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Influence of Production Strategy on Gross Waste Output and Temporal Pattern of Gilthead Seabream (*Sparus Aurata*) Farming: Implications for Environmental Management

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Abstract: This study compares the farm management model used in the Mediterranean gilthead seabream (GHSB; *Sparus aurata*) industry (S1)—stepped entry of juveniles throughout the year with several production cycles and fish ages overlapping in a single farm—with that used in the salmon industry (S2)—the whole is farm filled with fish that are the same age at once with a fallowing period between rearing cycles—in terms of waste production by coupling digestibility coefficients with growth, feeding, and eating behavior models into a mass balance model. We considered the total C, N, and P content in the different waste fractions (particulate and dissolved wastes). The model, which simulated real farming conditions, showed relevant quantitative and qualitative differences between both strategies, with stocked biomass and water temperature as the main drivers, the amount of feed wasted by chewing as the most relevant fraction differentiating both strategies, and the fallowing period as the main distinguishing management feature. We discuss the influence of both farming strategies on some key performance and environmental aspects, such as benthic recovery, the breakdown of the life cycle of pathogens, and adaptability to climate change. Our results suggest that changing the GHSB industry's production model is necessary for its sustainability.

Keywords: fallowing; modelling; production strategy; recovery; *Sparus aurata*; waste output

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1. Introduction

Aquaculture has achieved a prominent role in the provisioning of seafood for a growing and demanding human population in a scenario where most fishing resources are exploited to their maximum capacity or are overexploited [1,2]. Globally, major efforts are being made for the sustainable development of aquaculture under the Blue Growth Initiative [3] and the 2030 Agenda [4]. In developed countries, aquaculture works according to an economies of scale model [5], namely production costs are reduced by increasing the production scale to widen the profit margin. EU governments have implemented different initiatives for aquaculture promotion and, after several years of decreasing production, a moderate but encouraging increase has recently been experienced [1]. However, in the EU, aquaculture accounts for only 20% of the total aquatic production [6], and therefore, the current demand for aquatic products still relies on imports and fisheries. Hence, the EU not only needs to reduce its dependence on fisheries and imports, but it should also encourage aquaculture at the farm level to achieve a strong and competitive industry.

In the Mediterranean basin, fish farming is the main aquaculture practice, both in terms of biomass production and economic profit [6]. Most fish production takes place in floating cage facilities in the open sea [7], with gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*) as the main reared species [8]. The most common fish stock management method in Mediterranean farms entails a stepped input of fish batches throughout the year so that batches of fish of different ages overlap, market-sized fish are harvested throughout the year, and farms are never empty. This strategy implies an increased risk of disease transmission and environmental impact [9–12] and forces farmers to manage several types of feed and feeding schemes simultaneously and to combine the diverse maintenance and husbandry tasks that are typical of different rearing stages, thus hindering the organization of work. In the current global scenario, this productive model is evolving towards the one used by the salmon industry [13]: large companies with several farms (licenses), wherein each single farm works as a big batch. The rearing method used in this model entails filling all the cages with fish of the same age at once, carrying out the harvest in a shorter period of time—as the commercial size/s is/are reached—and completing a mandatory fallowing period of variable length prior to the introduction of a new generation of fish [13]. This allows for the biological cycle of many pathogens to be broken [11] and a total or partial recovery of the environment [8,14,15]. This rearing strategy is commonly known as "all in/all out." The Mediterranean fish farming industry is expected to evolve towards the salmon model to enhance production while adapting the business model to a blue economy scenario, which would also enable efficient sanitary and environmental management.

The Mediterranean fish farming industry employs feed-based aquaculture practices, with carnivorous fish based far from the shore. This results in the consumption of a considerable amount of resources—mainly raw materials for feed manufacturing and fuel [16,17]—and the generation of huge amounts of waste of biological and dietary origin [18]—mainly in the form of dissolved organic and inorganic nutrients (urinary and branchial excretion) and particulate organic matter (feces and uneaten feed). How effectively aquaculture companies manage their waste has a considerable influence on long-term sustainability [19]. Waste output and environmental impact can be minimized through on-farm feeding management [20,21] and site selection [22]. The Mediterranean fish farming industry is in the process of changing its production strategy. In such a scenario, an important part of the planning phase is the prediction of waste output over time as a first step for subsequent environmental management actions, namely risk, carrying capacity, and environmental impact assessment and monitoring [23].

The expansion of aquaculture over the next few years should be accompanied by technical and management improvements to minimize environmental and social concerns [21,24]. Over the past few decades, several models have been developed to deal with different aspects related to the environmental management of aquaculture. In feed-based aquaculture, waste output models are based on the mass balance between feed input and fish feed consumption [19,25–28]. Because of their impact on fish metabolism, oceanographic and environmental conditions and welfare also influence waste production [29]. In the present study, we explore how the farming strategy can influence the amount of feed-derived waste that is delivered to the environment and its temporal pattern. We developed a series of simulations by coupling growth, feeding, and waste models. We used gilthead seabream (hereafter GHSB) as the model species because this is one of the most widely farmed fish in the Mediterranean, and it displays a particular eating behavior that involves some degree of feed waste. Simulations were carried out for both the classical Mediterranean stepped fish input and the forthcoming all in/all out strategy for the same annual harvest. These were then compared in terms of gross waste production and temporal variability.

2. Materials and Methods

2.1. Waste Output Modelling

Waste output from a fish culture can be estimated through a mass balance equation [19,25,28]. A fraction of the nutrients—carbon (C), nitrogen (N), and phosphorus (P)—included in the feed supplied to the fish (F_s) is retained as they grow (G), and the remaining nutrients are wasted in two ways: via dissolved waste (DW) as fish metabolism by-products (mainly urinary and branchial excretion) and as solid waste via, undigested feed, namely feces (*F*). In GHSB, a portion of F_s is wasted as a result of this type of fish's peculiar eating behavior: how it chews and crushes its food results in fragments of feed being wasted before swallowing [30,31]. We denominate this fraction as feed wasted by chewing (F_{ch}). Another portion of the F_s can be wasted due to inefficient control when dispensing the feed (feed supplied but unused: F_u). This is normally the consequence of inaccurate feed distribution over the cage surface or a feed delivery rate that is too rapid for the fish to ingest the feed properly [20,21]. The actual ingested feed (F_i) is equal to the difference between F_s and the sum of the feed wasted in both ways (F_{ch} + F_u). F_{ch} can be estimated as the function of pellet size and fish size, according to the method described by Ballester Moltó et al. [32]. Conversely, F_u cannot be predicted because this depends on feeding practices, which vary from farm to farm [18]; therefore, F_u was not considered in our model.

