anomalies	*MoSA*	%	MedAID, Theodorou et al. (2016) and Georgakopoulou et al. (2010)	See Table 3	Yes
Fingerling final weight	*w1*	g/fingerling	MedAID	5	No
Fingerling initial weight	*w0*	g/fingerling	MedAID	0	No
Absolute growth rate	*g*	g/month	MedAID	0.85	Yes
Feed conversion ratio	*r*	Ratio	MedAID	1.3	Yes
Economic inputs					
Fingerlings' unit sales price	*fiusp*	€/fingerling	MedAID	0.28	Yes
Feed unit cost	*f*	€/kg	MedAID	8.9	Yes
Energy unit cost	*n*	€/fingerling	MedAID	0.0216	Yes
Veterinarian-medicine unit cost	*v*	€/fingerling	MedAID	0.0067	Yes
Oxygen production unit cost	*o*	€/fingerling	MedAID	0.0058	Yes
Water supply unit cost	*u*	€/fingerling	MedAID	0.00041	Yes
Annual labor cost per employee	*l*	€/employee × year	MedAID	26,627	Yes
Annual other operating costs per tank	*m*	€/tank × year	MedAID/Orbis	Micro: 5500 Small: 5500 Medium: 11,577	Yes

(Continues)

TABLE 2 (Continued)

Parameter	Symbol	Unit	Source	Values	Triangular parameter
Annual depreciation rate	*a*	%	MedAID/Orbis	8	Yes
Annual capital investment per tank	*i*	€/tank × year	MedAID/Orbis	Micro: 44,000 Small: 44,000 Medium: 137,598	Yes

Source: Fernández Sánchez et al. (2021).

TABLE 3 Scenarios of severe skeletal anomalies (SA).

Scenario	Scenario name		Triangular parameters (*a*, *b*, *c*)
1	Low SA	Low incidence of severe SA	(4, 5.5, 7)
2	Medium SA	Medium incidence of severe SA	(12, 14, 16)
3	High SA	High incidence of severe SA	(20, 22, 24)

$$LDFSA = fiusp \times (BSA) - f \times \left(\frac{w1 - w0}{1000}\right) \times r \times (BSA) \times \frac{1}{3} \tag{10}$$

It is important to note that we have not considered the potential effects on growth rate and FCR, as these factors depend on the specific rearing conditions of each hatchery. Furthermore, we have not considered the costs of collecting deaths and waste, as well as the costs of disposal and disease diagnostics.

In contrast, Equation (11) demonstrates how to calculate the loss of dead fish *LDF* because of any type of mortality (including other reasons, lack of swim bladder, and severe skeletal anomalies), using a similar approach as with the *LDFSA*.

$$LDF = fiusp \times (B - N) - f \times \left(\frac{w1 - w0}{1000}\right) \times r \times (B - N) \times \frac{1}{3} \tag{11}$$

The scenarios shown in Table 3 were used to assess the potential effects of different rates of severe skeletal anomalies. These scenarios show the percentage of fish with severe skeletal anomalies from the total annual supply of fingerlings *B*, and they were established according to the findings of the studies of Cidad et al. (2018) (MedAID project), Theodorou et al. (2016) and Georgakopoulou et al. (2010). Cidad et al. (2018) found that mean skeletal anomalies in hatcheries were on average 3.4% for seabass and 10.6% for seabream, while Theodorou et al. (2016) found that the proportion of deformed seabream fry could go from 4% to 24%. Finally, Georgakopoulou et al. (2010) indicated that skeletal anomalies affect the produced juveniles in marine hatcheries by around 7%–20% on average. Considering the previous values, we built three scenarios as shown in Table 3 named low, medium and high.

After running the simulations, we discovered that micro hatcheries' positive profits were obtained in just a few observations of the simulations (about 3%). The findings reveal intriguing information about the significant financial and bankruptcy risks that micro hatcheries could face, which is highly unlikely in the real world. This finding could also be because of some inconsistencies reported in the labor costs, given the high proportion they represented from the total costs. The data on cost per employee from Fernández Sánchez et al. (2021) do not differ according to the type of hatchery, which is highly unlikely, considering that this type of company usually hires temporary personnel for specific activities to save resources given their low volume of production. Unfortunately, this issue could not be accounted for in our model because of data availability. Given this, the micro hatchery type will not be further analyzed, and the rest of the investigation will only focus on small and medium hatcheries.

3 | RESULTS

3.1 | Estimation of costs, revenues, and profits

Following the simulations conducted, it is preferable to describe initially the results of parameters such as the annual supply of fingerlings and distribution of costs before entering into the costs and revenues details, to give more context to the empirical application. Figure 2 shows that the annual supply of fingerlings *B* varies in the simulations according to the company type and the scenario of severe skeletal anomalies considered, with small hatcheries stocking between 8.43 and 16.29 million fingerlings, and medium hatcheries between 33.74 and 65.17 million fingerlings. Meanwhile, considering that the variations of the distributions of the costs per each type of hatchery do not differ significantly according to the scenario of severe skeletal anomalies, Figure 3 shows only the distribution of the costs per each type of hatchery for scenario 2 (medium level of severe skeletal anomalies). It can be seen that the highest costs for small and medium hatcheries are related to feeding costs, while labor costs represent the second most important type.

