Impact of new measured Mediterranean mineralization rates on the fate of simulated aquaculture wastes

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Abstract

In order to provide values of key parameters in aquaculture waste degradation modelling specifically for the Mediterranean, sampling campaigns were carried out in 2006. Accurate measurements of particulate carbon input and benthic respiration rates were performed using sediment traps and intact core incubations. The *in situ* measurements compared to data from Atlantic salmon production, showed lower carbon flux and oxygen consumption, while a greater degradation capability was observed. Moreover, a temperature dependence of the benthic parameters was highlighted.

Successively, the model FOAM was used for an accurate comparison between different parametrisations. FOAM simulates the organic carbon degradation and the net carbon accumulation on the sediment, providing a benthic state index. On comparison with previous results, there was a decrease in benthic impacts due to minor inputs of carbon and higher mineralization rates. Moreover a seasonal variation is now observed in the organic carbon concentration. Nevertheless, the new results remain consistent with the old ones on two points: a) the negligible benthic impact of faeces with respect to uneaten feed; and b) the dependence of that impact on the different feed release conditions.

1.Introduction

World aquaculture has been quickly growing during the last fifty years. It has passed from a production of less than a million tonnes in the early 1950s to 59.4 million tonnes by 2004 with an average annual rate of increase of 8.8 %. Marine aquaculture now represents 50.9 % of the total aquaculture yield (FAO, 2006). Its continuous expansion has been generating interest on predictive tools able to assess the possible impacts for coastal ecosystems.

Indeed, several experimental studies have indicated that particulate wastes originated by marine fish farms may have a significant environmental impact (Hall et al., 1990; Holmer & Kristensen, 1992; Karakassis et al., 2000; Cromey et al., 2002; Stigebrandt et al., 2004; Corner et al., 2006; Jusup et al., 2009; Reid et al., 2009). Particulate products increase the organic load on benthic environment and might result in changes in the structure and functions of the benthic system (Tsutsumi et al., 1991; Wu et al., 1994; Vezzulli et al., 2002, 2003; Pergent-Martini et al., 2006; Holmer et al., 2007; Hargrave et al., 2008). However, monitoring spatial and temporal dispersion of both uneaten feed and faeces is difficult and costly.

Therefore, the interest in tracking aquaculture wastes with mathematical models has been rapidly increasing over time (Westrich et al., 1984; Gowen et al., 1989; Gillibrand & Turrell, 1997; Henderson et al., 2001). Cromey et al. (2002) developed a particle tracking model including hydrographic data for modelling resuspension and changes in the benthic faunal community. Hydrodynamic models of settling, resuspension and decay of net-pen wastes coupled with transport models were also used for assessing the environmental impacts of marine aquaculture (Panchang et al., 1997; Dudley et al., 2000). Doglioli et al. (2004a) took into account the three-dimensional ocean circulation and its variability in tracking different aquaculture wastes developing the advection-dispersion model POM-LAMP3D (Princeton Ocean Model – three dimensional Lagrangian Assessment for Marine Pollution Model). However, they did not consider the environmental response to the organic load from the cages. De Gaetano et al. (2008) recently improved the predictive capability of POM-LAMP3D model coupling it with a numerical benthic degradative module FOAM (Finite Organic Accumulation Module). FOAM represents the biochemical component of the modelling system and it uses POM-LAMP3D outputs to estimate the potential environmental impact due to the organic load from the cages. In particular, FOAM computes the sediment status according to the ratio between the benthic oxygen supply and the oxygen demand by the sediment in order to simulate the biological reaction of the microbial benthic community to the variations in the organic enrichment.

The mineralization rates and the oxygen demand are key parameters for the accuracy of the model prediction. Nevertheless, the lack of data collected in Mediterranean conditions forced De Gaetano et al. (2008) to use the only values available; those measured under Salmon rearing cages along the

Maine coast (Findlay & Watling, 1997).

This study aims to fill this gap by providing new data from *in situ* measurements carried out in a Mediterranean fish farm. Moreover, these specific observations are used to provide new parameter values to FOAM. Then, an accurate comparison between results from actual and previous (De Gaetano et al., 2008) modelling set-up is presented, together with an assessment of the model prediction capability.

2. Material and method

2.1. Field experiment

The *in situ* measurements were aimed to: i) measure carbon flux to sediment; ii) determine three different benthic states below and around the fish farms and iii) estimate, for each sediment state, the rates of organic matter degradation.

Survey campaigns were performed in 2006 in the "Tortuga srl." off-shore fish farm located in the Manfredonia Gulf in the South Adriatic Sea (Figure 1). The farm is composed of 16 floating cages for the rearing of Gilthead Sea Bream (*Sparus aurata*) and Sea Bass (*Dicentrarchus labrax*) and has a production of about 650 ton year^{-1}. The sea cages are located at about 3 km from the coast on a water column ranging from 8 to 12 m. For its features (reared species, farm dimensions and yearly production), this farm can be considered a typical Mediterranean off-shore fish farm (Basurco et al., 2003; UNEP/MAP/MED POL, 2004; Dalsgaard and Krause-Jensen, 2006). Moreover, this site allows measurement of different sedimentary loads of organic carbon and associated microbial activities over a small area. The large range of C input, benthic O_2 and CO_2 fluxes expected allowed collection of a reliable set of data for the Mediterranean Sea.

During the pre-survey activity carried out in May 2006, thirty stations along a transect in the direction of the main water current were investigated for organic matter content in sediment. Successively in order to reduce costs, but also to cover a broad range of conditions (i.e. heavily to moderately organic load), six sampling stations (Figure 1) were chosen from the thirty used previously and sampled in July and October 2006.

