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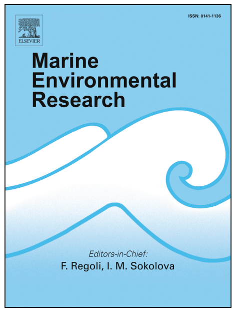

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Consumption of particulate wastes derived from cage fish farming by aggregated wild fish. An experimental approach.

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Abstract

Particulate wastes derived from cage fish farming are a trophic resource used by wild fish. This study assesses waste consumption by wild fish and the impact on the final balance of wastes. Consumption was determined according to the difference between the particulate matter exiting the cages and that reaching 5m away at three different depths, in the presence and absence of wild fish. Wild fish around the experimental cages were counted during feeding and non-feeding periods. A weighted abundance of 1057 fish 1000 m^{-3} consumed 17.75% of the particulate wastes exiting the cages, on average. Consumption was higher below the cages, where waste outflow was greater. However, waste removal by wild fish was noteworthy along the shallow and deep sides of the cages. Wild fish diminished the net particulate wastes by about 14%, transforming them into more easily dispersible and less harmful wastes. This study demonstrates the mitigating potential of wild fish in reducing environmental impact.

1. Introduction

The most important environmental effects of cage fish farming are related to the discharge of dissolved and particulate organic matter deriving from fish metabolism and feeding (Read and Fernandes, 2003). Dissolved waste boosts primary production around the farms (Dalsgaard and Krause-Jensen, 2006); however, in well fluxed areas this effluent does not constitute a threat to the environment because dissolved nutrients are rapidly diffused and assimilated (Pitta et al., 2009, 2005, 1998). In contrast, particulate wastes –such as faeces and wasted feed– settle on the seabed in the vicinity of the farms (Holmer et al., 2007; Pusceddu et al., 2007), misbalancing the benthic environment once assimilative capacity is exceeded (Hargrave et al., 2008, 1997). This input of trophic resources also stimulates biological activity in proximity to the cage facilities, and a number of organisms with different trophic strategies aggregate in and around them, consuming the wastes. Particular examples are biofouling communities attached to the structures (Gonzalez-Silvera et al., 2015), and wild fish in the water column (Ballester-Moltó et al., 2015). The biofiltering potential of fouling has been exploited with the aim of removing wastes by deploying pelagic (Cook et al., 2006; Lojen et al., 2005) and benthic (Aguado-Giménez et al., 2011; Angel et al., 2002; Gao et al., 2008) biofilters around cage farms. Similarly, integrated multitrophic aquaculture (IMTA) is developing on the same basis (Soto, 2009). Nevertheless, both biofiltering and IMTA waste removal effectiveness is poor when applied close to intensive cage fish farming, (Buschmann et al., 2001; Cranford et al., 2013; DFO, 2013) particularly in Mediterranean open-sea conditions (Aguado-Giménez et al., 2014).

Another natural compartment which works as biofilter of particulate wastes derived from fish farming is the aggregated wild fish assemblage it attracts. A profuse gathering of wild fish forms around most cage fish farms around the world (Carss, 1990; Dempster et al., 2004, 2002; Oakes and Pondella, 2009; Özgül and Angel, 2013; Sudirman et al., 2009). Some studies report up to tens of tons of wild fish assembled near cage farms (Dempster et al., 2004; Fernandez-Jover et al., 2008; Sanchez-Jerez et al., 2011). In some cases, the biomass of wild fish exceeds that of the fish being reared (Sudirman et al., 2009). Planktophagous wild fish aggregate close to the cage nets (Bacher et al., 2012; Dempster et al., 2010) where they feed mainly on the excess food delivered to the caged fish (Dempster et al., 2009; Fernandez-Jover et al., 2008; Damian Fernandez-Jover et al., 2007). Interaction of cage fish farming and wild fish is well-known and some authors attribute them the ability to diminish the environmental impact derived from particulate wastes (Dempster et al., 2009, 2005; Fernandez-Jover et al., 2008;

Katz et al., 2002). However, processing of pelleted feed by wild fish aggregated around cage fish farms has not been properly evaluated. Hence, the biofiltering role of wild fish should be assessed because of its potential positive effects, rather than other mitigation tools.

