**Renewal time and the impact of harmful algal blooms on the extensive mussel raft
culture of the Iberian coastal upwelling system (NE Europe)**

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Abstract

The extension and intensity of the upwelling season in the NW Iberian Peninsula (42°– 43°N) have decreased by 30% and 45% over the last 40 years, respectively. Accordingly, the renewal time (τ) of the Rías Baixas, four large coastal inlets where 15% of the World extraction of blue mussels occurs, has increased by 240%. We indirectly demonstrate here that the growing τ has caused the increasing occurrence of harmful microalgae in these embayments, dramatically affecting mussel raft cultivation. The equation $D = 365 \cdot \left(1 - \exp\left(-\frac{\tau}{c_1}\right)\right)$ explains 80% of the variability of the number of days per year that mussels cannot be extracted from the hanging ropes because of the occurrence of harmful microalgae (D). The coefficient $c_1 = 37 \pm 2$ days indicates that an average τ over the upwelling season of $> 25 \pm 1$ or 50 ± 3 days reduce mussel extraction to only 50% or 25% of the year, respectively.

Keywords: coastal upwelling; flushing time; harmful microalgae; climate change; mussel raft; NW Spain

1. Introduction

Coastal upwelling systems often experience the occurrence of harmful algal blooms (HABs), which represent a serious threat to humans, induce important ecological perturbations, and cause major economic losses in fisheries and aquaculture (GEOHAB, 2005). Although the number of species and their harmful effects is highly variable (Horner et al., 1997; Pitcher and Calder, 2000), those causing toxin syndromes are of primary concern for human health and, therefore, the economy of the affected regions. Paralytic shellfish poisoning (PSP) and diarrhetic shellfish poisoning (DSP) attributed to several members of the dinoflagellates genus regularly occur in the four major coastal upwelling systems of the world ocean. Within the California Current System, outbreaks of amnesic shellfish poisoning (ASP) caused by members of the diatom genus Pseudo-nitzschia are also recurrent (Horner et al., 1997; Trainer et al., 2000).

The NW Iberian Peninsula is the northern limit of the eastern boundary Large Marine Ecosystem that extend along the Atlantic coasts of Africa and Europe from 10°N to 44°N (Wooster et al., 1976; Bakun and Nelson, 1991). At our latitudes, coastal winds are favourable to the upwelling of the cold and nutrient-rich Eastern North Atlantic Central Water during the spring and summer and favourable to the downwelling of surface coastal waters during the autumn and winter (Wooster et al., 1976; Álvarez-Salgado et al., 2002). Four large coastal indentations of more than 2.5 km³, known as Rías Baixas, occupy the Spanish coast in the 42°N–43°N latitudinal range (Fig. 1). The Rías Baixas behave as an extension of the shelf during the upwelling season, with northerly winds enhancing the positive residual circulation pattern. On the contrary, during the downwelling season, the outer part of the ría circulates like a

negative estuary forced by the dominant southerly winds, whereas the inner part behaves as a positive estuary forced by continental runoff (Álvarez-Salgado et al., 2000; Piedracoba et al., 2005).

This unique combination of wind patterns and coastal morphology makes the Rías Baixas an exceptional site for the extensive culture of the blue mussel Mytilus galloprovincialis on hanging ropes. The trophic conditions of these coastal ecosystems —where the total particulate matter is below the pseudo faeces production threshold for mussels (3 mg l^{-1}) and a high proportion of phytoplankton cells is observed (Figueiras et al., 2002) — stimulate high and stable clearance rates (Fernández-Reiriz et al., 2007). As a consequence, the mussels cultivated in the Rías Baixas report the highest growth rate in the world, with a total production of about 250,000 tons of blue mussels per year, 40% of European and 15% of the world production (Labarta et al., 2004). In the case of the Ría de Arousa (Fig. 1), with 2300 mussel rafts, the organic carbon in mussels flesh represent about 10% of the net primary production of the ecosystem (Figueiras et al., 2002). The highest economic impact on the mussel harvest is caused by DSP episodes due to Dinophysis acuminata and D. acuta (Reguera et al., 2003). D. acuminata, albeit in low numbers, is always present in the Rías Baixas over the upwelling season, while D. acuta typically occurs in short pulses at the end of the upwelling season in September and October (Reguera et al., 1995) associated with downwelling episodes. Major PSP events in the Rías Baixas are ascribed to blooms of the chain-forming dinoflagellate Gymnodinium catenatum, which usually take place during downwelling events in late summer–early autumn (Fraga et al., 1988; Figueiras et al., 1994; Fermín et al., 1996). Both types of toxicity have a great impact on the economy of the region, with estimated

economic losses of 56–225 million euros per year from 1989 and 1998 (ECOHARM, 2003).