At each of the six stations, the water temperature was measured by means of a multiparametric probe (YSI, mod 556; accuracy ± 0.001°C). Three sediment traps were deployed approximately 1 m from the seabed at each sampling station for 48 hours. After recovery, the trapped material was filtered on fiberglass membranes (Whatman GF/F diameter 25 mm, nominal porosity 0.45 μm) by a vacuum pump, with pressure not exceeding 25 kPa to avoid particles breaking on the filter and matter loss in the dissolved phase. In order to determine the carbon flux to the sediment (φ_C mmolC m^{-2} d^{-1}), the recovered material was then analysed for particulate carbon by a CHN elemental analyser (mod. CHNS-O EA 1108, Carlo Erba).

Respiration rates and inorganic carbon production were measured by means of intact cores incubation. To this purpose, sediment cores (i.d. 0.08, length 0.40 m, n = 4) were collected in the six sampling stations by scuba divers. All cores were brought to the laboratory within a few hours from sampling for further processing and incubation procedures, described in detail in Dalsgaard et al. (2000). The day after the sampling, the water in the tank was exchanged and the cores incubated in the dark at the same *in situ* temperature for measuring dissolved oxygen flux (φ_{O2} mmolO_2 m^{-2} d^{-1}) and total inorganic carbon flux (φ_{CO2} mmolC O_2 m^{-2} d^{-1}).

Water samples were collected at regular time intervals with plastic syringes. Samples for φ_{O2} determinations were transferred to glass vials (Exetainers, Labco, High Wycombe, UK) and Winkler reagents were added immediately (Strickland & Parsons, 1972). Samples for φ_{CO2} were also transferred to glass vials and immediately titrated with 0.1 N HCl following the Gran procedure (Anderson et al., 1986).

In order to evaluate the status of the sampled sediment, the respiratory quotient *RQ* was computed. The respiratory quotient is defined as the ratio between measured total inorganic carbon and dissolved oxygen fluxes, as suggested by Dilly (2003):

$$RQ = \frac{\varphi_{CO2}}{\varphi_{O2}} \quad (1)$$

On the basis of the calculated *RQ*, three categories of sediment states were defined as in Table 1. The rationale behind this classification was that along a gradient of organic enrichment, the relative proportion of aerobic to anaerobic degradation changes, with implication for the accumulation of reducing power at the sediment level (Therkildsen & Lomstein, 1993; Boucher et al., 1994; Hargrave, 2008).

2.2 Modelling set-up

The adopted framework for the modelling was based on a hydrodynamic model (POM) coupled on-line with a three-dimensional Lagrangian dispersion model (LAMP3D) that drives an off-line biochemical module (FOAM).

POM (Blumberg & Mellor, 1987) is a primitive equation, free surface, sigma coordinate ocean model, based on Boussinesq and hydrostatic approximations. In our implementation the horizontal components of depth-averaged current were computed on an Arakawa-C grid.

LAMP3D (Doglioli et al., 2004a) is a single particles Lagrangian model providing the particle positions by so-called "random walk" approach. In this kind of model, the particle position is calculated at each step on the basis of the flow velocity (here computed by POM) representing the transport process and a random jump representing the turbulent diffusion. An interesting aspect of that approach is the possibility of assigning different characteristics at each numerical particle in both hydrodynamical behaviour and in biogeochemical content.

FOAM (De Gaetano et al., 2008) is a benthic degradation model, based on a simple idea proposed by Findlay & Watling (1997), where the sediment degradation capability depends on the sediment environmental state. Three main categories of sediment state are identified by 1) limitate organic load, 2) intermediate organic load and 3) elevated organic load. Following experimental outcomes, FOAM assumes that the three sediment states should be recognized by the index I calculated as:

$$I = \frac{O_2^{\sup}}{O_2^{dem}} \tag{2}$$

where $O_2^{\sup}$ is the oxygen supply to the benthos, while O_2^{dem} is the oxygen demand by microbial benthic community for the organic matter degradation at the sea bed. The oxygen supply is a function of the near bottom velocities and can be calculated by empirical relation:

$$O_2^{\sup} = A + B * \log(\bar{v}) \tag{3}$$

where A and B (Table 2) are constants and $\bar{v}$ is a time averaged current velocity taken at 1 m from the bottom. The oxygen demand is a function of the organic carbon flux toward the sea bottom (Flx^{Bot}) according to:

$$O_2^{dem} = C * Flx^{Bot} + D \tag{4}$$

where, again, C and D are just constants (Table 5).

Moreover, Findlay & Watling (1997) suggested that when I < 1, sediment conditions are close to anoxia. Therefore, the sediment state is defined as high organic load and its degradation capability is reduced to the lowest rate. When I ≈ 1, the sediment conditions are defined as intermediate organic load and the maximum degradation rate is detected. Finally when I > 1, the sediment is in low organic load conditions displaying intermediate degradation rates.

When the status is decided according to the I value, different mineralization rates are used by FOAM subtracting different quantities to the already calculated organic carbon fluxes. On the basis of the fluxes obtained, the organic carbon concentration Conc^{Bot} is calculated as:

$$Conc^{Bot} = \sum_{k=1}^{NT} Flx_k^{Bot} * dt \tag{5}$$

where NT is the number of the time intervals of the simulation. The main parameters for the three-nested modules are reported in Table 2. However, it is important to note that, as stated by Findlay & Watling (1997), Eq.(3) may be considered "robust across a variety of geographical or hydrological regions" and thus universally valid, while Eq.(4) is strongly dependent on environmental conditions where the organic matter is accumulated.

The same simulation experiments in the same offshore fish farm by De Gaetano et al. (2008) were performed in the present work in order to allow a better comparison of the simulation results uniquely introducing variations in the parametrization of FOAM for the benthic metabolism modelling.