The contribution of wild fish to the recycling of particulate wastes derived from cage fish farming is of concern in the context of an ecosystem approach to aquaculture (Angel and Freeman, 2009). Some estimative approaches have been based on wild fish stomach content (Fernandez-Jover et al., 2008), or under experimental conditions but far from real present-day intensive farming requirements (Felsing et al., 2005; Vita et al., 2004). We hypothesise that ichthyofauna may influence fish-farming derived particulate waste dynamics by reducing the organic discharge through feeding, largely uneaten feed, changing the physicochemical characteristics of the wastes and enhancing dispersibility. It is thus interesting to estimate the contribution of wild fish to the removal of particulate wastes flowing out of culture cages, in order to ascertain the net nutrient balance of the interaction between wild fish and reared fish. The aim of the study was therefore to experimentally assess the ability of the wild fish assemblage to remove particulate wastes under intensive cage-farming conditions. Also, particulate waste output balance including the effect of wild fish on the recycling of wastes is modelled for the main nutrients (nitrogen, carbon and phosphorus; Wu, 1995) involved in marine food webs.

2. Materials and methods

2.1. Contribution of wild fish to the removal of particulate wastes

2.1.1. Sampling particulate wastes

Knowing the amount of particulate wastes exiting the cages, our experimental approach to estimating the consumption of particulate wastes by wild fish is based on the diffusion of solid wastes in the vicinity of the cages, in the absence and presence of wild fish. To do this, we used passive waste samplers (PWSs, as shown in Balleser-Moltó et al., 2017) as a tool to trap particulate wastes flowing out of the cages and also in the water column where wild fish are usually consuming them. PWSs were directly attached to the cage net so that the particulate waste outflow was fully intercepted by the trap while excluding wild fish. PWSs were made in two shapes, depending on which part of the cage they were to be placed: PWSs attached vertically to the bottom of the cage were symmetrical funnel-shaped (PWS_b, in Ballester-Moltó et al., 2017), and those tied horizontally to the cage sides were sloped to avoid sample deposition on PWS walls, while facilitating the flux of particulate matter to the sample container (PWS_s, in Ballester-Moltó et al., 2017).

2.1.2. Experimental setup and calculations

The experimental setup (Figure 1) consisted of three PWSs tied to the cage net at three different depths: one PWS_b attached to the cage bottom vertically, and two PWS_s tethered to the sidewalls netting horizontally. The height of the net sides is divided into two halves, and one PWS_s is located in the middle of each half. Most potential waste-consuming wild fish aggregated around fish-farm cages move within the first metres close to the cage nets (Dempster et al., 2005). Then at a distance of 5 m away from the cage net, the same PWS configuration was deployed, with the homologous PWS_s suspended in the water column from two buoys, and the equivalent PWS_b hanging from the bottom net. To exclude fish from the sample retained in the containers of these PWS_s, a 2 cm mesh plastic net was placed at the final section of the funnel. There was therefore a corridor where wild fish move around the cages between the tied and hanging PWSs. Additionally, to measure the background particulate matter, two PWS_ss and two PWS_bs were suspended in the water column from two buoys, following the same setup as the PWSs fastened to the cage. In order to maximise the sample volume and the sensitivity of the assays, all PWSs faced towards the mainstream. For this, current direction was verified visually before installing the PWSs, and a current meter (Nortek AquaDopp) remained moored at -6 m depth to record current direction and speed (sampling frequency: 15 minutes) throughout the trials duration. Both background PWSs and current meter were attached to the signalling perimeter buoy of the farm lease 150 m upstream, away from the cages.

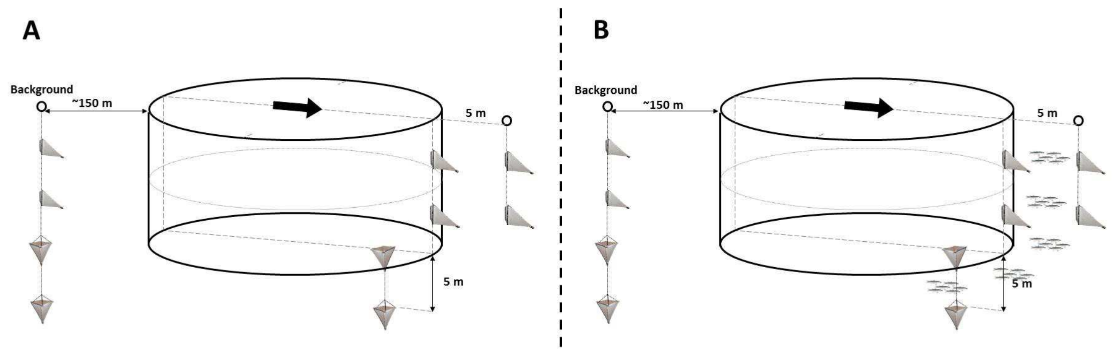

Figure 1: Scheme of the experimental setup. Arrangement of Passive Waste Samplers attached to the cage and in the water column. A) Trials in the absence of wild fish. B) Trials in the presence of wild fish.