Moreover, in terms of economic figures, profits for small hatcheries would range between 25,631 and 914,353 euros per year, with mean values in the range of 443,912 and 548,966 euros per year; while profits for medium hatcheries would range between 1,684,939 and 5,250,786 euros per year, with mean values between 3,332,938 and

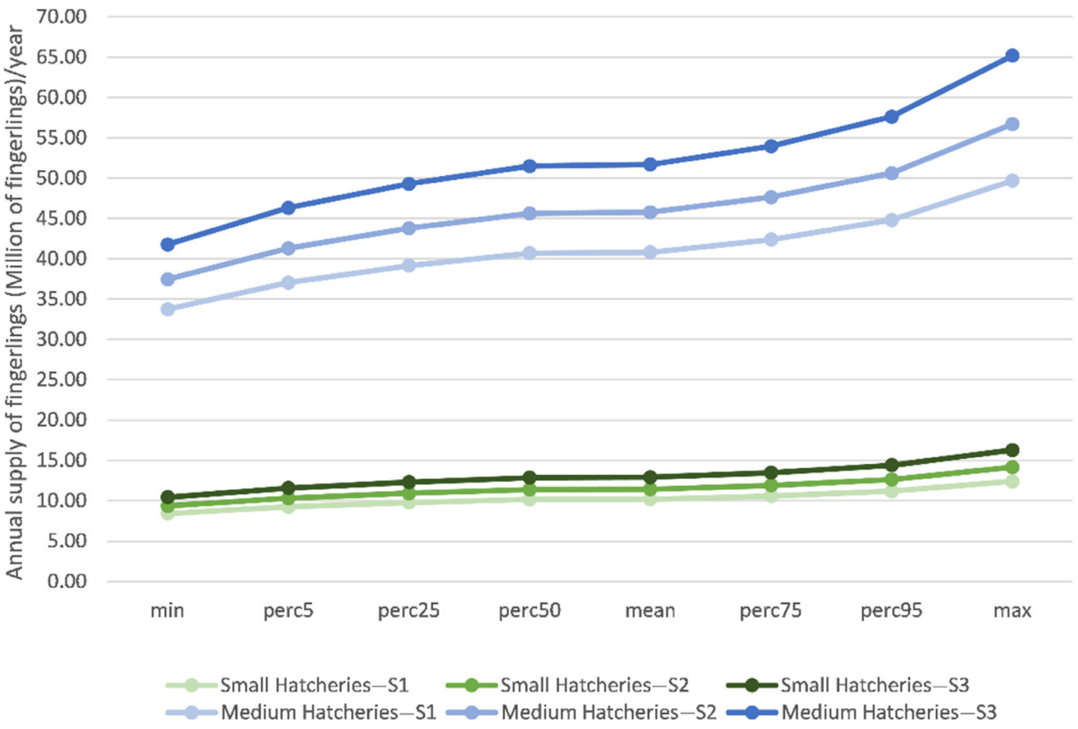


FIGURE 2 Annual supply of fingerlings per type of hatchery and scenario.

3,753,151 euros per year. In the same context, Figure 4a,b presents as an example the results of the revenues, costs, and profits for the scenario of medium incidence of severe skeletal anomalies (S2), for small and medium hatcheries, respectively. Regardless of the scenario considered, when these figures are compared across the two types of hatcheries, it is clear that a hatchery with higher production is more financially stable. This issue is in line with the findings of Stephanis (1995), who found that hatcheries with higher production volumes have lower costs, and as a result, supply exceeds demand and prices fall, hence, smaller hatcheries will struggle to compete with well-managed hatcheries producing a higher quantity of fry.

Another aspect that evaluates the financial stability of hatcheries is that of the breakeven and shutdown points of production (Table 4). The breakeven point represents the level of production in which the sales revenues are equal to the production costs, or in economic parlance, the profits are normal. Meanwhile, the shutdown point defines the production limit in which the companies would still operate, or in economic terms, the minimum level of production in which the company is able to cover its total variable costs. At any production below that, companies prefer to shut down than keep running at a loss. For small and medium hatcheries, the annual harvested minimum production values (8.43 and 33.74 million fingerlings, respectively) are above the range of breakeven and shutdown points obtained in the simulations (minimum and maximum values shown in Table 4). The results indicate that financial stability exists for both types of hatcheries, but medium ones evidence a higher level of stability.

3.2 | The economic impact of mortalities and severe skeletal anomalies

Figure 5a,b presents the results of the loss of dead fish because of other reasons but severe skeletal anomalies (LDFOR) and LDFSA per scenario of severe skeletal anomalies and type of hatchery. It can be seen that in the case of small hatcheries (Figure 5a), the losses because of any type of mortality (LDF) ranged between 275,000 and 2,003,000 euros per hatchery, with mean values of 564,000 euros (S1), 886,000 euros (S2) and 1,268,000 euros (S3) per company. For medium hatcheries (Figure 5b), the losses because of any type of mortality (LDF) ranged from 1.1 to 8 million euros per hatchery, with mean values of 2.3 million euros (S1), 3.6 million euros (S2) and 5.1 million euros (S3) per company.