The sea cages are located in the Ligurian Sea at about 1.5 km from the coast, and they cover an area of 0.2 km^2 (Figure 2). The bottom depth ranges between 38 and 41 m. The farm is composed of eight fish cages with a capacity of 2000 m^3 each one. The reared fishes are Gilthead Sea Bream and Sea Bass for an annual mean production of about 200 ton $year^{-1}$. Public local authorities monitor the impact of the farm on the surrounding environment by means of periodical samplings in the four stations around the cages (Figure 2). All the samples are collected with a Van Veen grab, and they are analysed for total carbon (gC kg^{-1} d^{-1}). The data from sampling campaigns from 2000 to 2005 have been here employed to validate model results.

Different type of waste released from the cages (i.e. uneaten feed and faecal pellets) was considered. Moreover, different settling velocity values measured specifically under Mediterranean conditions (Vassallo et al., 2006 for the feed and Magill et al., 2006 for the faecal pellets) were employed considering the maximum and the minimum values of settling velocity both for feed and faeces. Faecal pellets released were simulated by assuming a continuous release, while for the feed release two different typologies were considered: continuous release, using demand feeders, or periodic release as the feed is supplied manually by an operator twice per day. The simulation experiments performed are summarised in Table 3.

3. Results

3.1. Experimental field results

The variation range (minimum, maximum and average value) of carbon flux to the sediment φ_C, oxygen demand φ_{O2} and total inorganic carbon flux φ_{CO2} measured at the six sampling stations during July and October are reported in Table 4 along with values collected by Findlay & Watling (1997) for Atlantic salmon. The carbon flux to the sediment φ_C measured in July was significantly smaller than in October (t-test, p<0.01). While, the oxygen demand φ_{O2} and the respiration rates φ_{CO2} in July obtained higher values than in October (t-test, p < 0.01). The measurements made by Findlay & Watling (1997) for an Atlantic fish farm displayed significantly higher values for φ_C (t-test, p<0.01) and for φ_{O2} (t-test, p < 0.01). On the other hand, the Atlantic sediment showed a lower average degradation capability involving lower values of mineralization rates in all sediment states, even if significant differences were only found for elevated organic load sediment conditions (t-test, p<0.01).

Following the approach of Findlay & Watling (1997), the relationship between oxygen demand φ_{O2} and carbon flow to the sediment φ_C was evaluated and is displayed in Figure 3. Unlike for Atlantic conditions (dashed grey line), the relationship for Mediterranean conditions was affected by changes in water temperature. Both sampling campaigns shown positive relationship between φ_{O2} and φ_C. In July experiment, when the water temperature is around 27°C, the molar ratio is 1.4 and the y-intercept is 54.5, while in October experiment, when the water temperature is around 18°C, the molar ratio is 0.4 and the y-intercept is 31.8. These values of molar ratio and y-intercept are adopted for the parameters *C* and *D* in Eq.(4).

Since temperature deeply affected the oxygen demand by the sediment, the benthic metabolism rate was analysed by separating data for the two sampling campaigns. In Figure 4A, the data of φ_{CO2} measured in July are reported in relation to φ_{O2}, while Figure 4B shows the relationship for the data measured in October. The data are grouped according to the three categories of sediment state based on the *RQ* (Table 1), in order to determine the average mineralization rate per sediment state and per sampling campaigns. The variation range of φ_{CO2} for each state and campaign is summarized in the lower part of Table 4.

FOAM assumed the degradation capability of sediment to be equal to the mean values of φ_{CO2} for each sediment state and campaign (large crosses in Figure 4 and Table 4).

3.2. Simulated results

In the light of the experimental results obtained, two different scenarios have been simulated based on the parameter values obtained from July and October *in situ* measurements. In Table 5, these values are reported along with those used by De Gaetano et al. (2008).

For the two simulated scenarios, the results are presented with respect to: i) the extension of the impacted area, defined as the whole area where particles are still present even after the benthic degradation activity; ii) the organic carbon concentration, defined as the carbon quantity per impacted unit area in m^2 and iii) the occurrence of the different categories of sediment states.

For a direct comparison Table 6, Table 7 and Table 8 show the present results along with those of De Gaetano et al. (2008).

The impacted area was consistently smaller than in De Gaetano et al. (2008). Impacted areas in July were smaller than in October (see Table 6). A negligible impact was always associated with fish faeces when compared to uneaten feed. For the slowly sinking feed particles for both periodic and continuous feeding release (Exp A1 and B1), the impacted area was always larger than for the quickly sinking particles. The slowly sinking feed particles released periodically (Exp. B1) resulted in the largest impact area.

In all scenarios, the faeces completely degraded (Table 7). The quickly sinking feed particles released periodically (Exp. B2) resulted in the greatest organic carbon accumulation. The predicted organic carbon concentration due to the uneaten feed for conditions in July is always smaller than for ones in October. Moreover, with the exception of the quickly sinking feed particles released in periodical mode (Exp. B2), the organic carbon concentration for conditions in October is greater than in De Gaetano et al. (2008).

Looking at both faecal releases (Exp. C1 and C2), the sediment is practically always in the limited organic load category (Table 8). Largest occurrences for elevated organic load sediment state are instead registered when the feed is released periodically (Exp. B1 and B2). For conditions in October, the uneaten feed simulations (Exp. A1, A2, B1 and B2) display less days of moderate and elevated organic load category occurrence, while a greater occurrence is observed for conditions in July.

The modelled average carbon flux on the seabed (gC m^{-2} d^{-1}) for the simulated scenarios for Atlantic and Mediterranean conditions at four station around the farm are reported in Figure 5, along with the *in situ* measurements (gC kg^{-1} d^{-1}). A comparison between the absolute values of model outputs and *in situ* data was not possible because, in order to express both of them in the same units, strong assumptions on sediment density and sampling methodology have to be inferred. For this reason, the same approach used in De Gaetano et al. (2008) is utilized.