This experimental setup was deployed in two Mediterranean gilthead seabream (*Sparus aurata*) cage fish farms during the summer of 2015. The first one is sited 3.2 km off the coast of El Campello (Alicante, SE Spain). This farm was selected because it aggregates a profuse assemblage of wild fish close to the facilities, including several pelagic species consuming wasted feed (Fernandez-Jover et al., 2008). Trials carried out at this farm are used to determine the amount of particulate wastes reaching 5 m away from the cages at three different cage strata in the presence of wild fish. The second farm is located 5.5 km off the coast of San Pedro del Pinatar (Murcia, SE Spain). This farm was selected due to the absence of planktophagous wild fish around it (see below). Trials carried out at this farm were used to determine the natural dispersal of particulate wastes from the cages up to 5 m away at three different cage strata. At both farms, the cages selected to carry out the assays were always in the outermost part of the farm, faced to the main current and with no cages interrupting the stream, minimising the amount of solid wastes from other cages reaching the PWSs. The contribution of wild fish to the consumption of particulate wastes was estimated at the three cage strata, based on the difference between the two trials, after subtracting the respective backgrounds. There were selected only those trials from both fish farms in which the final resulting current direction vector did not deviate more than 45° from the initial orientation of the PWSs, and mean current intensity was similar in the direction at which PWSs were deployed (Table 1).

Table 1: Current direction prevalence and speed in the direction PWSs were faced in both experiments in the absence and presence of wild fish.

	Day	Current direction prevalence (%)	Speed ($m \cdot s^{-1}$)
Absence of wild fish			
Trial 1	1	40.43	0.087 ± 0.009
	2	37.50	0.067 ± 0.008
Trial 2	1	47.92	0.086 ± 0.006
	2	39.58	0.086 ± 0.008
Presence of wild fish			
Trial 3	1	31.82	0.070 ± 0.011
	2	35.42	0.075 ± 0.008
Trial 4	1	35.61	0.077 ± 0.007

	2	43.75	0.086 ± 0.008
Trial 5	1	45.01	0.087 ± 0.007
	2	41.67	0.088 ± 0.010

Trials at both farms were carried out on two consecutive days. The first day, early in the morning, scuba divers assembled the PWSs facing the mainstream (as explained above). After 24 h, sample containers were replaced by empty ones, and after 48 h the containers were finally removed and the setup was disassembled. Samples were cool transported (4 °C) to the laboratory, rinsed with distilled water while being sieved (500 µm) to remove any debris, washed with 0.5 M ammonium formate solution to eliminate marine salt (Albentosa et al., 1996), then centrifuged (5000 rpm at 4 °C for 12 minutes; (Bureau and Cho, 1999) to remove the supernatant. The resulting sample was dried in an oven (105 ± 1 °C up to constant weight, about 24 hours). After this, samples were weighed and particulate matter flux (PMF) flowing out through each depth was expressed as g (dry matter) · m^{-2} · d^{-1} after subtracting the corresponding background. PMF at each depth 5 m away from the cages is expressed as a percentage with respect to the PMF flowing out the cages at each depth. To obtain the removal of particulate wastes by wild fish at each depth, the mean percentage of PMF reaching 5 m away from the cages in the absence of wild fish was subtracted from the percentage of PMF reaching 5 m away in the presence of wild fish.

2.1.3. Visual wild fish counts during the trials

Abundance estimates of aggregated wild fish during trials is necessary in order to attribute the wastes consumed to a particular fish assemblage. For that, abundance of potential fish consumers of particulate wastes issuing from the cages during trials was estimated through underwater visual counts. Censuses were carried out always by the same experienced scuba diver. Each census consisted of 5 min timed counts along a vertical transect from surface to 5 m below the bottom of the cages of those planktophagous fish swimming within a sampling volume of approximately 1000 m^3 (5 m length: from the suspended PWS to the cage; 10 m width: 5 m on each side of the diver; 20 m depth), during feeding and non-feeding periods (n = 4). Daily mean abundance of wild fish was weighted according to the relative duration of feeding (1/24 h) and non-feeding (23/24 h) periods.