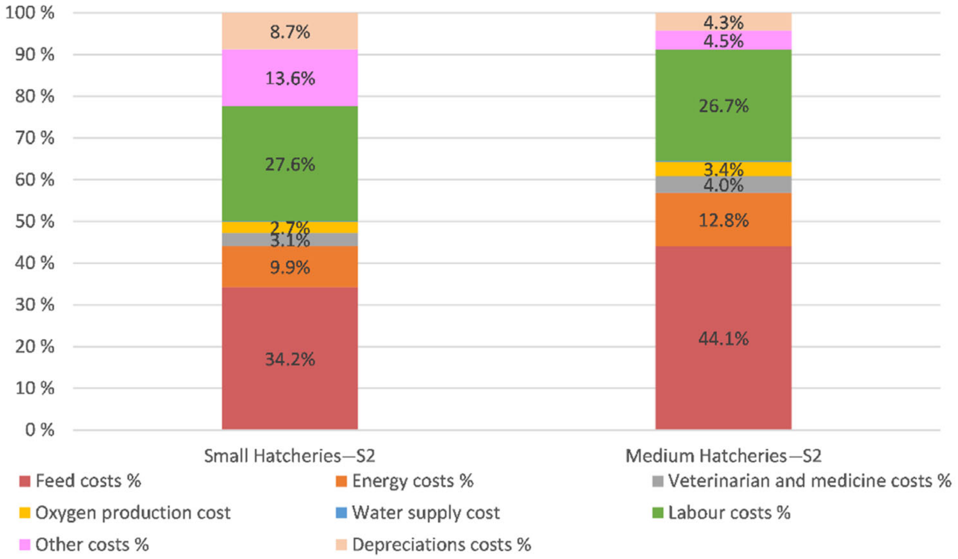
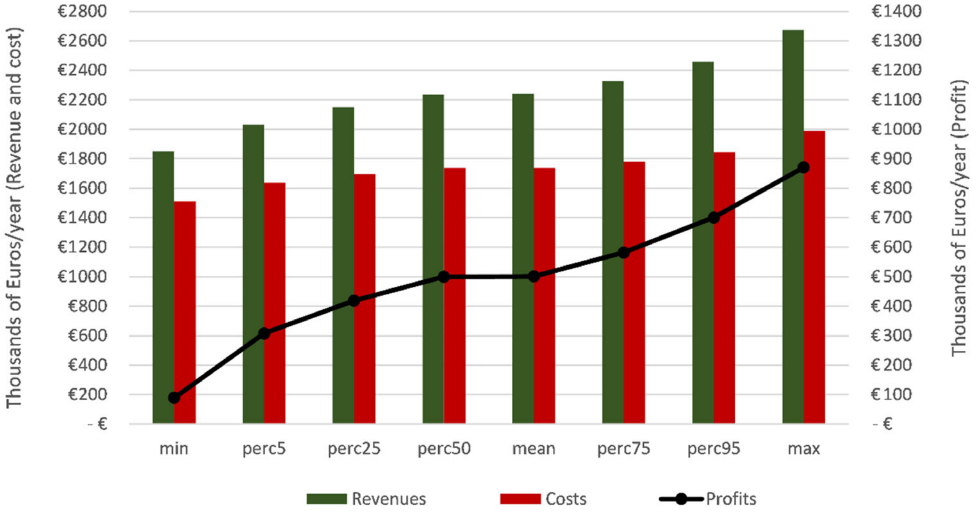
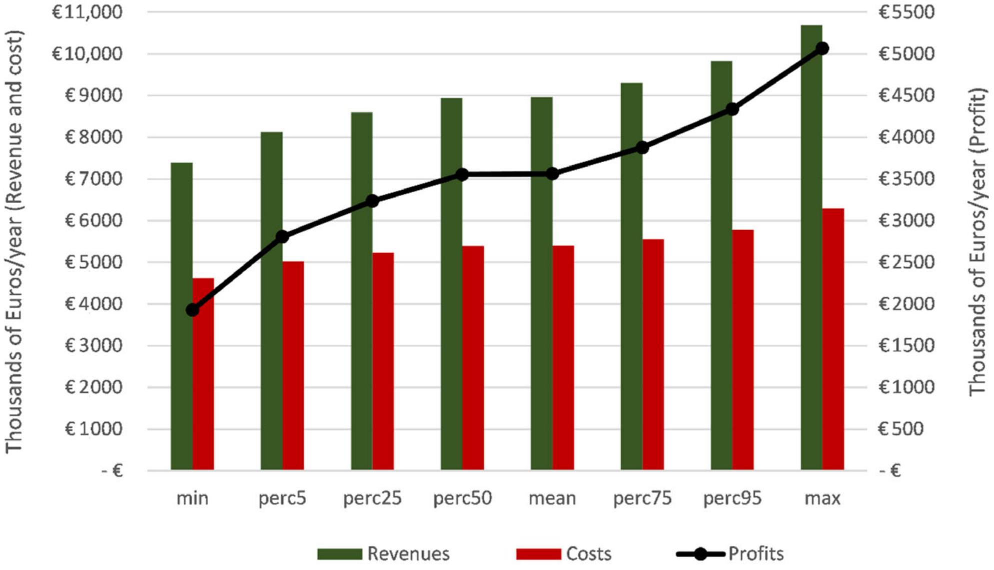


FIGURE 3 Costs distribution—Scenario 2 (medium level of skeletal anomalies).



(a)



(b)

FIGURE 4 (a) Revenues, costs, and profits—small hatcheries—Scenario 2 (medium level of skeletal anomalies). (b) Revenues, costs, and profits—medium hatcheries—Scenario 2 (medium level of skeletal anomalies).

The analysis of the economic impacts of the mortalities caused by severe skeletal anomalies showed that the specific losses because of severe skeletal anomalies (LDFSA) ranged from 92,000 to 1,023,000 euros for each small hatchery, with mean values of 146,000 euros (S1), 418,000 euros (S2) and 741,000 euros (S3) per company. Meanwhile, for medium hatcheries, these economic impacts ranged between 366,000 and 4,094,000 euros per hatchery, with mean values of 585,000 euros (S1), 1.67 million euros (S2), and 2.97 million euros (S3) per company. The analysis of the previous results shows that, as expected, the bigger the hatcheries, the higher the production, and thus, the higher the absolute impacts on mortality in general and because of severe skeletal anomalies.

TABLE 4 Breakeven and shutdown production points.