This manuscript shows that the increasing flushing time of upwelled water observed in the Rías Baixas over the last decade, caused by a decrease of the extension and intensity of the upwelling season off NW Spain, is the reason behind the growing number of days that blue mussels on hanging ropes cannot be extracted because of the presence of harmful microalgae.

2. Material and methods

2.1. Offshore Ekman transport off NW Spain from 1966 to 2006

The northerly component of shelf wind–stress (τ_y) causes upwelling favourable offshore Ekman transport (I_w) along the western coast of the Iberian Peninsula (Wooster et al., 1976; Bakun and Nelson, 1991), and southerly winds result in the opposite effect. Ekman transport can be roughly estimated by Bakun’s (1973) method:

$$I_w = \frac{\tau_y}{\rho_w \times f} = - \frac{\rho_A \times C_D \times |V| \times V_y}{\rho_w \times f} \quad (1)$$

where ρ_A is the density of air (1.22 kg m^{-3} at 15°C), C_D is an empirical dimensionless drag coefficient ($1.4 \cdot 10^{-3}$ according to Hidy, 1972), f is the Coriolis parameter ($9.946 \cdot 10^{-5} \text{ s}^{-1}$ at 43° latitude), ρ_w is the density of seawater ($\sim 1025 \text{ kg m}^{-3}$), and $|V|$ and V_y are the average daily module and northerly component of the geostrophic winds in a $2^\circ \times 2^\circ$ cell centred at $43^\circ\text{N } 11^\circ\text{W}$, representative for the study area (shaded area in Fig. 1). Average daily geostrophic winds were estimated from atmospheric surface pressure charts, provided at 6–hour intervals by the Spanish Institute of Meteorology. Positive values of I_w (in $\text{m}^2 \text{ s}^{-1}$) indicate upwelling–favourable offshore Ekman transport.

Conversely, negative values of I_W indicate downwelling—favourable onshore Ekman transport. Weekly—averaged geostrophic I_W values are not significantly different from I_W values calculated from coastal winds measured at the meteorological station of Cape Fisterra (Otero et al. 2008).

A time—series of daily values of I_W from January 1966 to December 2006 ($n=14274$) was analysed. Values outside the lower extreme boundary ($LEB = Q_1 - 3 \cdot H = -3.02 \text{ m}^2 \text{ s}^{-1}$) and upper extreme boundary ($UEB = Q_3 + 3 \cdot H = 3.02 \text{ m}^2 \text{ s}^{-1}$) were rejected before analysis of the time—series; Q_1 and Q_3 are the lower and upper quartile, and H is the inter—quartile range. They represented ~3% of the whole time series. To obtain the 1966–2006 and the 1966–1968, 1967–1969, 1968–1970, ..., 2004–2006 mean seasonal cycles of I_W , $SC[I_W]$, a harmonic analysis of the annual (period, 365 days) and semi—annual (period, 365/2 days) components of the time series has been performed by adjusting I_W data to the following trigonometric equation:

$$SC[I_W] = A_0 + A_1 \cdot \cos\left(\frac{2 \cdot \pi}{365} \cdot t + \varphi_1\right) + A_2 \cdot \cos\left(\frac{4 \cdot \pi}{365} \cdot t + \varphi_2\right) \quad (2)$$

where A_0 is the annual average I_W , A_1 and A_2 are the amplitude of annual and semi—annual components; φ_1 and φ_2 are the diphas of the annual and semi—annual components; and t is the Julian day (ranging from 1 to 365/366).