2.2. Processing of wasted feed by wild fish

2.2.1. Digestibility of pelleted feed by wild fish

Considering that wild fish mostly exploit the excess feed emanating from the cages, since the nutritional value of faeces from cultured fish is insignificant for omnivorous wild fish (Israel et al. 2014), we first needed to know how wild fish process the wasted feed. For that, we performed digestibility assays with some of the most representative wild fish species aggregated around aquaculture cages in the western Mediterranean: *Mugil cephalus*, *Boops boops*, *Oblada melanura* and *Trachinotus ovatus*. Wild fish were hooked around El Campello fish farm and transported to our experimental facilities. Firstly, fish species were separately stocked in 2000 l tanks (open sea water system) until their adaptation to captivity was perceptible, approximately after two months. Digestibility assays were carried out in 600 l troncoconical tanks with a purge system for faeces collection. Tanks were connected to a recirculating system with biological and mechanical filtration. 20 % of the water volume was renewed daily. Dissolved oxygen was always above 90 % saturation. Water temperature was set at 21 ± 1 °C by using a thermal water conditioning unit, and the photoperiod was 12:12 light:dark.

Three batches of each fish species were fed with a standard conventional gilthead seabream aquafeed. Stocking and experimental conditions, and feed composition are shown in Tables 2 and 3. To minimise stress through handling, they were weighed only when the assays finished. The experimental procedure is described in Ballester-Moltó et al. (2016a). Faeces collection length was extended until the minimum volume of faeces needed for analyses was reached (Table 3). Faeces obtained daily from each batch were pooled, homogenised and freeze-dried (Heto, PowerDry LL3000). Total nitrogen (TN) and carbon (TC) content was determined with an elemental autoanalyser (LECO 932), and total phosphorus (TP) content was analysed spectrophotometrically (AOAC, 1997a), in both *aquafeed* and wild fish faeces. Crude fibre content (Fibertec System 1020 HE; AOAC, 1997b) was used as internal inert marker (Krontveit et al., 2014) for digestibility calculations.

Table 2: Experimental conditions for digestibility assays with wild fish.

	Number of fish per batch (± sem)	Days	Pellet size (mm)	Fish weight (g) ± sem	Fish density (kg · m^{-3}) ± sem
Boops boops	79.00 ± 3.21	11	1.9	12.37 ± 1.13	1.63 ± 0.65
Mugilidae	49.33 ± 0.33	11	4	69.29 ± 0.83	5.70 ± 0.06
Trachinotus ovatus	27.33 ± 0.33	17	4	66.95 ± 2.94	3.05 ± 0.10
Oblada melanura	5.00 ± 0.00	21	6	393.60 ± 32.60	3.28 ± 0.26

Table 3: Approximate composition of *aquafeed* used in the digestibility assays with wild fish.

	Diets		
Pellet size (mm)	1.9	4	6
Crude protein (%)	49.00	46.00	44.00
Crude lipids (%)	16.50	19.00	20.00
Ash (%)	7.20	5.60	5.70
Crude fibre (%)	2.10	3.40	4.50
Moisture (%)	9.08	8.37	7.65

An Apparent Digestibility Coefficient (ADC) was calculated for TN, TC and TP ($ADC_{N\text{-}C\text{-}P}$) for each wild fish species, according to the equation of Maynard & Loosli (1969), and dry matter digestibility (ADC_{dm}) was calculated as a ratio between the inert marker content in diet and faeces (Fernández et al., 2007), as follows:

$ADC_{dm\text{-}N\text{-}C\text{-}P}$ (%) = 100 - [100 · % M_{diet} / % M_{faeces}) · (% N_{faeces} / % N_{diet})], and

ADC_{dm} (%) = 100 - [100 · % M_{diet} / % M_{faeces}),

where M is the inert marker and N is the nutrient (TN, TC or TP).

2.2.2. Modelling the transformation of cage-derived wasted feed due to consumption by wild fish

A simulation was performed to estimate the dry matter (dm), TN, TC and TP particulate wastes generated by the gilthead seabream under culture, considering both the absence and presence of a wild fish assemblage aggregated around the cages. Simulation was based on the rearing conditions during the trials with wild fish, as shown in Table 4. The different fractions of particulate wastes must be estimated, i.e. wasted feed and faeces. Because of deficiencies during feed delivery, a fraction of the feed supplied is unused (F_u) by rearing fish. This fraction is very difficult to know, since it strongly depends on particular feeding operation conditions (Chamberlain and Stucchi, 2007). Normally, it is assumed that 3 % of the feed supplied (F_s) is wasted (Cromey et al., 2002), and we used this value for simulations. Furthermore, gilthead seabream wastes a considerable amount of feed in the form of pellet fragments as a consequence of its chewing behaviour (Andrew et al., 2003). Conversely, the fraction of feed lost by chewing (LbC) can be estimated as a function of feed pellet size (P_s) and fish weight (F_w), as follows (Ballester-Moltó et al., 2016b):

LbC (%) = -3.9074 + 1.3869 · P_s + 0.0029 · P_s · F_w.