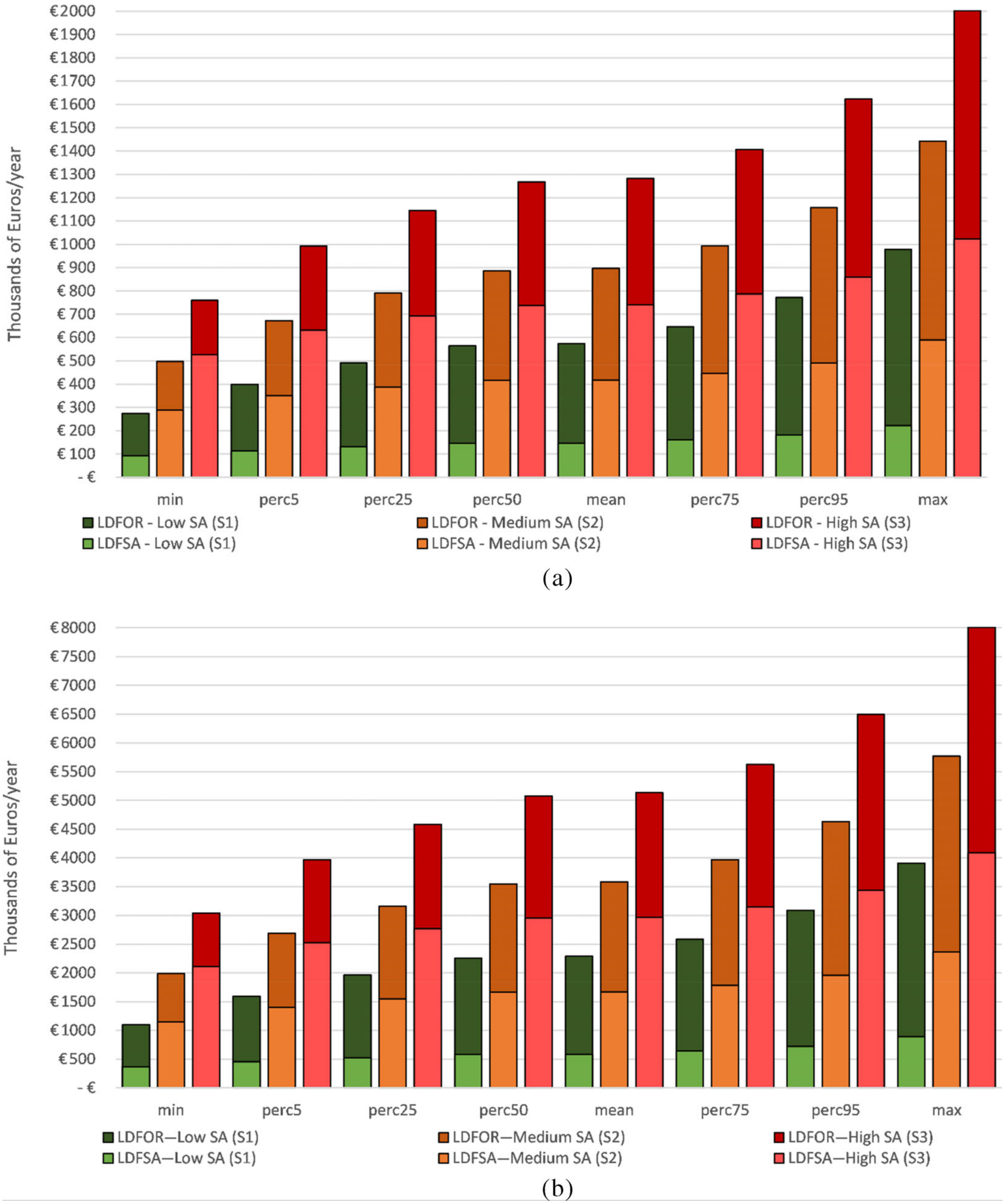
Type of company—scenario	Min	Perc5	Perc25	Perc50	Mean	Perc75	Perc95	Max
Breakeven point (millions of fingerlings/year)								
Small hatcheries—Low SA (S1)	4.9	5.536	5.812	6.036	6.048	6.269	6.614	7.304
Small hatcheries—Medium SA (S2)	5.02	5.683	5.974	6.205	6.22	6.45	6.807	7.565
Small hatcheries—High SA (S3)	5.168	5.861	6.162	6.41	6.424	6.665	7.041	7.88
Medium hatcheries—Low SA (S1)	14.92	16.93	17.84	18.58	18.62	19.35	20.48	22.99
Medium hatcheries—Medium SA (S2)	15.4	17.52	18.49	19.26	19.31	20.07	21.27	24.04
Medium hatcheries—High SA (S3)	15.99	18.21	19.25	20.08	20.13	20.94	22.21	25.3
Shutdown point (millions of fingerlings/year)								
Small hatcheries—Low SA (S1)	4.443	5.025	5.288	5.495	5.507	5.713	6.034	6.692
Small hatcheries—Medium SA (S2)	4.563	5.174	5.447	5.665	5.678	5.894	6.227	6.953
Small hatcheries—High SA (S3)	4.711	5.349	5.639	5.871	5.883	6.11	6.464	7.268
Medium hatcheries—Low SA (S1)	14.22	16.15	17.04	17.75	17.8	18.5	19.61	22.06
Medium hatcheries—Medium SA (S2)	14.7	16.73	17.68	18.43	18.48	19.23	20.4	23.1
Medium hatcheries—High SA (S3)	15.29	17.43	18.44	19.26	19.3	20.1	21.35	24.36

Abbreviation: SA, skeletal anomalies.

3.2.1 | Extending the results of the economic impacts of severe skeletal anomalies to Mediterranean production of seabream and seabass

As previously mentioned, the main aim of the present investigation is to calculate the direct costs related to fish mortalities because of severe skeletal anomalies in typical Mediterranean aquaculture hatcheries. Considering this, we used the results of the previous simulations to analyze how these impacts affect the different Mediterranean countries involved in the production of seabream and seabass, assuming that the whole production of these countries follows the mean losses per fingerling obtained in the simulations. The analysis does not account for differences in hatchery production methods between countries, as we assume that the production is uniform across the Mediterranean countries involved. We highlight that the results of the analysis do not depend on the hatchery size, as the LDFSA is calculated considering the parameters of fingerlings' unit sale price and feed unit cost, which do not vary across different types of hatcheries (see Equation (10)). The section aims to provide approximate figures of the impact of skeletal anomalies in Mediterranean aquaculture for each scenario, regardless of the production methods used by the hatcheries or their particular characteristics. For the assessment, we used the production data of seabream and seabass in 2019 according to FEAP (2020) (see Table 5).

The impacts of severe skeletal anomalies on the seabream and seabass Mediterranean production according to the scenarios considered are shown in Figure 6a,b. The simulation results show that the impacts of severe skeletal anomalies range from 8.4 to 18.3 million euros for seabream Mediterranean production (Figure 6a), and from 6.6 to 14.32 million euros for seabass Mediterranean production (Figure 6b), based on the scenario of low level of severe skeletal anomalies (S1). Moreover, if the scenario of medium level of skeletal anomalies (S2) is considered, the economic burden of severe skeletal anomalies ranges from 27.1 to 48.95 million euros for seabream Mediterranean production, and from 21.3 to 38.4 million euros for seabass Mediterranean production. And finally, under the most adverse scenario of severe skeletal anomalies (S3), the losses for seabream Mediterranean production would range from 49.6 to 85.2 million euros, while the losses for seabass Mediterranean production would range from 38.9 to 66.8 million euros.