The measured carbon flux toward the sediment (grey bar) is highest in station S2 and lowest in S4, where a strong removal of C and a subsequent negative flux are observed. The study area is in fact characterized by a strong current flowing toward north-west, which has been measured (e.g. Astraldi & Manzella, 1983) and numerically simulated in the past (Doglioli et al., 2004a,b). Note that while this trend is captured by the addition of the FOAM degradative model (as in De Gaetano et al., 2008), it had been not reproduced in the first version of the model, which did not take into account degradative processes (as in Doglioli et al., 2004a).

As regards the actual results, the higher degradation rates for conditions in July result in the lowest values of organic carbon flux (empty dots). On the other hand, the conditions in October (filled dots) shows highest carbon fluxes only in the stations with the greatest organic accumulation (S1 and S2). These trends seem to be in a better agreement with the measured pattern of accumulation with respect to the Atlantic conditions adopted by De Gaetano et al. (2008) (starred dots). This is also confirmed by the correlation values between *in situ* and modelled data (Table 9). Data are significantly correlated ($n=4$, $p<0.01$) but Mediterranean parametrization (mainly July parametrization) allows higher correlation coefficient revealing better fit between modelled and measured trends.

4. Summary and discussion

The values of carbon flux to the sediment measured using sediment traps in our study range between 1.3 and 107.0 mmol $m^{-2}d^{-1}$ and were within the range reported for other Mediterranean areas with cage fish farming (1-45 mmol $m^{-2}d^{-1}$ Pusceddu et al., 2007). Despite significantly higher than background sedimentation, such organic C flux to the sediment is still moderate and did not result in excess oxygen demand at the benthic level. Respiratory quotients calculated from O_2 and CO_2 fluxes were in fact below those reported for more sheltered and organically enriched Mediterranean coastal lagoons where anaerobic mineralization rates play a major role in the overall microbial respiration activity (Bartoli et al., 2005).

Figure 3 shows that the linear assumption by Findlay and Watling (1997), between carbon input and oxygen demand, holds also in Mediterranean conditions. The previous version of the FOAM module (De Gaetano et al., 2008) used Atlantic salmon data, where organic carbon flux was significantly higher and ranged between ~80 to ~550 mmol $m^{-2}d^{-1}$ (Findlay & Watling, 1997). This is not surprising as Mediterranean fish farms are generally smaller in comparison with the Atlantic ones and produce lower quantities of fish per year. Differences in the carbon flux can be also due to the feed used, for example new generation feed has increased floating properties (Vassallo et al., 2006), allowing fish more time to eat the pellets and give lower volumes of wastes.

The relationship between the carbon flux to the sediment and the oxygen consumption found by Findlay & Watling (1997) was re-evaluated for average conditions for Mediterranean aquaculture. Mediterranean temperature variations force this relationship. Two different linear trends were assessed during the July and October sampling campaigns. The results for July imply greater values of oxygen demand than in Findlay & Watling (1997), while the October trend shows lower O_2 demand. This is not surprising and has been recently reviewed by Glud (2008), who showed how measurements of oxygen demand coupled to carbon input to the sea floor were still very limited. He also underlines the need for seasonal studies, as it is likely that carbon sedimentation and oxygen respiration rates are probably partially uncoupled. Organic carbon sedimentation, measured using traps, can be considered an instantaneous measurement whilst oxygen demand reflects the occurrence of processes with a longer time scale (Glud, 2008).

With equal carbon flux to the sediment and water circulation regime, the higher oxygen demand of July forces model towards a larger occurrence of the moderate organic load conditions (β category of sediment state) compared to De Gaetano et al. (2008). The opposite is observed in October, when the occurrence of an elevated re-oxidation of anaerobic metabolism end-products (limited organic load condition) increased.

The mineralization rate results were higher than found by Findlay & Watling (1997) apart from the intermediate organic load state for conditions in October which shows lower ability to degrade organic load. Moreover, the mineralization rates measured in July were the highest, giving rise to higher degradation and consequently lower organic accumulation on the seabed and thus a smaller impacted area than in the other scenarios.

Therefore, the new parameters allow a better discrimination between the two scenarios evidencing the temperature-dependence of the processes involved. This dependence also influences the impact typologies: July is characterized by a more frequent occurrence of moderate and elevated organic load and by a higher degradation causing lower organic carbon concentration on the sea bed and a smaller impacted area. Managers and policy makers may take care of these differences in planning the installation of new fish-farms or the expansion of existing ones. A balance among the organic matter spread or load and the occurrence of different sediment states may be accurately evaluated with the application of the model.

Further investigations are necessary to systematically characterize the Mediterranean fish farms.

This can be achieved applying the entire model POM-LAMP3D and FOAM to several sites. Moreover, several sampling campaigns should be carried out in order to obtain a whole range of variations of FOAM parameters with temperature and improve the prediction capability of the model. It is in fact expected that parameters may continuously vary with temperature allowing a more reliable model set-up in function of detected (or expected) water temperature. At this purpose, further field experiments are needed to completely characterize the metabolic dynamics of sediments covering the whole range of Mediterranean Sea temperatures.