Knowing F_s during the trials (Table 4), both fractions of wasted feed, F_u and LbC, are estimated using the suggestions of the above authors. On the other hand, in agreement with Kanyılmaz et al. (2015), the amount of faeces (F) and its nutrient content are estimated using the diet composition data and digestibility values shown in Table 5 (Ballester-Moltó et al., 2016a), as follows:

$$F_{dm\text{-}N\text{-}C\text{-}P} = \text{Supplied feed} \cdot (100 - ADC_{dm\text{-}N\text{-}C\text{-}P}\ (\%) / 100).$$

In this way, the amount of waste in different fractions (F, F_u and LbC) and its nutrient content is estimated for each day of experimentation for each separate cage. Next, assuming that wild fish will consume wasted feed (F_u and LbC) only (Israel et al., 2014), and using their mean waste consumption (as explained in section 2.1.2.), then F production by wild fish is estimated from the digestibility values obtained in section 2.2.1, as explained above.

Table 4: Rearing conditions in the cages where trials were developed.

	Number of fish	Cage diameter (m)	Depth of cage side (m)	Fish weight (g)	Pellet size (mm)	Moisture (%)	Feed supplied (kg wet weight) Day 1	Day 2
Absence of wild fish								
Trial 1	584,000	30.0	10.0	126	4	8.5	1250	1250
Trial 2	623,000	30.0	10.0	13	1.9	9.1	375	375
Presence of wild fish								
Trial 3	94,000	15.5	15.0	270	4.5	8.3	225	225
Trial 4	94,000	15.5	13.5	142	4	8.6	150	150
Trial 5	91,000	15.5	13.0	113	3	8.7	112	50

Table 5: Dry matter, TN, TC and TP content (% dry weight) in gilthead seabream *aquafeed* and their corresponding digestibility coefficients (ADC; % ± standard error), as used for particulate waste output estimates of reared fish (data from Ballester-Moltó et al., 2016a).

	Dry matter	TN	TC	TP
Feed content (% of d.m.)	100 ± 0.0	8.7 ± 0.1	50.3 ± 0.1	0.8 ± 0.0
ADC (%)	84.4 ± 0.0	96.0 ± 0.3	88.7 ± 0.3	71.5 ± 1.5

3. Results

3.1. Wild fish abundance around experimental cages

At the San Pedro del Pinatar farm, abundance of potential particulate-waste consuming wild fish around the experimental cages was always zero. Only a few solitary fish predators were observed, such as *Thunnus thynnus, Lichia amia, Dasyatis pastinaca, Pteromylaeus bovinus* and *Seriola dumerilli*, regardless of feeding events. Conversely, abundance of wild planktophagous fish around experimental cages at El Campello farm was noteworthy: 2137 ± 160 and 1010 ± 130 individuals per 1000 m^3 on average were counted around experimental fish cages during feeding and non-feeding times. The most abundant wild fish species were *Sardinella aurita* (37 %), *Caranx rhonchus* (25 %), *Oblada melanura* (25 %), *Trachurus sp*. (6 %), *Sardinella maderensis* (3 %) and *Trachinotus ovatus* (3%). Other potential particulate-waste consumers, with abundances below 1 %, were *Mugil cephalus*, *Sarpa salpa*, *Diplodus vulgaris*, *Diplodus sargus*, *Diplodus puntazzo* and *Spondyliosoma cantharus*. At this farm, predator wild fish (*Seriola dumerilii, Sphyraena sphyraena, Pomatomus saltatrix* and *Dentex dentex*) were also observed but not included in the analyses. Weighted daily mean wild fish abundance was 1057 ± 203 individuals.

3.2. Wild fish contribution to the removal of particulate wastes

Once the PMF background was subtracted, the proportion of particulate wastes reaching 5 m away relative to the total particulate wastes flowing out the cages (Table 6) was higher in the absence than presence of wild fish. Also, in both cases, this proportion increased with depth. Accordingly, particulate waste consumption by wild fish also increases from the upper cage sides to the bottom. The mean contribution of wild fish to the removal of particulate wastes was about 18 % of the total particulate wastes exiting the cages.

Table 6: Contribution to the removal of particulate wastes at different cage strata by planktophagous wild fish, as estimated from the balance of particulate matter collected in PWS fastened to the cage net and 5 m away.