The general model used in the present work is as follows:

$$F_i = F_s - F_{ch} = G + DW + F \tag{1}$$

All of the terms in Equation (1) were calculated from specific submodels on a daily basis. F_s—the daily ration—was determined according to the specific feeding rate (SFR = % BW_i day^{-1}) equation developed by Aguado-Giménez [21] through multiple regression analysis from a feeding chart provided by a prominent GHSB feed manufacturer:

$$SFR = e^{(-4.954 - 0.289\ \cdot LnBW_i + 2.034\ \cdot LnT)}\ \left(\text{Adj. R}^2 = 0.90\right) \tag{2}$$

where BW_i is the mean initial fish weight in g, and T is the water temperature in °C.

The SFR was recalculated daily according to growth predictions (*G* in Equation (1)). We used the thermal growth coefficients (TGC) [26] and the GHSB growth model developed by Mayer et al. [33]. This is the only GHSB model developed under real commercial conditions that is available. The authors showed that TGC varies over time and identified two growth stages, with 117 g acting as a critical value for fish weight. Therefore, the two following separate equations were used to estimate GHSB growth:

$$BW_f = \left[BW_i^{1/3} + TGC_1 \cdot \Sigma(t_o - t)\right]^3,\ \text{when } BW < 117\ \text{g};\ TGC_1 = 0.001646\ (\text{Adj. R}^2 = 0.97), \tag{3}$$

$$BW_f = \left[BW_i^{2/3} + TGC_2 \cdot \Sigma(t_o - t)\right]^{3/2},\ \text{when } BW > 117\ \text{g};\ TGC_2 = 0.016095\ (\text{Adj. R}^2 = 0.98) \tag{4}$$

where BW_f and weight BW_i are the mean final and initial fish weight in g, respectively, and $\Sigma(t_o - t)$ is the effective temperature in °C—summation of the temperature during a given time interval minus the temperature below which growth is zero: 12 °C for GHSB [34].

F_{ch} (as a % of F_s) was estimated as a function of the fish body weight (*BW*, in g) and pellet size (P_s, in mm) according to the model of Ballester-Moltó et al. [32], as follows:

$$F_{ch} = -3.9074 + 1.3869 \cdot P_s + 0.0029 \cdot BW \cdot P_s\ \rightarrow\ \left(\text{Adj. R}^2 = 0.89\right) \tag{5}$$

This model can provide negative values when pellets and/or fish are too small. In this case, F_{ch} is assumed to be zero [32].

F_i should be digested before the fish utilize it for *G* and maintenance. The undigested fraction is eliminated as feces (*F*) and can be estimated using the method of Cho and Bureau [26], as follows:

$$F = F_i \cdot (100 - ADC\ \%) \tag{6}$$

where *ADC* is the apparent digestibility coefficient. The digestibility of nutrients is species-specific and depends on their content in the diet and the bioavailability of said nutrients [19]. The digestibility of fish diets of different origins can therefore provide different digestibility values. In addition, for some fish species, digestibility tends to increase slightly as the fish grow [35]. However, Ballester-Moltó et al. did not find significant changes in the digestibility of elemental nutrients (C, N, and P) throughout the development of GHSB fed with commercial feeds [36]; therefore, we used the total C, N, and P *ADC* coefficients from these authors (Table 1) for the *F* estimates.

DW was solved from Equation (1) as follows:

$$DW = F_i - (G + F) \tag{7}$$

Table 1. Simulation conditions to estimate the gross waste output and temporal pattern in GHSB farming. (BW_i: mean initial weight; BW_f: mean final weight; TN, TC, and TP: total nitrogen, carbon, and phosphorus content, respectively; d.m.: dry matter; ADC: apparent digestibility coefficient).

BW_i (g)	BW_f (g)	Annual Harvest (Tons)	Num. Fish Inputs Per Year	Num. Fish Per Input	Pellet Sizes Per Fish Weight Range *	Feed Composition (% d.m.) **			GHSB Carcass Composition (% d.m.) **			ADC (%) **		
						TC	TN	TP	TC	TN	TP	TC	TN	TP
									55.5	8.4	1.7	88.7	95.9	71.4
20	500	1500	S1: 4	S1: 750,000	20–70 g: 2 mm	48.6	8.7	0.8						
20	500	1500	† S2: 1	S2: 3,000,000	71–220 g: 4 mm	50.1	8.9	0.7						
					221–500 g: 6 mm	52.2	8.4	0.8						

* As provided in commercial feeding charts. ** Data from Ballester-Moltó et al. [36]. † Because of fallowing in S2, fish input and harvests occur every two years.

2.2. Simulation Conditions

We performed simulations of the gross and temporal pattern waste output produced by GHSB farming in the form of total carbon (TC), total nitrogen (TN), and total phosphorus (TP) under two scenarios: (S1), stepped fish input, and (S2), all in/all out with a fallowing period of 8 months. We performed simulations for an annual production of around 1500 tons over a 4-year time period. The sizes of feed pellets based on the weight range of the fish are presented in Table 1, as are their content in TC, TN, and TP, *ADC* values, fish carcass composition [36], and other simulation conditions. To compare both strategies, gross waste output was estimated on a yearly basis for the duration of a full production cycle starting in April once production was stabilized. In S1, four fish inputs are carried out sequentially throughout the year. Fish of different ages (size) are therefore present within the farm at any given time. The dates of fish entry—four per year—were set according to a schedule resembling the Mediterranean GHSB stock management farming conditions [37]—i.e., in April, June, August, and September for a culture length of 16, 15, 15, and 17 months, respectively—predicted according to Mayer et al. [33]. The temperature regime is shown in Figure 1. In this system, the fish are harvested sequentially as different batches reach commercial size (500 g mean final weight). In S2, all of the fish needed to reach the required production quota enter the farm on the same date (in April). A fallowing period of 8 months was set between harvest and the following entry in April and was set within 2 years from the previous input date. At the end of each production cycle, all of the fish are harvested upon reaching commercial size.