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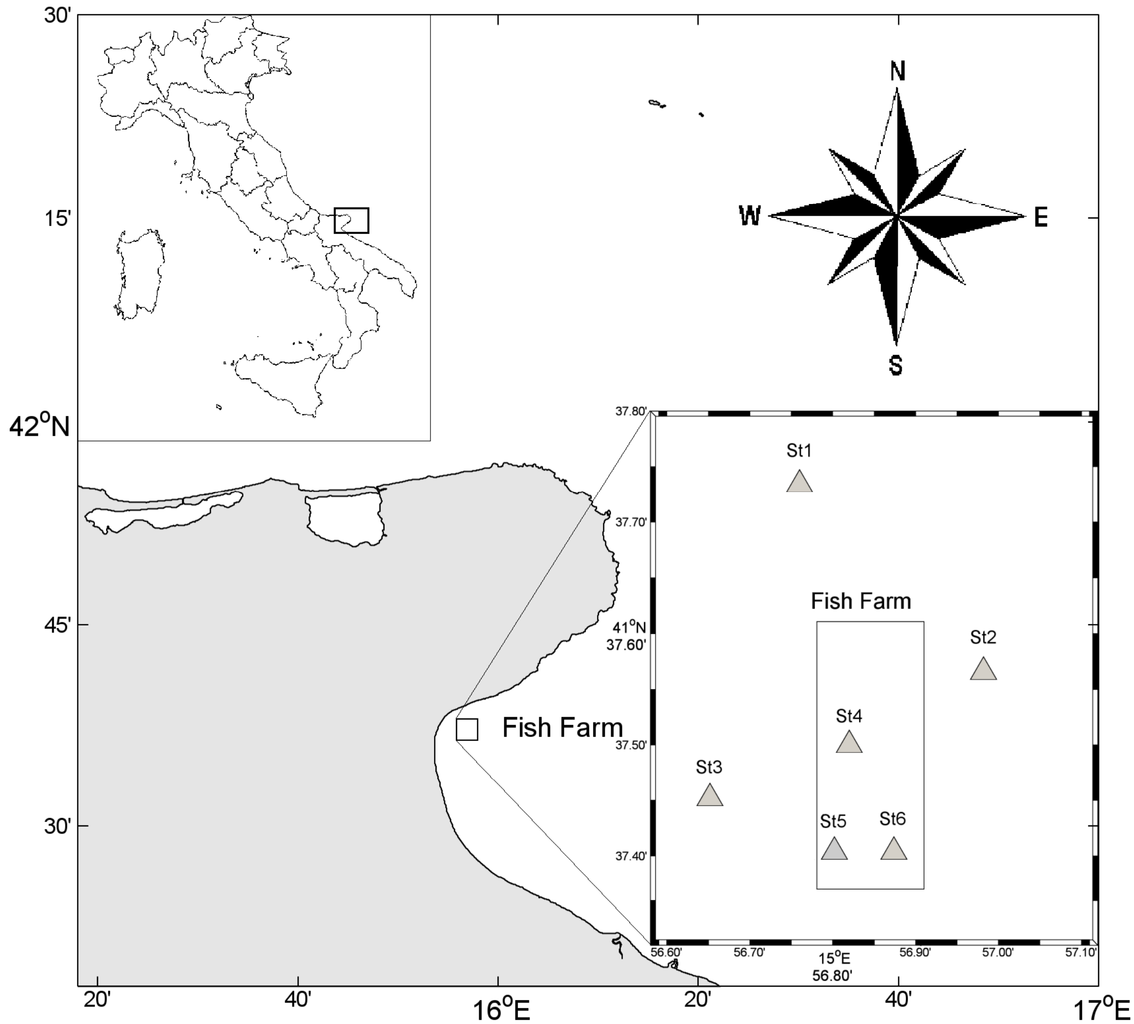
Figure 3: Relationships between the carbon flux to the sediment and the benthic metabolism as measured by O_2 consumption. Dashed black line identifies the general trend of July samplings (○); solid black line identifies the general trend of October samplings (●) and dotted grey line follows the trend assessed by Findlay & Watling (1997).

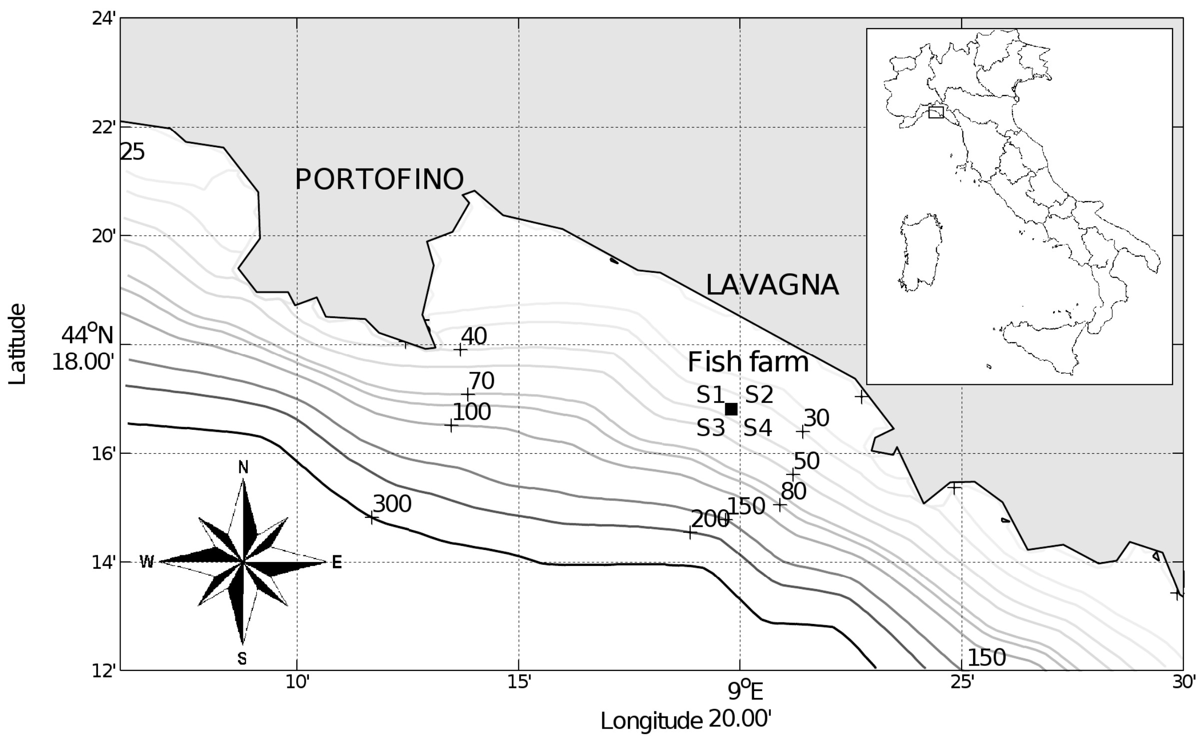
Figure 4: Relationship between measured dissolved oxygen flux (O_2^{dem}) and total inorganic carbon flux. Solid and dashed lines identify the threshold of limited and elevated organic load states of the sediment ($RQ < 0.8$ and $RQ > 1.2$), respectively. A) July data; B) October data.