Depth	Without fish (No-Fi)	With fish (Fi)	Wild fish removal
Upper sidewall	17.17 ± 5.14 %	8.90 ± 2.41 %	8.27 ± 1.79 %
Lower sidewall	30.62 ± 6.75 %	11.07 ± 0.43 %	19.55 ± 2.54 %
Bottom	40.37 ± 16.32 %	14.93 ± 1.59 %	25.43 ± 1.78 %
		Mean	17.75 ± 2.04 %

3.2. Transformation of cage-derived wasted feed after consumption by wild fish

3.2.1. Digestibility trials with wild fish

The widest variability in digestibility was observed for TP, ranging between 34.67 % for *B. boops* and 79.29 % for *O. melanura* (Table 7). TN, TC and dm digestibility were very similar between species, ranging between 95.19 % for *Mugilidae* and 97.06 % for *O. melanura* for TN, between 87.03 % for *O. melanura* and 89.03 % for *T. ovatus* for TC, and between 79.51 % for *B. boops* and 82.78 % for *O. melanura* for dm. To simulate the wastes processing by wild fish, mean digestibility values were used.

Table 8: Apparent digestibility coefficients (mean % ± standard error) of dry matter (ADC_{dm}) total nitrogen (ADC_N), carbon (ADC_C) and phosphorus (ADC_P) in wild fish fed with seabream *aquafeed*.

	Boops boops	*Mugilidae*	*Trachinotus ovatus*	*Oblada melanura*	Mean
ADC_{dm}	79.51 ± 1.18	82.59 ± 0.64	82.51 ± 0.37	82.78 ± 0.37	**81.84 ± 0.85**
ADC_N	96.84 ± 0.41	95.19 ± 0.54	95.71 ± 0.26	97.06 ± 0.28	**96.20 ± 0.45**
ADC_C	88.17 ± 0.29	88.22 ± 0.19	89.03 ± 0.38	87.03 ± 0.29	**88.11 ± 0.41**
ADC_P	34.67 ± 0.29	66.57 ± 0.60	76.32 ± 0.64	79.29 ± 0.88	**64.21 ± 10.21**

3.2.2. Processing of wasted feed by wild fish

As stated above, wild fish aggregated around the experimental farm reduced by 17.75 % the particulate wastes exiting the cages. Balancing this consumption in terms of dm TPW, it diminished by 13.98 % in the presence of wild fish. Likewise, particulate TPW of TN, TC and TP wastes decreased by 34.42 %, 18.23 % and 6.85 %, respectively. F_u and LbC fractions for dm and all nutrients also fell by 61.36 % and 41.89 %, respectively. Conversely, dm, TN, TC and TP of the F fraction increased by 4.31 %, 3.79 %, 4.18 % and 4.95 %, respectively (Figure 2).