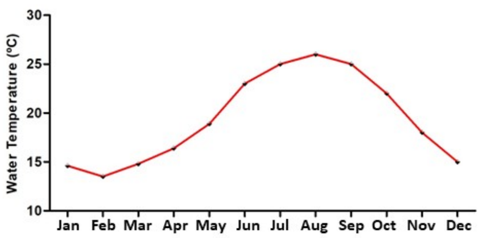

Figure 1. Water temperature regime used for simulations.

3. Results

3.1. Feed Supplied and Stocked Biomass

The simulations of both strategies started at the beginning of the farming period (April year 1). Table S1 (in Supplementary Materials) shows the evolution of the biomass of the different batches, the biomass harvested at the end of each production cycle, and the cumulative biomass of both strategies. These simulations show that the F_s and stocked biomass (Figure 2A,B) increase gradually in both strategies. However, both the F_s and stocked biomass are higher in S2 up until the end of the first production cycle (end of July year 2). At this point, all of the stock is harvested in S2, while only a quarter of the stock is harvested in S1. In the following 8 months (August year 2 to April year 3), the F_s and fish biomass equal zero in S2 because of fallowing; In S1, the F_s and fish biomass ranges are 70–465 and 570–1150 tons/month, respectively, with ups and downs resulting from the successive fish inputs and harvests that are characteristic of this strategy during this period. Once production stabilizes in S1 (from year 2), F_s remains within the range of 70–470 tons month^{-1} indefinitely, and stocked biomass stays within the range of 570–1260 tons month^{-1}, provided that the fish input and harvesting schedule are maintained within the simulation conditions. In S2, the stocked biomass increases from 60 tons on the fish-input date to a final biomass production of 1500 tons 16 months later; the F_s increases from 25 to 517 tons/month and follows the temporal patterns shown in Figure 2A,B.

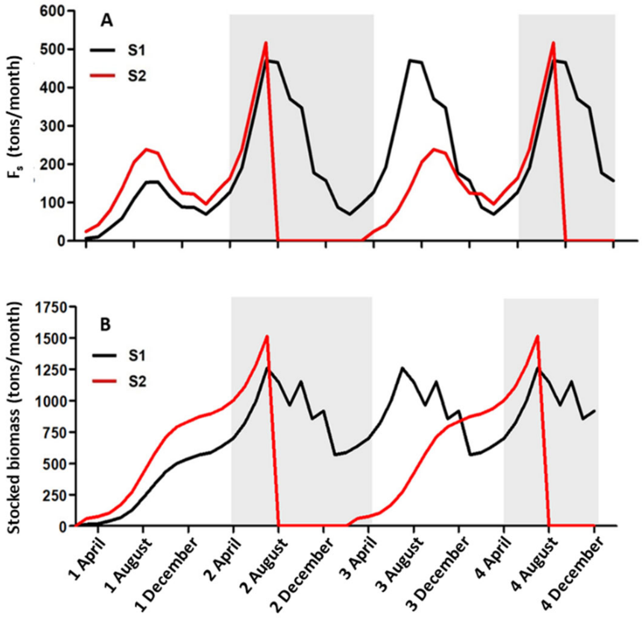

Figure 2. (**A**) Variation in the feed supplied (F_s) and (**B**) stocked biomass over time for both production strategies according to simulation conditions. S1: stepped inputs and harvests; S2: all in/all out.

In line with the simulation conditions, the temporal pattern shows that that the maximum F_s and stocked biomass occur in July in both strategies. In S1, minimum F_s and stocked biomass occur in January, while in S2, both equal zero for 8 months. In both strategies, F_s decreases during the winter months, and then gradually increases as the water temperature does.

3.2. Gross Waste Output

The annual gross waste production for the first year is higher in S2 than it is in S1 for all waste fractions and nutrients (Table 2). Thereafter, the waste discharge becomes higher in S1 for all waste fractions and nutrients and continues to be higher provided that the same farming conditions are maintained (Figure 3A–C). In the years in which fallowing takes place in S2 (even years for the simulation conditions), the gross annual waste production decreases for all nutrients and waste fractions. Then, during the first year of each production cycle (odd years for the simulation conditions), the differences between S1 and S2 become more marked, namely 12–16% higher in S1 than in S2.

Table 2. Differences in % between S1 and S2 regarding gross annual waste output for each waste fraction and nutrient.

		Feces (*F*)			Feed Lost by Chewing (F_{ch})			Dissolved Waste (*DW*)		
		C	**N**	**P**	**C**	**N**	**P**	**C**	**N**	**P**
S1 < S2	Year 1	38.17	37.52	38.51	58.89	58.12	58.65	38.81	37.85	42.15
S1 > S2	Year 2	55.90	57.23	56.07	35.30	35.96	35.32	54.47	56.37	49.74
S1 > S2	Year 3	43.89	41.52	43.18	61.98	61.45	62.07	44.80	41.71	46.31
S1 > S2	Year 4	55.90	57.23	56.07	35.30	35.96	35.32	54.47	56.37	49.74
S1 > S2	...	43.89	41.52	43.18	61.98	61.45	62.07	44.80	41.71	46.31