Figure 5: Daily organic carbon loading rate in the four sampling stations around the modelled fish farm. Data from sampling observation are reported in gC $kg^{-1}d^{-1}$ and are referred to 2000-2005 (light gray bar). Results obtained by FOAM simulations with the three applied settings are reported in gC $m^{-2}d^{-1}$. Empty dots represent results obtained with July parametrization (○); filled dots represent ones with October parametrization (●); starred dots represent De Gaetano et al. (2008) results (*).



30'
15'
42°N
45'
30'
20'
40'
16°E
20'
40'
17°E
N
W
E
S
Fish Farm
37.80'
37.70'
41°N
37.60'
37.50'
37.40'
St1
St2
St3
St4
St5
St6
Fish Farm
56.60'
56.70'
15°E
56.80'
56.90'
57.00'
57.10'

Figure 1



PORTOFINO
LAVAGNA
Fish farm
S1
S2
S3
S4
25
40
70
100
300
200
150
80
50
30
150
N
S
W
E
24'
22'
20'
44°N 18.00'
16'
14'
12'
10'
15'
9°E 20.00'
25'
30'
Latitude
Longitude

Figure 2

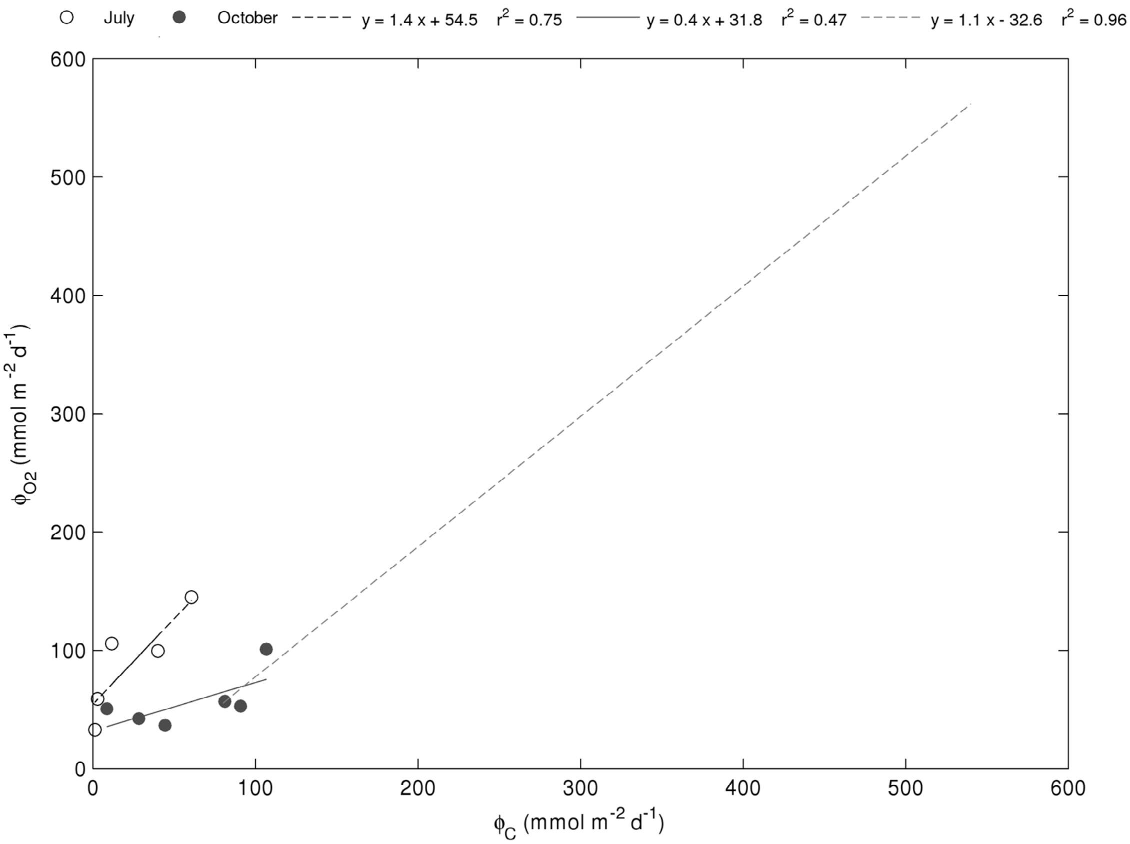
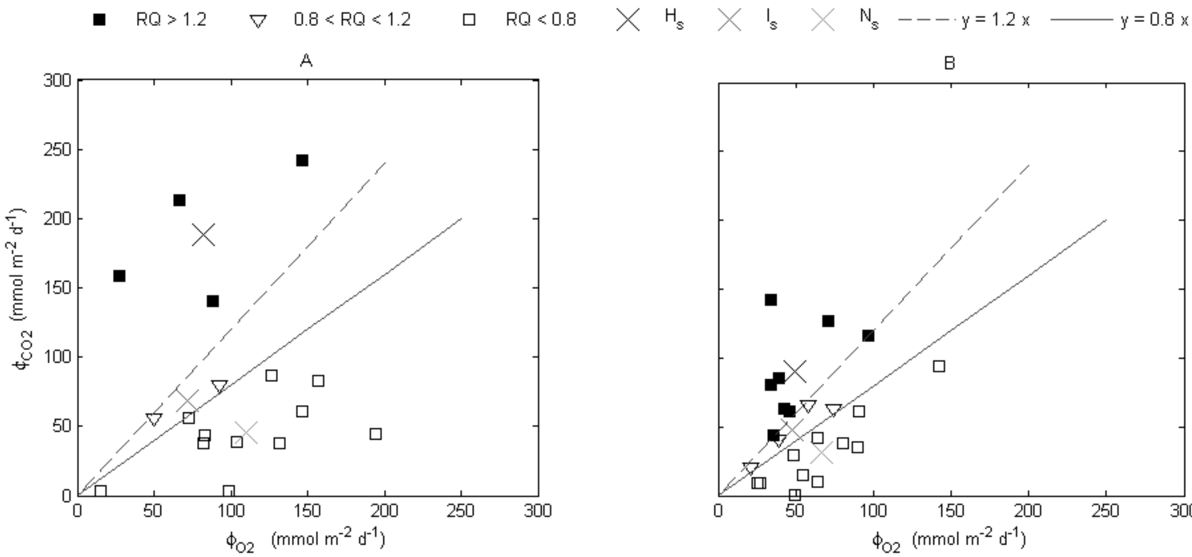