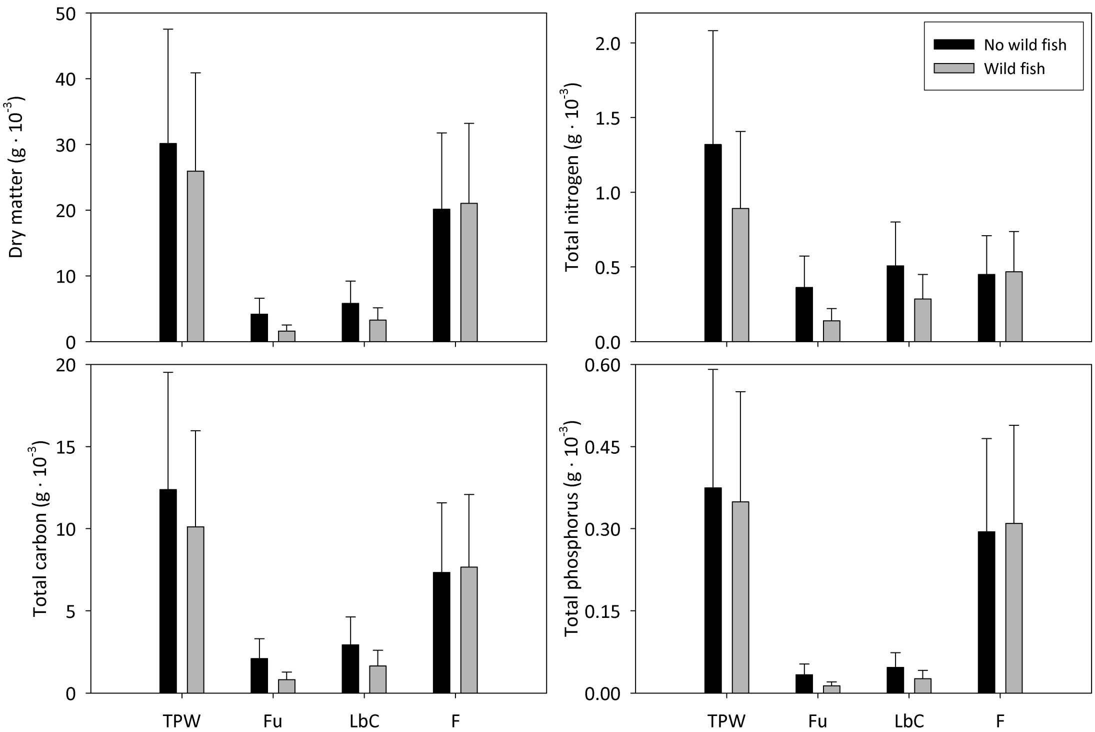

Figure 2: Daily estimates of dry matter, total nitrogen, carbon and phosphorus particulate wastes in their different fractions: TPW: total particulate wastes; F_u: uneaten feed; LbC: feed lost by chewing; F: faeces (TPW = F_u + LbC + F).

4. Discussion

This study shows that the consumption of particulate wastes derived from fish farming by wild fish was substantial: 17.75 % on average of the solid wastes generated under the experimental conditions were removed by aggregated planktophagous wild fish. This contribution varies with depth, so it takes place more markedly around those parts of the cages where wastes flow more intensely, i.e., at the deepest parts of the cages. Digestibility of *aquafeed* by wild fish was very similar to that of reared fish (Ballester-Moltó et al., 2016a). Wild fish diminished total particulate wastes including both F_u and Lbc fractions, while the F fraction increased, as a result of the consumption and assimilation of wasted feed. TN and TC in F_u and Lbc fractions decreased more markedly than TP wastes due to their higher digestibility. Therefore, wild fish aggregated around cage farms act as a natural biofilter diminishing substantially the organic load produced by fish being reared. However, the magnitude of this effect is influenced by wild fish abundance and their trophic level.

Mediterranean fish farms show a wide spatial and temporal variability with regard to wild fish assemblages aggregated around them (Dempster et al., 2002; Fernandez-Jover et al., 2008; Segvić-Bubić et al., 2011; Valle et al., 2007). Among them, there are some farms with a high abundance of planktophagous fish, and others with only small groups or lone predatory fish. Furthermore, some fish farms are home to profuse wild fish assemblages throughout the year (Fernandez-Jover et al., 2008), while in others the abundance decreases markedly during the coldest months (Ballester-Moltó et al., 2015). On the other hand, some farms aggregate wild fish close to the cages either on the surface or mid-water, while in others this occurs near the seabed below the cages (Dempster et al., 2005). Spatial variability has been attributed to coastal geomorphology, seabed topography, distance from the coast, and habitat diversity in the vicinity of the farms (Dempster et al., 2005), while temporal variability seems to be related to seasonal conditions and fish phenology (Ballester-Moltó et al., 2015). Additionally, aggregated wild fish adapt their attendance at the host farm to feeding times (Bacher et al., 2015; Ballester-Moltó et al., 2015). Availability of trophic resources to wild fish around the farms is also highly variable, since it strongly depends on farming intensity and feeding practices (Chamberlain and Stucchi, 2007). Consequently, the extent of the wild fish contribution to removing uneaten feed cannot be generalised and needs to be evaluated on a case by case basis. With regard to temporal variability, Ballester-Moltó et al. (2015) postulated that consumption of wastes by aggregated wild fish during the cold season may be reduced due to their lower intake.

The contribution of wild fish to the removal of solid wastes derived from cage fish farming has been investigated previously by other authors. Vita et al. (2004) estimated wild fish are able to withdraw about 80 % of the particulate organic matter leaving the cages, and Felsing et al. (2005) 40–60 %. These results are notably higher than the average 17.75 % obtained in the present study. Despite their approaches not being truly comparable to ours, we consider that their results overestimate wastes removal. Both authors mentioned above did not take into account waste outflow and removal by wild fish along the cage sides, which can be substantial. Such high contributions also assume a large amount of faeces were consumed by wild fish, which is improbable according to Israel et al. (2014). Nevertheless, differences between the above values and ours could also be due to the huge variability between farming and environmental conditions. In our study, solid waste removal by wild fish was higher close to the bottom of the cages (25.43 %). Notwithstanding, near the surface (8.27 %) and along the cage sidewalls (19.55 %) it was also noteworthy. A spatial segregation of wild fish around the cages occurs depending on their feeding strategy. In the Mediterranean, wild fish assemblages around cage fish farms are dominated by one or a few gregarious species (Dempster et al., 2005, 2002). *Sardinella aurita*, *Caranx rhonchus* and *Oblada melanura* accounted for 87 % of wild fish abundance at El Campello farm, with abundances of 920 individuals per 1000 m^3 on average throughout the day concentrated in the water column around the deepest part of the cages, just where most particulate waste exits the cages (Ballester-Moltó et al., 2017). Other fish species with the same trophic strategy, such as *Trachurus mediterraneaus*, *Sardinella maderensis* and *Trachinotus ovatus*, were found to coexist within the dominant fish shoal foraging on the same resources. Small scattered groups of dominant and scarce species also feed at other cage strata but to a lesser extent. Less abundant fish with different feeding behaviour such as *Mugilidae*, are found at the surface next to the cages sucking the oil and dust emanating from the wasted feed, in agreement with Dempster et al. (2005).