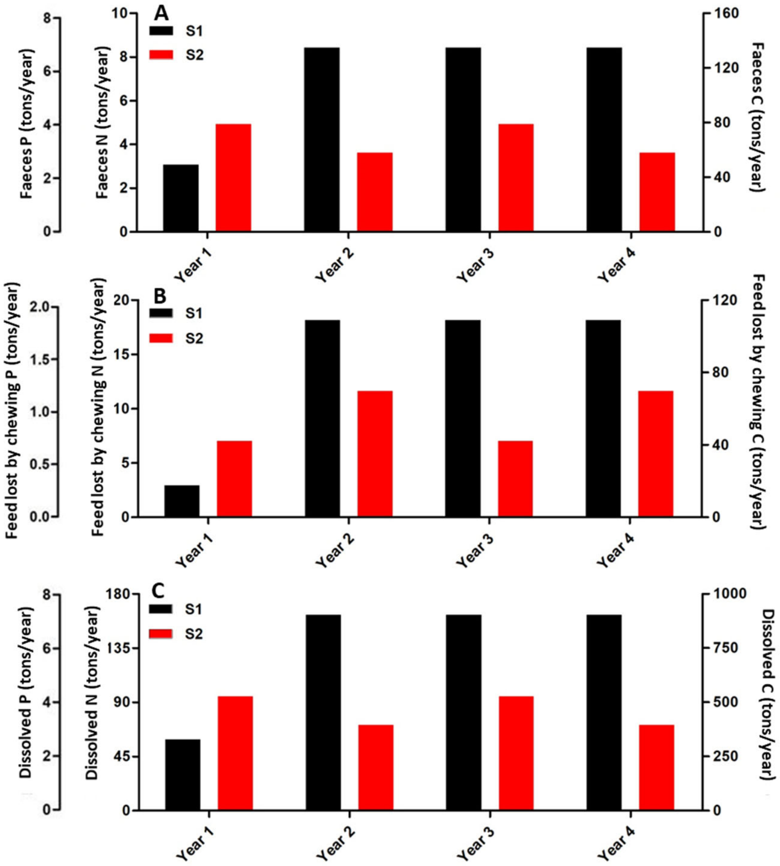

Figure 3. Annual gross C, N, and P waste production in different waste fractions for both production strategies (S1: stepped inputs and harvests; S2: all in/all out). (**A**) feces (*F*); (**B**) feed lost by chewing (F_{ch}); (**C**) dissolved wastes (*DW*).

In both strategies, *DW* is the greatest waste fraction (Figure 3C). In S1, once husbandry stabilizes (midsecond year), the annual gross *DW* output is 863, 163, and 6 tons year^{-1} for C, N, and P, respectively. In S2, the maximum *DW* download is 476, 95, and 3 tons year^{-1} for C, N, and P, respectively. This occurs during the first year of each production cycle.

Regarding particulate waste, the most abundant waste fraction differs depending on the nutrient, but regardless of the farming strategy (Figure 3A,B), there is more C and P waste in *F* (S1: 141 and 7 tons/year of C and P, respectively; S2: 79 and 3 tons/year of C and P, respectively) than in F_{ch} (S1: 111 and 2 tons/year of C and P, respectively; S2: 71 and 1 tons/year of C and P, respectively), whereas the opposite is true for N waste, with F_{ch} experiencing more N waste (S1: 18 tons/year of N; S2: 11 tons/year of N) than *F* (S1:

8 tons/year of N; S2: 5 tons/year of N). In year 1, the differences between S1 and S2 are particularly noticeable for the three nutrients in F_{ch}, with S2 having concentrations that are about 60% higher (Figure 3B; Table 1).

3.3. Waste Output Temporal Pattern

The Simulations revealed a temporal pattern in the waste output (Figure 4A–C) that was related to fluctuations in F_s and in the stocked biomass (Figure 2A,B). Quantitatively, nutrient release was lower in S1 than it was in S2 for all of the waste fractions throughout the first production cycle. The waste output is only higher in S1 than in S2 at the beginning of the fallowing period and at the end of the winter period before the next production cycle in S2. From then on, and during the rest of the second part of the production cycle, waste production is higher in S2 than it is in S1 (Figure 4A–C).

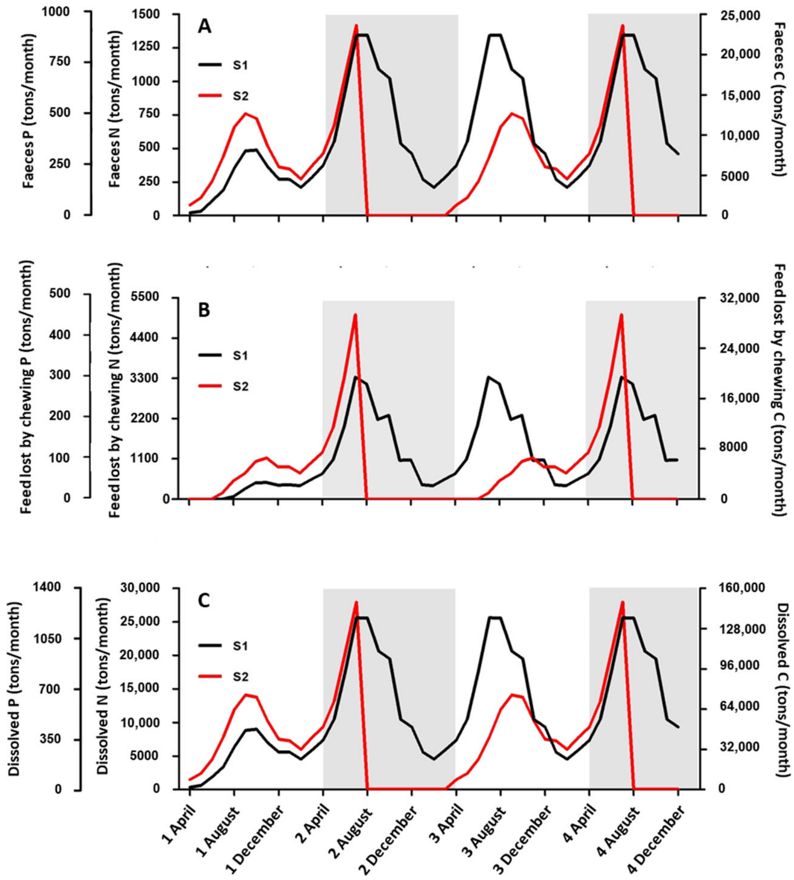

Figure 4. Temporal waste output pattern of C, N, and P in different waste fractions for both production strategies (S1: stepped inputs and harvests; S2: all in/all out). (**A**) feces (F); (**B**) feed lost by chewing (F_{ch}); (**C**) dissolved wastes (DW).

The range of nutrient release per waste fraction for both farming strategies is presented in Table 3. According to the simulation conditions, maximum waste discharge occurs during the summer months for all waste fractions and nutrients in both strategies. In S1, waste output is also relevant during early autumn (Figure 4A–C); during the winter months, the waste discharge experiences a significant reduction until minimum values are reached (Figure 4A–C). In S2, minimum waste release occurs during the fallowing periods, as expected. Modelling showed the most obvious differences between both farming strategies in F_{ch}, which were noticeably higher (about 30%) for S2 at the end of its production cycle (in the summers of even years during the simulation; Figure 4B).

Table 3. Range of nutrient release (kg/month^{-1}) and month in which minimum and maximum output were reached for different waste fractions in both farming strategies once production stabilized. For S2, minimum and maximum nutrient release occurred in even years under simulation conditions.