July
October
y = 1.4 x + 54.5 r2 = 0.75
y = 0.4 x + 31.8 r2 = 0.47
y = 1.1 x - 32.6 r2 = 0.96
φO2 (mmol m-2 d-1)
φC (mmol m-2 d-1)
0
100
200
300
400
500
600

Figure 3



RQ > 1.2
0.8 < RQ < 1.2
RQ < 0.8
H_s
I_s
N_s
y = 1.2 x
y = 0.8 x
A
B
ϕ_{CO2} (mmol m^{-2} d^{-1})
ϕ_{O2} (mmol m^{-2} d^{-1})

Figure 4

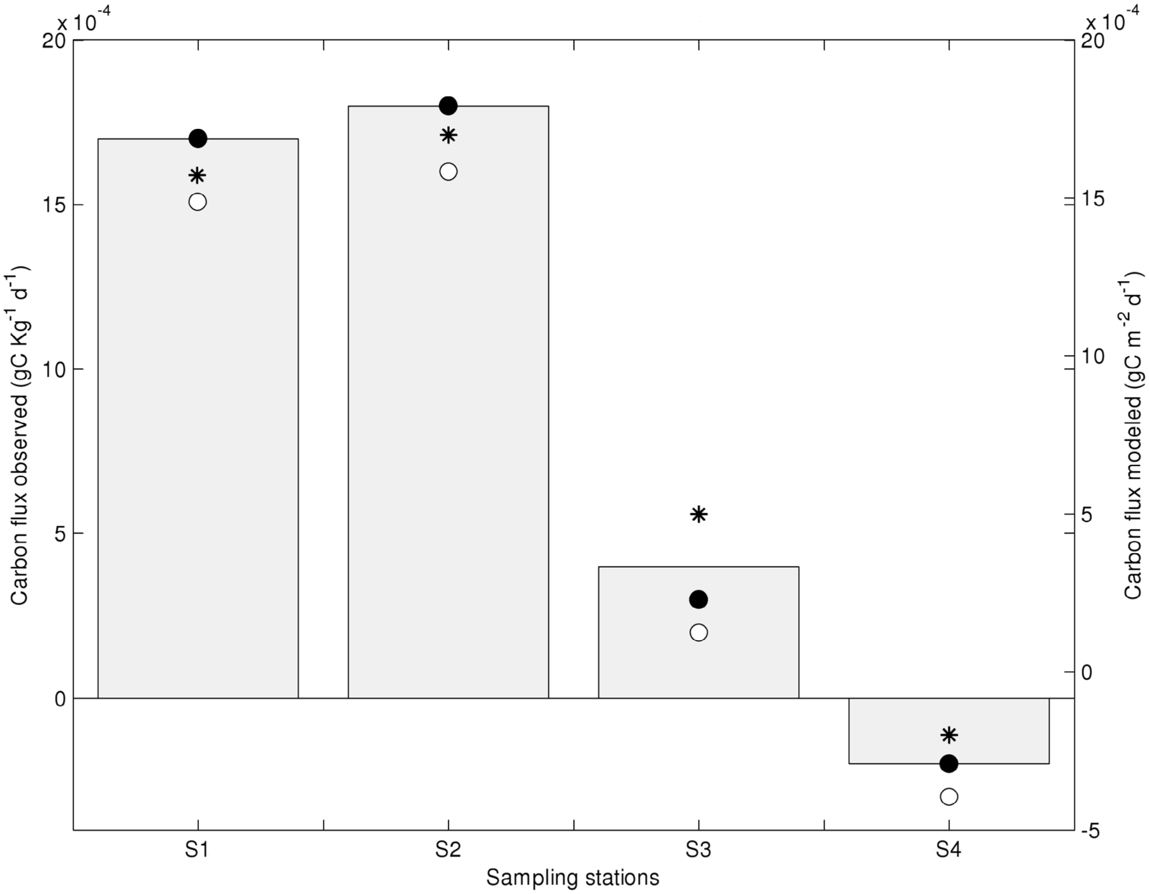

x 10^-4
20
15
10
5
0
Carbon flux observed (gC Kg^-1 d^-1)
x 10^-4
20
15
10
5
0
-5
Carbon flux modeled (gC m^-2 d^-1)
S1
S2
S3
S4
Sampling stations