(a)

(b)

FIGURE 5 (a) Loss of dead fish because of other reasons but severe skeletal anomalies (LDFOR) and loss of dead fish because of severe skeletal anomalies (LDFSA) per scenario for small hatcheries. (b) LDFOR and LDFSA per scenario for medium hatcheries.

3.3 | Economic impact of variations in model parameters

Following the same methodology and triangular distributions used in the previous sections, this section provides a sensitivity analysis to see how larger changes in some model parameters, such as the fingerling sale price, feed unit cost, and FCR, might affect the results, considering the other parameters in a condition of ceteris paribus (although

TABLE 5 Production of seabream and seabass in Mediterranean aquaculture (2019).

Country	Production in 2019 (thousands of fingerlings)
Seabream production	
Turkey	240,000
Greece	238,000
Italy	90,000
France	55,115
Spain	36,396
Cyprus	27,000
Croatia	15,000
Total	701,511
Seabass production	
Turkey	245,000
Greece	173,000
France	57,777
Spain	55,244
Croatia	16,000
Cyprus	3000
Total	550,021

Source: FEAP (2020).

varying according to the triangular distribution). Table 6 shows the values for the different scenarios of variation considered for the different parameters.

Our findings show that, as the selling price of fingerlings rises, so do revenues, while there are no effects on the costs (see Figure 7; Table 7). This issue results in a positive effect on profits of around 134.10% for small hatcheries and 75.46% for medium hatcheries, for a 30% increase in the sale price of fingerlings. These results show that with larger companies in terms of production, there is a lower variation in their profits when there are changes in the price of fingerlings; however, these higher production companies still have higher profits per fingerling produced, no matter the changes.

Moreover, it can also be appreciated that with an increase in the fingerlings' sale price, there is also a reduction in the breakeven and shutdown points, indicating higher economic stability with this change. On the contrary, with lower prices, there is an increase in the breakeven and shutdown points. The magnitude of the effects on the breakeven and shutdown points are considerably higher with a reduction in the price in comparison to an increase in the price. Also, it can be observed that the effect remains the same with all the different types of hatcheries, considering the linearity of the proposed model and that there are no changes in the costs, just in the incomes.

In addition, with higher prices of fingerlings, there is a significant increase in the economic impacts of severe skeletal anomalies, but this is because of higher losses on the opportunity costs of dead fish because of skeletal anomalies. This represents a 32.22% increase for a 30% increase in the price of fingerlings. On the contrary, lower fingerling sale prices result in a less economic loss of dead fish because of skeletal anomalies as the loss in opportunity costs decreases, but at the same time, lower profits.

Moreover, according to the equation of feed costs in Table 1, the effects of percentage changes are the same for equal percentage variations in the parameters of feed unit cost and FCR. As a result, Figure 8 and Table 8 present the equivalent results for both variables. Our findings show that changes in the feed unit costs or FCR do not affect

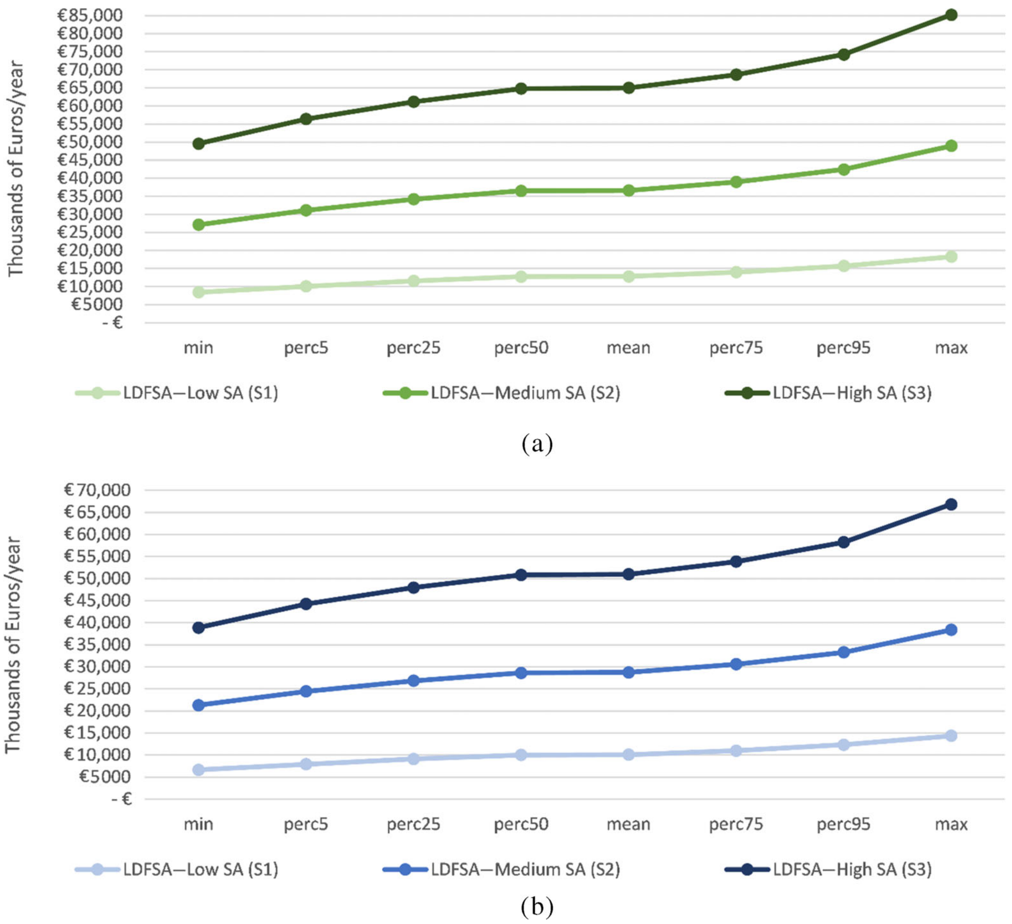


FIGURE 6 (a) Loss of dead fish because of severe skeletal anomalies (LDFSA) for the total seabream Mediterranean production per scenario. (b) LDFSA for the total seabass Mediterranean production per scenario.

revenues, but there is a decrease in total costs because of lower feed costs considering a more convenient price or efficient feed regime, respectively, resulting in a positive effect on profits of around 35.65% for small hatcheries and 20.06% for medium hatcheries, for a 30% decrease in any of the mentioned parameters. Similarly, as previously exposed, these findings show that bigger companies in terms of production have a lower variation in their profits when there are changes in the FCR or feed unit cost; however, these higher production companies still have higher profits per fingerling produced, no matter the changes.