		Feces (F)		Feed Lost by Chewing (F_{ch})		Dissolved Wastes (DW)	
		Min. (February)	**Max. (July)**	**Min. (February)**	**Max. (July)**	**Min. (February)**	**Max. (July)**
S1	C	3.460	22.846	2.230	20.525	24.352	138.528
	N	209	1.343	368	3.335	4.528	25.620
	P	137	914	35	322	251	961
		Min. (August–April)	**Max. (July)**	**Min. (August–April)**	**Max. (July)**	**Min. (August–April)**	**Max. (July)**
S2	C	0	24.461	0	31.163	0	154.740
	N	0	1.418	0	5.046	0	27.942
	P	0	971	0	489	0	1.217

4. Discussion

By coupling growth, feeding, and chewing models with digestibility coefficients into a mass balance model, we resolved gross waste production and temporal pattern issues and compared GHSB farming strategies. The simulations revealed noteworthy differences in waste output in relation to production planning, which should be considered for the environmental management of the Mediterranean aquaculture industry, particularly in scenarios adapting to more efficient commercial strategies and climate change. Once again, modelling has proven itself as a useful tool that can be implemented to understand aquaculture processes [38]. Waste outputs largely depend on the nutrient composition of the feed, fish requirements, feed utilization, husbandry practices, and stock management [19,28,39,40]. New parameters of these variables that are more adjusted to particular farming conditions or that are related to new feed formulations can shift the final output of the different waste fractions; however, the usefulness of the model employed in the present work to make comparisons remains intact.

Our simulations revealed that the main driver of gross waste output estimation and to determine its temporal pattern is the stocked biomass at any time. Fish biomass varies over time because of fish growth; thus, changes in the stocked biomass also vary depending on the fish-size distribution frequency in the farm, which was different between the two farming strategies compared herein. Moreover, fish growth strongly depends on water temperature; therefore, the water temperature regime at a given location indirectly influences the waste output temporal pattern, with minimum and maximum discharge occurring during the coldest and warmest months, respectively. Differences among S1 and S2 in relation to the stocked biomass over time mirror their differences in terms of gross waste production and their temporal pattern. However, other issues related to farming strategy not only strongly influence waste output quantitatively, but also qualitatively; this is the case for the F_{ch} fraction and the differences caused by the fallowing period.

For GHSB, the amount of F_{ch} is directly related to the fish size and the pellet size [32]. Our results show that F_{ch} is always larger in S2, especially during the last 3–4 months of the growing cycle, when all of the growing fish are larger in size and fed with larger pellets. Conversely, in S1, the portion of the population composed of large fish fed with large pellets is considerably smaller, resulting in the F_{ch} fraction being smaller, too. The most relevant environmental consequence of cage fish farming is the organic enrichment of the seabed in the vicinity of the farm, which is mostly caused by accumulation of supplied but uneaten feed and feces [41,42], especially below the cages [43]. In the case of GHSB, the fraction corresponding to F_{ch} should be added to the solid waste budget [18]. The uneaten feed fraction is difficult to estimate since this depends on the on-farm feeding methods [16]. On the one hand, this fraction of solid wastes can only be reduced by improving feeding control through precision fish farming [44]. On the other hand, the F_{ch} fraction in GHSB cultures can only be minimized by changing the pellet size management, which was previously suggested by Ballester-Moltó et al. [32]. Both precision farming—emerging technologies and automated systems—and alternative feeding regimes—smaller pellets for the largest fish—are strongly recommended for GHSB farming to minimize its environmental footprint [20,21], and are recommended even more so if S2-type stock management is planned.

In the present work, the S2 strategy included a fallowing period of 8 months. A farm using this strategy would produce no waste during this time. Conversely, a farm employing an S1-type strategy would discharge waste during those 8 months. Fallowing is a management action with a dual objective: (i) to prevent/reduce the impact on the receiving environment [9,14,15] and (ii) to break the life cycle of diseases and parasites [11,12,45]. Both potential benefits can increase long-term farm productivity and sustainability [46]. From an environmental impact point of view, a full recovery of the receiving environment (the seabed being the main compartment that is affected) after the complete abatement of farming activity would be expected after some time—from months to years—although this process is not regularly monitored [14]. From a sustainability perspective, a periodic abatement between farming cycles would ensure the assimilation capacity of the environment, supporting long-term farming operations [15]; full environmental recovery, however, would not be expected. Moreover, cumulative deterioration could occur, and a loss of the functional capacity to assimilate the waste could put the continuity aquacultural activity at risk [47], regardless of the farming strategy. Because of the absence of production breaks in the S1-type farming strategy and the consequent continuous supply of organic matter and nutrients, the risk of the ecological capacity of the system collapsing could be higher compared to S2.

Regarding fish health, fallowing has been proven to be a useful tool that can be implemented to manage the spread of infections and diseases [11]. However, implementing this procedure is complex in areas where cage aquaculture has expanded since disease propagation can easily occur at the local level [48–50], making synchronization necessary among farms [11]. In Mediterranean countries, no fallowing period has been set, and virtually all GHSB farms operate under an S1-type strategy. This is probably the reason why general health status of the fish produced in Mediterranean cage fish farms, and that of the GHSB in particular, has deteriorated over the last decade [51], with sustained outbreaks of parasitic infestations of *Sparycotyle chrysophrii* and a high incidence of nodavirus (VER-VNN) infections [52]. These pathologies, which could actually be considered as chronic, lead to a considerable decrease in the performance and profitability of aquaculture farms. The management of fish health is a matter of concern for the Mediterranean aquaculture industry, as losses due to diseases are increasing [51]. Consequently, S2-type strategies with synchronized fallowing periods should be encouraged.

The fallowing duration depends on its goal. For Norwich pisciculture, Black et al. suggested a period of a few weeks between rearing cycles when the intention was to break the life cycle of pathogens, and much longer stops (one or more years) when the aim was to reduce the impact on the seabed to allow it to recover [10]. In Scotland, a routine sanitary fallowing of 4 weeks was recommended between successive rearing cycles, and longer periods (up to 6 months) were recommended if a notifiable disease was detected [12]. In Australia, a fallowing length of 3 months is regularly used [47] despite the lack of legislative requirements. Given that both the recovery capacity of the environment and disease transmission are site-specific [11,14], determining an effective duration for the fallowing period is challenging and can result in a period of time that is either too risky or too cautious. In many cases, the fallowing duration is largely at the discretion of the farm manager [47].