Figure 5

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Sediment states		***RQ* values**
α	Limitated organic load	$RQ < 0.8$
β	Moderate organic load	$0.8 < RQ < 1.2$
γ	Elevated organic load	$RQ > 1.2$

Table 1

POM-LAMP3D parameters	**value**
POM physical domain (km)	46x16
LAMP3D physical domain (km)	8x4
Horizontal resolution (m)	400x200
Vertical resolution (m)	10
Barotropic cycle time step (s)	1
Smagorinsky diffusivity coefficient	0.1
Asselin filter coefficient	0.05
Ekman depth ΔE (m)	50
Wind drag coefficient *Cd*	0.001
Horizontal standard deviation σ (m) Particle cycle time step (s)	3.46 60
Number of particles	620000
FOAM parameters	**value**
Physical domain (km) (same as in De Gaetano et al., 2008)	8x4
Horizontal resolution (m) (same as in De Gaetano et al., 2008)	40x20
O_2 supply parameter, *A* ($mmolO_2m^{-2}d^{-1}$)	736.3
O_2 supply parameter, *B* ($mmolO_2s\ m^{-3}d^{-1}$)	672.5

Table 2

Exp.	**Waste typology**	**Settling velocity**	**Release condition**
A1	feed	slow	continuous
A2	feed	quick	continuous
B1	feed	slow	periodical
B2	feed	quick	periodical
C1	faeces	slow	continuous
C2	faeces	quick	continuous

Table 3

			min	max	mean ± std
φ_C (mmolC m^{-2} d^{-1})	**July**		1.3	60.6	23.4 ± 26.0
	October		8.8	106.9	60.3 ± 38.7
	Atlantic		80	540	310.0 ± 141.4
φ_{O2} (mmolO_2 m^{-2} d^{-1})	**July**		32.7	144.5	88.2 ± 43.4
	October		36.2	100.9	56.4 ± 23.0
	Atlantic		55.4	561.4	308.4 ± 155.6
φ_{CO2} (mmolC m^{-2} d^{-1})	**July**	α	3.6	87.2	45.1 ± 26.8
		β	56.2	80.2	68.2 ± 16.9
		γ	140.9	242.2	188.6 ± 47.1
	October	α	0.2	94.1	31.1 ± 27.7
		β	20.7	66.2	47.8 ± 21.3
		γ	44.2	141.8	89.9 ± 34.8
	Atlantic	α	10.9	57.1	27.5 ± 15.2
		β	12.9	106.3	57.5 ± 38.4
		γ	18.8	53.6	30.6 ± 17.8

Table 4

FOAM benthic parametrization	**July**	**October**	**De Gaetano et al. (2008)**
O_2 demand parameter, *C* ($mmolO_2mmolC^{-1}$)	1.4	0.4	1.07
O_2 demand parameter, *D* ($mmolO_2m^{-2}d^{-1}$)	54.5	31.8	-32.6
Mineralization rate in α state ($mmolC\ m^{-2}d^{-1}$)	45.1	31.1	27,5
Mineralization rate in β state ($mmolC\ m^{-2}d^{-1}$)	68.2	47.8	57.5
Mineralization rate in γ state ($mmolC\ m^{-2}d^{-1}$)	188.6	89.9	30,6

Table 5

IMPACTED AREA				
Exp.	**Simulation Typology (release)**	**July**	**October**	**De Gaetano et al. (2008)**
		mean ± std (m^2)	mean ± std (m^2)	mean ± std (m^2)
A1	Slow feed (continuous)	3393 ± 419	3521 ± 540	3576 ± 582
A2	Quick feed (continuous)	3200 ± 22	3202 ± 35	3202 ± 41
B1	Slow feed (periodical)	4118 ± 605	4451 ± 542	4513 ± 563
B2	Quick feed (periodical)	3245 ± 203	3268 ± 251	3277 ± 266
C1	Slow faeces	<1	51± 200	377 ± 656
C2	Quick faeces	5 ± 59	342 ± 525	941 ± 962

Table 6

ORGANIC CARBON CONCENTRATION				
Exp.	**Simulation Typology (release)**	**July**	**October**	**De Gaetano et al. (2008)**
		mean ± std ($gC\ m^{-2}$)	mean ± std ($gC\ m^{-2}$)	mean ± std ($gC\ m^{-2}$)
A1	Slow feed (continuous)	1301 ± 357	1464 ± 408	1450 ± 404
A2	Quick feed (continuous)	1353 ± 417	1551 ± 464	1490 ± 453
B1	Slow feed (periodical)	1075± 331	1226± 372	895 ± 380
B2	Quick feed (periodical)	1405 ± 340	1560 ± 379	1590 ± 387
C1	Slow faeces	< 1	< 1	< 1
C2	Quick faeces	< 1	< 1	< 1

Table 7

OCCURRENCE OF DIFFERENT SEDIMENT STATES										
Exp.	**Simulation Typology (release)**	**July**			**October**			**De Gaetano et al. (2008)**		
		states (% days)			states (% days)			states (% days)		
		α	β	γ	α	β	γ	α	β	γ
A1	Slow feed (continuous)	49	44	7	94	5	1	74	22	4
A2	Quick feed (continuous)	43	52	5	96	3	1	71	27	2
B1	Slow feed (periodical)	85	4	11	89	8	3	87	4	9
B2	Quick feed (periodical)	86	4	10	90	6	4	88	4	8
C1	Slow faeces	100	0	0	100	0	0	99	0	1
C2	Quick faeces	100	0	0	99	1	0	99	0	1

Table 8

	in situ
in situ	1
De Gaetano et al. (2008)	0.9958
July	0.9994
October	0.9989

Table 9