Furthermore, the results indicate that a reduction in the FCR or feed unit cost also reduces the breakeven and shutdown points, implying higher financial stability with a reduction in the mentioned variables. However, there is a higher effect with hatcheries of higher production.

Moreover, decreases in the FCR or the feed unit cost translate into small positive changes in the economic losses because of severe skeletal anomalies because of the lower savings on the feed costs. These losses increase by around 2.62% for a 30% decrease in the FCR or feed unit cost. Despite the previous, profits increase with a decrease in these variables. On the contrary, an increase in these variables would imply a lower economic impact of severe skeletal anomalies, which in the end is worthless considering the lower profits obtained.

TABLE 6 Variation of different parameter scenarios.

	Values used for the scenarios						
	Scenarios						
Variable	S1 −30% of base	S2 −20% of base	S3 −10% of base	Base (avg value)	S4 10% of base	S5 20% of base	S6 30% of base
Fingerlings' sale price	0.20	0.22	0.25	0.28	0.31	0.34	0.36
Feed unit cost	6.23	7.12	8.01	8.90	9.79	10.68	11.57
FCR	0.91	1.04	1.17	1.30	1.43	1.56	1.69

Abbreviation: FCR, feed conversion ratio.

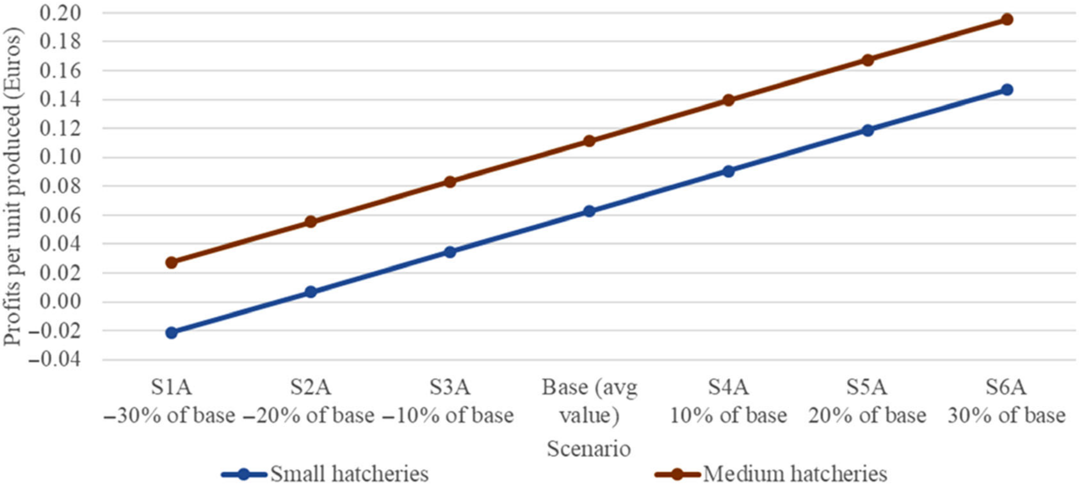


FIGURE 7 Profits per fingerling produced after changes in the fingerlings' sale price—Scenario 2 (medium level of skeletal anomalies).

4 | DISCUSSION

Given the preceding findings, it is clear that increasing the sale price of fingerlings has the greatest positive effect on the profits and the economic impacts because of severe skeletal anomalies. However, because this issue depends on external factors related to market conditions, it should be considered with caution. Nonetheless, certain upgrades or simply acknowledging certain final product conditions might enhance the probability of increasing the final consumers' willingness to pay (Cantillo et al., 2020). Several studies have found that consumers are willing to pay premiums for products including certification labels such as the Aquaculture Stewardship Council (ASC) and the Marine Stewardship Council (MSC) (Banovic et al., 2019; Bronnmann & Asche, 2017; Bronnmann & Hoffmann, 2018; Chen et al., 2015; Hinkes & Schulze-Ehlers, 2018). In addition, several studies have claimed that consumers are willing to pay premiums for more sustainable aquaculture products (Davidson et al., 2012; Fernández-Polanco et al., 2013; Fonner & Sylvia, 2015; van Osch et al., 2017, 2019) and products developed with alternative production methods such as organic, Integrated Multi-Trophic Aquaculture (IMTA) and Closed Containment Aquaculture (CCA) (Ankamah-Yeboah et al., 2018; Mauracher et al., 2013; Olesen et al., 2006, 2010; Stefani et al., 2012; Yip et al., 2017). Also, there is the possibility to set higher prices for final consumers by highlighting the health and

TABLE 7 Variations in economic variables after changes in the fingerlings' sale price—Scenario 2 (medium level of skeletal anomalies).

Variable	**Values used for the scenarios**						
	Scenarios						
	S1A −30% of base	**S2A −20% of base**	**S3A −10% of base**	**Base (avg value)**	**S4A 10% of base**	**S5A 20% of base**	**S6A 30% of base**
Fingerlings' sale price	**0.2**	**0.22**	**0.25**	**0.28**	**0.31**	**0.34**	**0.36**
Variations with respect to base values (%)							
Small hatcheries							
Revenues	−30.00%	−20.00%	−10.00%	0.00%	10.00%	20.00%	30.00%
Costs	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Profits	−134.10%	−89.40%	−44.70%	0.00%	44.70%	89.40%	134.10%
Breakeven point	42.86%	25.00%	11.11%	0.00%	−9.09%	−16.67%	−23.08%
Shutdown point	42.86%	25.00%	11.11%	0.00%	−9.09%	−16.67%	−23.08%
Medium hatcheries							
Revenues	−30.00%	−20.00%	−10.00%	0.00%	10.00%	20.00%	30.00%
Costs	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Profits	−75.46%	−50.31%	−25.15%	0.00%	25.15%	50.31%	75.46%
Breakeven point	42.86%	25.00%	11.11%	0.00%	−9.09%	−16.67%	−23.08%
Shutdown point	42.86%	25.00%	11.11%	0.00%	−9.09%	−16.67%	−23.08%
All types of companies							
Loss of dead fish because of skeletal anomalies	−32.22%	−21.48%	−10.74%	0.00%	10.74%	21.48%	32.22%