The chosen production strategy can also serve as a mechanism through which fish farms can adapt to the effects of climate change. In the case of GHSB growing in cage farms in the Mediterranean, sea water warming will enhance the growth rate, and the fish will reach commercial size faster, provided that the upper temperature tolerance threshold is not exceeded [37,53]. However, the increased temperature is expected to favor the spread of parasites and diseases and may even result in the emergence of new ones. This would have a strong negative effect on farming performance, forcing producers to use more chemotherapeutants to alleviate these detrimental effects. Hence, the adoption of farming strategies that include fallowing periods—such as S2-type strategies—would allow for better adaptation to global warming.

Wherever a marine farm is placed, the seabed will experience an impact. The seabed will never return to its original condition unless the activity ceases definitively; even so, the unpredictability of ecological succession phenomena makes it impossible to guarantee that the exact same state that existed before will be reached. Production strategies and husbandry practices must contribute to minimizing any affection in the environment, preserving its functionality and capacity to assimilate to the impacts for a long period while maintaining fish welfare and obtaining profitability. To achieve this, the carrying capacity of the farming area must be estimated with certainty in advance, and the producers must commit to the best aquaculture practices. Carrying capacity is site-specific and depends on a variety of physical, production, environmental, and social variables [54], and coupling it with our modelling would be very useful.

An S2-type strategy is in line with the salmon business model. The trend of this industry has been to reduce the number of companies while increasing production [12]. As a consequence, most of the remaining companies are growing, resulting in a greater number of farms. The Mediterranean fish industry is experiencing a similar evolution [55]. This type of business structure allows for the undertaking of a global S1-type strategy in which each separate farm follows an S2-type strategy: each single farm completely fills its facilities on a different date, so the company has products available throughout the year. Thus, the fallowing period at each individual farm can be longer—from the complete emptying of fish to the next input on the same date as the previous cycle—so that companies can satisfy both environmental and health requirements, becoming more sustainable.

In conclusion, a change is needed in the business model of the Mediterranean fish farming industry, adopting production strategies that enable better environmental and fish health management. This can be achieved with S2-type strategies, which will help to improve both profitability and sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14050788/s1. Table S1: Changes in the biomass each fish batch over time according to the input date, biomass harvested at the end of each production cycle (in red), and cumulative stocked biomass. Biomass in tons. Fish input dates are at the beginning of the months in red.

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References

1. Food and Agriculture Organization (FAO). *The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals*; FAO: Rome, Italy, 2018; Available online: http://www.fao.org/3/i9540en/i9540en.pdf (accessed on 22 October 2021).
2. Ahmed, N.; Thompson, S. The blue dimensions of aquaculture: A global synthesis. *Sci. Total Environ.* **2019**, *652*, 851–861. [CrossRef] [PubMed]
3. Food and Agriculture Organization (FAO). FAO's Blue Growth Initiative and aquaculture. In Proceedings of the Eight Session of the Committee on Fisheries, Sub-Committee on Aquaculture (COFI:AQ/VIII/2015/7), Brasilia, Brazil, 5–9 October 2015. Available online: http://www.fao.org/3/a-i5191t.pdf (accessed on 22 October 2021).
4. Food and Agriculture Organization (FAO). *The 2030 Agenda and the Sustainable Development Goals: The Challenge for Aquaculture Development and Management*; FIAA/C1141; FAO Fisheries and Aquaculture: Rome, Italy, 2017; Available online: http://www.fao.org/cofi/38663-0a3e5c407f3fb23a0e1a3a4fa62d7420c.pdf (accessed on 22 October 2021).
5. Gasca-Leyva, E.; León, C.J.; Hernández, J.M.; Vergara, J.M. Bioeconomic analysis of production location of sea bream (*Sparus aurata*) cultivation. *Aquaculture* **2002**, *213*, 219–232. [CrossRef]
6. APROMAR. Informe La Acuicultura en España 2019. 2019. Available online: http://apromar.es/sites/default/files/2019/InformeAcui/APROMAR%20Informe%20ACUICULTURA%202019%20v-1-2.pdf (accessed on 1 April 2021).
7. Massa, F.; Onofri, L.; Fezzardi, D. Aquaculture in the Mediterranean and Black Sea: A Blue Growth perspective. In *Handbook of the Economics and Management of Sustainable Oceans*; Social and Political Science Collection; Nunes, P.A.L.D., Svensson, L.E., Markandya, A., Eds.; Edward Elgar Publishing: Cheltenham, UK, 2017; Chapter 4; pp. 93–123.
8. Federation of European Aquaculture Producers (FEAP). Annual Report 2017. 2017. Available online: https://issuu.com/feapsec/docs/feap_ar2017 (accessed on 22 October 2021).
9. Carroll, M.L.; Cochrane, S.; Fieler, R.; Velvin, R.; White, P. Organic enrichment of sediments from salmon farming in Norway: Environmental factors, management practices, and monitoring techniques. *Aquaculture* **2003**, *226*, 165–180. [CrossRef]
10. Black, K.; Hansen, P.K.; Holmer, M. Salmon Aquaculture Dialogue: Working Group Report on Benthic Impacts and Farm Sitting. 2008, p. 53. Available online: https://www.researchgate.net/publication/228874660_Salmon_Aquaculture_Dialogue_Working_Group_Report_on_Benthic_Impacts_and_Farm_Siting (accessed on 22 October 2021).
11. Werkman, M.; Green, D.M.; Murray, A.G.; Turnbull, J.F. The effectiveness of fallowing strategies in disease control in salmon aquaculture assessed with an SIS model. *Prev. Vet. Med.* **2011**, *98*, 64–73. [CrossRef]
12. Ellis, T.; Turnbull, J.F.; Knowles, T.G.; Lines, J.A.; Auchterlonie, N.A. Trends during development of Scottish salmon farming: An example of sustainable intensification? *Aquaculture* **2016**, *458*, 82–99. [CrossRef]
13. Marine Harvest. Salmon Farming Industry Handbook. 2018, p. 113. Available online: http://marineharvest.no/globalassets/investors/handbook/2018-salmon-industry-handbook.pdf (accessed on 22 October 2021).
14. Aguado-Giménez, F.; Piedecausa, M.A.; Gutiérrez, J.M.; García-Charton, J.A.; Belmonte, A.; García-García, B. Benthic recovery after fish farming cessation: A "beyond-BACI" approach. *Mar. Pollut. Bull.* **2012**, *64*, 729–738. [CrossRef]
15. Zhulay, I.; Reiss, K.; Reiss, H. Effects of aquaculture fallowing on the recovery of macrofauna communities. *Mar. Pollut. Bull.* **2015**, *97*, 381–390. [CrossRef]
16. García-García, B.; Rosique-Jiménez, C.; Aguado-Giménez, F.; García-García, J. Life cycle assessment of gilthead seabream (*Sparus aurata)* production in offshore fish farms. *Sustainability* **2016**, *8*, 1228–1237. [CrossRef]
17. García-García, B.; Rosique-Jiménez, C.; Aguado-Giménez, F.; García-García, J. Life cycle assessment of seabass (*Dicentrarchus labrax*) produced in offshore fish farms: Variability and multiple regression analysis. *Sustainability* **2019**, *11*, 3523. [CrossRef]
18. Ballester-Moltó, M.; Sánchez-Jerez, P.; Cerezo-Valverde, J.; Aguado-Giménez, F. Particulate waste outflow from fish farming cages. How much is uneaten feed? *Mar. Poll. Bull.* **2017**, *119*, 23–30. [CrossRef]
19. Bureau, D.P.; Hua, K. Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. *Aquac. Res.* **2010**, *41*, 777–792. [CrossRef]
20. Aguado-Giménez, F. *Practical Recommendations to Improve Feed Supply in Gilthead Seabream (Sparus aurata) On-Growing in Floating Cages*; Training and Technology Transfer Service—Council of Water, Agriculture, Livestock and Fisheries—Autonomous Community of the Region of Murcia: Murcia, Spain, 2019; p. 49. Available online: http://www.carm.es/web/pagina?IDCONTENIDO=63006&IDTIPO=100&RASTRO=c2889$m58245,58256 (accessed on 16 April 2021). (In Spanish)
21. Aguado-Giménez, F. Effect of Feed Delivery Rate and Pellet Size on Rearing Performance, Feed Wastage and Economic Profitability in Gilthead Seabream (*Sparus aurata*) Ongrowing. *Water* **2020**, *12*, 954. [CrossRef]
22. Sanchez-Jerez, P.; Karakassis, I.; Massa, F.; Fezzardi, D.; Aguilar-Manjarrez, J.; Soto, D.; Chapela, R.; Avila, P.; Macias, J.C.; Tomassetti, P.; et al. Aquaculture's struggle for space: The need for coastal spatial planning and the potential benefits of Allocated Zones for Aquaculture (AZAs) to avoid conflict and promote sustainability. *Aquac. Environ. Interact.* **2016**, *8*, 41–54. [CrossRef]
23. Fernandes, T.F.; Eleftheriou, A.; Ackefors, H.; Eleftheriou, M.; Ervik, A.; Sanchez-Mata, A.; Scanlon, T.; White, P.; Cochrane, S.; Pearson, T.H.; et al. Read The scientific principles underlying the monitoring of the environmental impacts of aquaculture. *J. Appl. Ichthyol.* **2001**, *17*, 181–193. [CrossRef]
24. White, K.; O'Neill, B.; Tzankova, Z. At a Crossroads: Will Aquaculture Fulfill the Promise of the Blue Revolution? *Aquaculture Clearinghouse Report.* 2004. Available online: https://www.researchgate.net/publication/255584452_At_a_Crossroads_Will_Aquaculture_Fulfill_the_Promise_of_the_Blue_Revolution (accessed on 22 October 2021).