Faeces are the main fraction of solid wastes produced throughout the fish farming process (Bureau and Hua, 2010), however their nutritional value is very low (Bailey and Robertson, 1982; Israel et al., 2014). This waste is exceptionally ingested by wild fish, and in such a case by low trophic level species, mainly herbivores (Robertson, 1982). During our visual counts most planktophagous wild fish rejected faeces, and rarely some outlying *Clupeids* (*Sardinella aurita* and *S. maderensis*) fed on it. The high nutritional value of wasted feed make wild fish prefer it against faeces. Fernandez-Jover et al. (2008) showed that 67–90 % of the stomach contents of aggregated wild fish were pellets, so wasted feed represents the main trophic subsidy from the farms for those fish. These authors estimated that 0.3–10 % of the supplied feed is consumed by wild fish, which is more consistent with our results. Simulations revealed that a considerable proportion of particulate wastes (about 5 g per fish and day, a credible feeding rate equivalent to 2.59 % of the supplied feed, and to 86 % of the F_u fraction (3 %) considered in the simulations) was removed by wild fish. Digestibility assays showed that wild fish use *aquafeed* similarly to reared fish (Ballester-Moltó et al., 2016a). Once the consumption of wasted feed and the production of faeces by wild fish is balanced, a reduction of about 14 % in the particulate organic load is obtained. This reduction was important in terms of TC (18.23 %) and TN (34.42 %), and to a lesser extent for TP (6.85 %), as a result of its poorer digestibility. Additionally, faeces are easier to mineralise by bacteria whilst sinking and once settled on the seabed (Doglioli et al., 2004; D. Fernandez-Jover et al., 2007; Magill et al., 2006; Piedecausa et al., 2009).

Hence, wild fish transform a considerable portion of wasted feed, the most refractory fraction of the waste, into faeces and dissolved excreted products, a more labile and less detrimental waste which can be more easily transported away from the farming area by currents, and also through fish movement in and out of the farm (Chen et al., 2003; Fernandez-Jover et al., 2007; Fernandez-Jover et al., 2008). We demonstrate here that wild fish have a major potential for mitigating environmental impact deriving from the organic enrichment caused by fish farming. Integrated multitrophic aquaculture has been proposed as an alternative to reduce the organic discharge from finfish aquaculture, particularly by culturing bivalve molluscs to reduce suspended particulate wastes (Troell et al., 2003). An arbitrary value of particle capture efficiency to describe the capacity of waste recycling is 50 % (Cranford et al., 2013). These authors remark that mussels are able to remove only 0.9 % to 3.5 % of particles, depending on the current speed. This illustrates their limited biofiltering efficiency, considerably lower than the capacity of wild fish shown in our study. The role of wild fish should be considered in environmental impact assessments. However, in accordance with Dempster et al. (2005), spatio-temporal variability of assemblages and differences in feeding practices between farms make it impossible to predict nutrient dispersal by wild fish prior to knowing the assemblage structure.

Fish species at different trophic levels use excess feed either as a direct trophic resource or indirectly via predation on aggregated prey, and this influence of excess feed on wild fish has been detected in fish captured by local fisheries. Artisanal fishers capture farm-influenced fish at a scale of tens of km from the farm, and therefore, additionally to the biofilter effects of wild fish, there is an indirect exportation of the lost feed into fisheries via wild fish (Izquierdo-Gómez et al., 2014). In any case and in agreement with Dempster et al. (2002), aggregated wild fish around farms should be protected from exploitation by local fisheries because they provide a useful 'ecosystem service' to farmers by reducing the impact of lost feed on the benthos.

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Highlights:

Consumption by wild fish of particulate wastes derived from fish farming is assessed

Experimental and modelling methods were coupled to estimate waste consumption

Wild fish consumed a relevant amount of wasted feed

Wild fish provide an ecosystem service to farmers by reducing environmental impact

Waste removal is difficult to predict due to assemblage spatio-temporal variability