nutritional benefits of the products, which could be obtained by either using fortified products or enhancing characteristics that some consumer segments might overlook such as the Omega 3 content, the improvement in the heart and brain function, and the high content of protein (Banovic et al., 2019; Bi et al., 2016; Fernández-Polanco et al., 2013). Also, labels highlighting safety claims and fair trade claims (Fernández-Polanco et al., 2013; Fonner & Sylvia, 2015; Hinkes & Schulze-Ehlers, 2018), and alternative fish ingredients such as insects and vegetables have shown positive premiums for consumers (Davidson et al., 2012; Ferrer Llagostera et al., 2019). These additional profits because of the previous improvements will be reflected in the product's whole supply chain, positively affecting the hatcheries, as grow-out firms will demand higher quality fingerlings, for which hatcheries could ask significantly higher prices.

Another aspect that affects the fingerlings' sale prices is the image of aquaculture and its products. Some consumer segments might be willing to pay higher prices if they have a better perception of the aquaculture industry and its products, which would also reflect in the whole supply chain, affecting the hatcheries positively. Aquaculture's rapid growth, especially intensive aquaculture production, has raised questions and criticism about its environmental compatibility with other activities, as well as the potential negative economic and social effects (Burbridge et al., 2001). Also, many studies have indicated that consumers currently prefer wild fish over farm fish (Cantillo et al., 2020). As a result, governments and stakeholders of the industry should invest in marketing campaigns that help to change the current negative perception of aquaculture products (Bronnmann & Hoffmann, 2018).

These campaigns should focus on highlighting the benefits of aquaculture compared with wild fish, such as job opportunities (Alexander et al., 2016; Flaherty et al., 2019; Hynes et al., 2018; Katranidis et al., 2003; Murray &

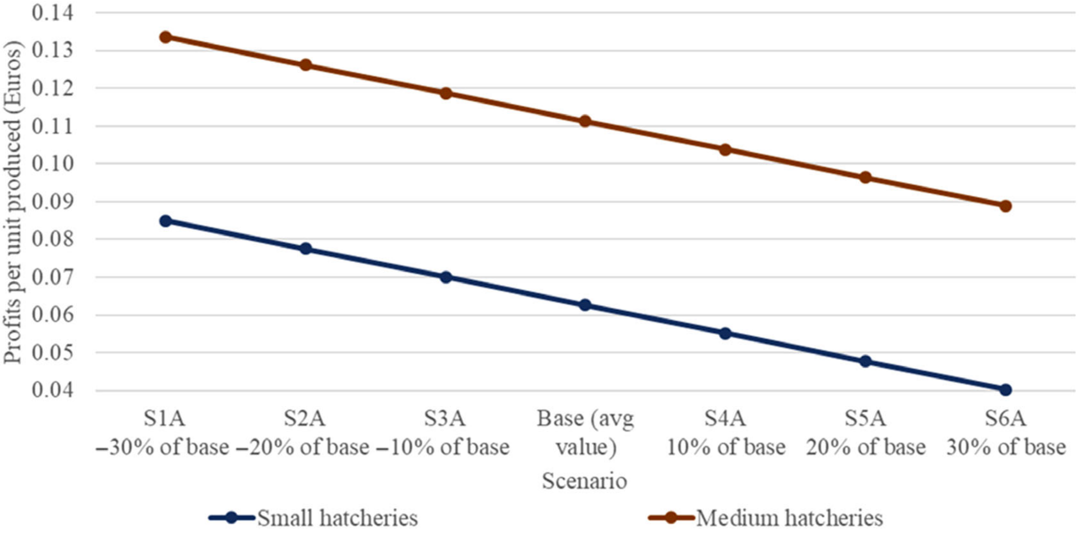


FIGURE 8 Profits per fingerling produced after changes in the feed conversion ratio or feed unit cost—Scenario 2 (medium level of skeletal anomalies).

D'Anna, 2015), lower prices and a superior availability throughout the year in comparison to fisheries' products (Alexander et al., 2016; López-Mas et al., 2021; Ruiz-Chico et al., 2020a, 2020b), higher control in the production process (López-Mas et al., 2021), contribution to the prevention of overfishing, and health and nutritional benefits (Alexander et al., 2016). In addition, the campaigns should focus on contrasting the current negative aspects associated with aquaculture, which sometimes are rooted in consumers' insufficient knowledge. Some of these negative aspects are environmental concerns (Alexander et al., 2016; Mazur & Curtis, 2008), comparatively low quality in comparison to wild-caught products (López-Mas et al., 2021; Ruiz-Chico et al., 2020a, 2020b), being less fresh and with higher antibiotic concentrations than with wild-caught products (López-Mas et al., 2021), being considered unnatural and unhealthy because of the improper use of feeds and chemicals (Ruiz-Chico et al., 2020a, 2020b), adverse effects on traditional fishing (Ruiz-Chico et al., 2020a) and concerns about animal welfare (Alexander et al., 2016; Kupsala et al., 2013).

Furthermore, other options for increasing a hatchery's profits are to look for strategies that reduce the FCR or look for suppliers who offer lower feed unit costs. Although these options slightly increase the economic losses because of severe skeletal anomalies, higher profits are expected, making it an appropriate solution for increasing hatcheries' economic stability. For the FCR, Besson et al. (2020) suggest that it should be included as a trait in breeding programs for genetic improvement, as its inclusion increases profits and reduces the environmental impacts simultaneously, considering that feed is the most relevant environmental cost, because of its manufacturing and its biological transformation into nitrogen-based waste by the fish (Aubin et al., 2009). Moreover, some studies have shown that restricted rations might be a feasible option for improving the feed conversion efficiency (Andrew et al., 2004; Bavčević et al., 2010; Bonaldo et al., 2010; Eroldoğan et al., 2008; Mihelakakis et al., 2002), considering that with this technique, fish tend to optimize their digestion in order to get the most out of the nutrients in their food (Meyer-Burgdorff et al., 1989; Zoccarato et al., 1994). However, this option requires an optimum feeding strategy as restricted rations decrease growth (Bonaldo et al., 2010), so a balance between keeping an efficient feed conversion and an appropriate growth rate needs to be found (Bavčević et al., 2010).