25. Aguado-Gimenez, F.; Garcia-Garcia, B.; Hernandez-Lorente, M.D.; Cerezo-Valverde, J. Gross metabolic waste output estimates using a nutritional approach in Atlantic bluefin tuna (*Thunnus thynnus*) under intensive fattening conditions in western Mediterranean Sea. *Aquac. Res.* **2006**, *37*, 1254–1258. [CrossRef]
26. Cho, C.Y.; Bureau, D.P. Development of bioenergetic models and the Fish-PrFEQ software to estimate production, feeding ration and waste output in aquaculture. *Aquat. Living Resour.* **1998**, *11*, 199–210. [CrossRef]
27. Lupatsch, I.; Kissil, G.W. Predicting aquaculture waste from gilthead seabream (*Sparus aurata*) culture using a nutritional approach. *Aquat. Living Resour.* **1998**, *11*, 265–268. [CrossRef]
28. Piedecausa, M.A.; Aguado-Giménez, F.; Cerezo Valverde, J.; Hernández, M.D.; García García, B. Simulating the temporal pattern of waste production in farmed gilthead seabream (*Sparus aurata*), European seabass (*Dicentrarchus labrax*) and Atlantic bluefin tuna (*Thunnus thynnus*). *Ecol. Model.* **2010**, *221*, 634–640. [CrossRef]
29. Martins, C.I.M.; Galhardo, L.; Noble, C.; Damsgård, B.; Spedicato, M.T.; Zupa, W.; Beauchaud, M.; Kulczykowska, E.; Massabuau, J.-C.; Carter, T.; et al. Behavioural indicators of welfare in farmed fish. *Fish Physiol. Biochem.* **2012**, *38*, 17–41. [CrossRef]
30. Andrew, J.E.; Anras, M.L.B.; Kadri, S.; Holm, J.; Huntingford, F.A. Feeding Responses of Hatchery-Reared Gilthead Sea Bream (*Sparus aurata* L.) to a Commercial Diet and Natural Prey Items. *Mar. Freshw. Behav. Physiol.* **2003**, *36*, 77–86. [CrossRef]
31. Andrew, J.E.; Holm, J.; Huntingford, F.A. The effect of pellet texture on the feeding behaviour of gilthead sea bream (*Sparus aurata* L.). *Aquaculture* **2004**, *232*, 471–479. [CrossRef]
32. Ballester-Moltó, M.; Sánchez-Jerez, P.; García-García, B.; García-García, J.; Cerezo-Valverde, J.; Aguado-Giménez, F. Controlling feed losses by chewing in gilthead sea bream (*Sparus aurata*) ongrowing may improve the fish farming environmental sustainability. *Aquaculture* **2016**, *464*, 111–116. [CrossRef]
33. Mayer, P.; Estruch, V.D.; Jover, M. A two-stage growth model for gilthead sea bream (*Sparus aurata*) based on the thermal growth coefficient. *Aquaculture* **2012**, *358–359*, 6–13. [CrossRef]
34. Mayer, P.; Estruch-Fuster, V.D.; Blasco, J.; Jover, M. Predicting the growth of gilthead sea bream (*Sparus aurata* L.) farmed in marine cages under real production conditions using temperature- and time-dependent models. *Aquac. Res.* **2008**, *39*, 1046–1052. [CrossRef]
35. Guillaume, J.; Kaushik, S.; Bergot, P.; Métailler, R. *Nutrition and Feeding of Fish and Crustaceans*; Food Sciences Series; Springer: London, UK, 2002; p. 408.
36. Ballester-Moltó, M.; Follana-Berná, G.; Sanchez-Jerez, P.; Aguado-Giménez, F. Total nitrogen, carbon and phosphorus digestibility in gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*) fed with conventional and organic commercial feeds. Implications for particulate waste production. *Aquac. Res.* **2016**, *48*, 3450–3463. [CrossRef]
37. Stavrakidis-Zachou, O.; Lika, K.; Anastasiadis, P.; Papandroulakis, N. Projecting climatic change impacts on Mediterranean finfish production: A case study in Greece. *Clim. Change* **2021**, *165*, 67–85. [CrossRef]
38. Chowdhury, M.A.K.; Siddiqui, S.; Hua, K.; Bureau, D.P. Bioenergetics-Based Factorial Model to Determine Feed Requirement and Waste Output of Tilapia Produced under Commercial Conditions. *Aquaculture* **2013**, *410–411*, 138–147. [CrossRef]
39. Islam, M.S. Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: Review and analysis towards model development. *Mar. Poll. Bull.* **2005**, *50*, 48–61. [CrossRef]
40. Chamberlain, J.; Stucchi, D. Simulating the effects of parameter uncertainty on waste model predictions of marine finfish aquaculture. *Aquaculture* **2007**, *272*, 296–311. [CrossRef]
41. Dauvin, J.-C.; Pezy, J.-P.; Baffreau, A.; Bachelet, Q.; Baux, N.; Méar, Y.; Murat, A.; Poizot, E. Effects of a salmon fish farm on benthic habitats in a high-energy hydrodynamic system: The case of the Rade de Cherbourg (English Channel). *Aquaculture* **2020**, *518*, 734832. [CrossRef]
42. White, P. Environmental consequences of poor feed quality and feed management. In *On-Farm Feeding and Feed Management in Aquaculture*; FAO Fisheries and Aquaculture Technical Paper, 583, Hasan, M.R., New, M.B., Eds.; FAO: Rome, Italy, 2013; pp. 553–564.
43. Pusceddu, A.; Fraschetti, S.; Mirto, S.; Holmer, M.; Danovaro, R. Effects of intensive mariculture on sediment biochemistry. *Ecol. Appl.* **2007**, *17*, 1366–1378. [CrossRef] [PubMed]
44. Føre, M.; Frank, K.; Norton, T.; Svendsen, E.; Alfredsen, J.A.; Dempster, T.; Eguiraun, H.; Watson, W.; Stahl, A.; Sunde, L.M.; et al. Precision fish farming: A new framework to improve production in aquaculture. *Biosyst. Eng.* **2017**, *173*, 176–193. [CrossRef]
45. Morton, A.; Routledge, R.D.; Williams, R. Temporal Patterns of Sea Louse Infestation on Wild Pacific Salmon in Relation to the Fallowing of Atlantic Salmon Farms. *N. Am. J. Fish. Manag.* **2005**, *25*, 811–821. [CrossRef]
46. Keeley, N.B.; Forrest, B.M.; Macleod, C.K. Benthic recovery and re-impact responses from salmon farm enrichment: Implications for farm management. *Aquaculture* **2016**, *435*, 412–423. [CrossRef]
47. MacLeod, C.K.; Moltschaniwskyj, N.A.; Crawford, C.M.; Forbes, S.E. Biological recovery from organic enrichment: Some systems cope better than others. *Mar. Ecol. Prog. Ser.* **2007**, *342*, 41–53. [CrossRef]
48. Arechavala-Lopez, P.; Sanchez-Jerez, P.; Bayle-Sempere, J.T.; Uglem, I.; Mladineo, I. Reared fish, farmed escapees and wild fish stocks—A triangle of pathogen transmission of concern to Mediterranean aquaculture management. *Aquac. Environ. Interact.* **2013**, *3*, 153–161. [CrossRef]
49. Qviller, L.; Kristoffersen, A.B.; Lyngstad, T.M.; Lillehaug, A. Infectious Salmon Anemia and Farm-Level Culling Strategies. *Front. Vet. Sci.* **2020**, *6*, 481. [CrossRef]

50. Viljugrein, H.; Staalstrøm, A.; Molvaelr, J.; Urke, H.A.; Jansen, P.A. Integration of hydrodynamics into a statistical model on the spread of pancreas disease (PD) in salmon farming. *Dis. Aquat. Org.* **2009**, *88*, 35–44. [CrossRef]
51. Subasinghe, R.P. Disease control in aquaculture and the responsible use of veterinary drugs and vaccines: The issues, prospects and challenges. In *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture*; Rodgers, C., Basurco, B., Eds.; CIHEAM: Zaragoza, Spain, 2009; pp. 5–11.
52. Muniesa, A.; Basurco, B.; Aguilera, C.; Furones, D.; Reverté, C.; Sanjuan-Vilaplana, A.; Jansen, M.D.; Brun, E.; Tavornpanich, S. Mapping the knowledge of the main diseases affecting seabass and seabream in the Mediterranean. *Transbound. Emerg. Dis.* **2020**, *67*, 1089–1100. [CrossRef]
53. Rosa, R.; Marques, A.; Nunes, M.L. Impact of climate change in Mediterranean aquaculture. *Rev. Aquac.* **2012**, *4*, 163–177. [CrossRef]
54. Ross, L.G.; Telfer, T.C.; Falconer, L.; Soto, D.; Aguilar-Manjarrez, J. (Eds.) Site Selection and Carrying Capacities for Inland and Coastal Aquaculture. In Proceedings of the FAO Fisheries and Aquaculture Proceedings No. 21, Stirling, UK, 6–8 December 2010; FAO: Rome, Italy, 2013; p. 282.
55. EUROFISH Magazine. Greek and Spanish Companies Unite to Become the Largest Aquaculture Producer in the Mediterranean. 2021. Available online: https://eurofishmagazine.com/news/item/782-greek-and-spanish-companies-unite-to-become-the-largest-aquaculture-producer-in-the-mediterranean (accessed on 22 October 2021).