On the other hand, lower mortality rates would imply higher profits for hatcheries. Thus, it can be considered a viable option for improving the company's financial stability. Accordingly, stakeholders are encouraged to invest in inputs, technology, and knowledge that will allow them to reduce mortality rates. In addition, lowering the mortality

TABLE 8 Variations in economic variables after changes in the feed conversion ratio (FCR) or feed unit cost—Scenario 2 (medium level of skeletal anomalies).

Variable	Values used for the scenarios						
	Scenarios						
	S1A −30% of base	S2A −20% of base	S3A −10% of base	Base (avg value)	S4A 10% of base	S5A 20% of base	S6A 30% of base
FCR	0.91	1.04	1.17	1.3	1.43	1.56	1.69
Feed unit cost	6.23	7.12	8.01	8.9	9.79	10.68	11.57
Variations with respect to base values (%)							
Small hatcheries							
Revenues	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Costs	−10.27%	−6.85%	−3.42%	0.00%	3.42%	6.85%	10.27%
Profits	35.65%	23.77%	11.88%	0.00%	−11.88%	−23.77%	−35.65%
Breakeven point	−10.27%	−6.85%	−3.42%	0.00%	3.42%	6.85%	10.27%
Shutdown point	−11.25%	−7.50%	−3.75%	0.00%	3.75%	7.50%	11.25%
Medium hatcheries							
Revenues	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Costs	−13.24%	−8.83%	−4.41%	0.00%	4.41%	8.83%	13.24%
Profits	20.06%	13.37%	6.69%	0.00%	−6.69%	−13.37%	−20.06%
Breakeven point	−13.24%	−8.83%	−4.41%	0.00%	4.41%	8.83%	13.24%
Shutdown point	−13.83%	−9.22%	−4.61%	0.00%	4.61%	9.22%	13.83%
All types of companies							
Loss of dead fish because of skeletal anomalies	2.22%	1.48%	0.74%	0.00%	−0.74%	−1.48%	−2.22%

rate reduces the risk of failing to meet the expected fish demand on time for some clients, avoiding an imminent high risk of losing clients.

The literature shows many options that could reduce the mortality rates in aquaculture. A significant part of them is related to fish nutrition, as marine fish larvae are extremely vulnerable during their early stages of development, and they have specific biotic and abiotic requirements to survive, develop, and grow properly (Hamre et al., 2013). Results from the literature indicate that supplementation of good quality dietary protein (Kvåle et al., 2009), phospholipids (Tocher et al., 2008), n-3 highly unsaturated fatty acids (Hamre et al., 2013), minerals such as iodine and selenium (Hamre et al., 2008), vitamins such as the vitamin D3 (Sivagurunathan et al., 2022), and probiotics (Piccolo et al., 2015), affect the survival rate of fish positively.

5 | CONCLUSIONS

The study aimed to conduct an economic analysis of the impact of severe skeletal anomalies on seabream and seabass aquaculture hatcheries, examining various scenarios that took into account different rates of severe skeletal anomalies and different types of hatcheries based on their production. As expected, the findings show higher economic impacts of severe skeletal anomalies to medium hatcheries because of their higher volume of production, with economic impacts ranging from around 366,000 to 4,094,000 euros per hatchery depending on the scenario of severe skeletal anomalies considered. Meanwhile, small hatcheries experience lower severe skeletal anomalies losses ranging from 92,000 to 1,023,000 euros per hatchery according to the scenario considered.

The previous results translated to the entire seabream Mediterranean production shows that the annual economic losses because of severe skeletal anomalies can range from around 8.4 to 85.2 million euros per year depending on the scenario considered. Whereas, for the seabass Mediterranean industry, the yearly economic losses because of severe skeletal anomalies can range from 6.6 to 66.8 million euros per year according to the scenario considered. Considering the previous, if both results are summed, the annual economic losses of severe skeletal anomalies for seabream and seabass Mediterranean aquaculture can go from around 15 to 152 million euros per year. Moreover, considering the mean values, the annual economic losses of severe skeletal anomalies for the Mediterranean seabream and seabass aquaculture industry are 22.88 million euros per year, 65.34 million euros per year, and 115.98 million euros per year, for scenarios 1 (low incidence of severe skeletal anomalies), 2 (medium incidence of severe skeletal anomalies), and 3 (high incidence of severe skeletal anomalies), respectively.

According to a previous study, European aquaculture loses more than 50 million euros per year on average, and a 50% reduction in skeletal anomalies could save 25 million euros per year, increase production and profitability, and improve aquaculture's image (Boglione, Gisbert, et al., 2013, p. 2). However, this study does not specify how these estimates were obtained, which species were considered in the analysis, or whether it considers the possible economic effects of nonsevere skeletal anomalies. As a result, it is not easy to compare those findings to the current results, but the magnitude of the values appears to be consistent with the second scenario of the current investigation, which is expected to be the average scenario.

Furthermore, the study's findings suggest that increasing the sale price of fingerlings, lowering the FCR, and lowering feed unit cost are three options for increasing the financial stability of hatcheries. The study's primary limitation is the inability to obtain primary source information on the incidence of skeletal anomalies in the aquaculture industry, which is usually considered confidential by aquaculture companies. Another limitation is that the data used was gathered from a small number of companies (10 hatcheries), so the information presented here should be treated with caution, bearing in mind that it is the first attempt to understand the economic effects of severe skeletal anomalies. In addition, another limitation is that our model accounts for the effect of increased mortality rates and FCRs, considering them as two independent parameters. Future research should include an analysis of the effect of increasing mortality rates on parameters such as FCR and growth rates. Also, future research should look into the economic consequences of nonsevere skeletal anomalies, which are more difficult to quantify. A more specific approach using a case study analysis is recommended in this case.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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