2.2. Safety of the cultivation of blue mussel in the Galician rías from 1998 to 2006

Mussel rafts have been grouped by the Galician Government into 3 areas in the Ría de Muros–Noia, 9 areas in the Ría de Arousa, 3 areas in the Ría de Pontevedra and 5 areas in the Ría de Vigo (see Fig. 1). The criterion followed by the Galician Government to close a particular area to mussel extraction was based on the official

mouse bioassay, entrusted to the “Instituto Tecnológico para o Control do Medio Mariño” (INTECMAR). Over the period 1998–2006, mouse bioassays were performed in 3 sampling points for the 3 areas of the Ría de Muros, 24 points for the 9 areas of the Ría de Arousa, 8 points for the 3 areas of the Ría de Pontevedra and 10 points for the 5 areas of the Ría de Vigo. The mussel raft cultivation areas of each ría were grouped on basis of the number of days per year that each area was officially closed to extraction (see Table 1). Two areas, i and j , will belong to the same group when $|m_i - m_j| / \sqrt{\sigma_i^2 + \sigma_j^2} < 1$, where m_i and m_j are the average number of days per year that the areas i and j were close to extraction from 1998 to 2006; and σ_i and σ_j the respective standard deviations. Conversely, if $|m_i - m_j| / \sqrt{\sigma_i^2 + \sigma_j^2} \geq 1$, areas i and j will not belong to the same group. As a result of this analysis, a unique group is retained in the Ría de Muros–Noia and in the Ría de Pontevedra, and two groups are retained in the Ría de Arousa and the Ría de Vigo, where the inner and outer part of the rías has been differentiated (see Fig.1).

3. Results

The average 1966–2006 seasonal cycle of I_w , $SC[I_w]$, at the study latitudes (42°–43 °N) consist of an upwelling favourable season ($I_w > 0$) which extends from Julian day 83 ± 25 (24th March) to 283 ± 22 (10th October), i.e. 200 ± 33 days, and a downwelling favourable season ($I_w < 0$) the rest of the year, i.e. 165 ± 33 days (Fig. 2). The long-term average I_w for the upwelling and downwelling seasons over the last 40 years has been 0.29 ± 0.08 and $-0.29 \pm 0.08 \text{ m}^2 \text{ s}^{-1}$, respectively. This seasonal cycle explains 7.6% of the total variability of the daily time series, or 15.7% of the variability of the weekly–

average (7-day running mean) time series, or 23.2% of the fortnightly-average (15-day running mean) time series of I_W from 1966 to 2006.

When adjusting equation 2 for consecutive groups of 3 years (1966–1968, 1967–1969, ..., and 2004–2006) it results in a strong temporal variability of $SC[I_W]$ (Fig. 2). The percentage of the total variability explained by these seasonal cycles ranges from 3.3% to 16.3% for the daily time series, 6.8% to 10.1% for the 7-day running mean time series, and from 33.7% to 49.8% for the 15-day running mean time series of I_W . The variability observed in the seasonal cycles is not stochastic, but shows a marked log-term trend in the value of I_W (coefficient A_0 in equation 2; Fig. 3a), the timing of the upwelling and downwelling seasons (Fig. 3b), and the average value of I_W during both seasons (Fig. 3c). A significant decrease ($p < 0.001$) of A_0 occurred over the last 40 years (Fig. 3a), from an upwelling-favourable I_W value of $0.20 \pm 0.03 \text{ m}^2 \text{ s}^{-1}$ in the early 1960's to a slightly downwelling favourable value of $-0.10 \pm 0.08 \text{ m}^2 \text{ s}^{-1}$ in the early 2000's. Superimposed on this monotonic decreasing trend, two cycles of period 15–20 years are also evident, which can be associated to the well-known North Atlantic Oscillation climatic scenarios (Visbeck et al., 2001).

Therefore, the decrease in A_0 associates to a significant i) delay of the onset ($p < 0.05$), and ii) advance of the off set ($p < 0.001$) of the upwelling season (Fig. 3b); iii) decrease of the intensity of upwelling ($p < 0.001$) during the upwelling season, and iv) increase of the intensity of downwelling ($p < 0.001$) during the downwelling season (Fig. 3c). At the beginning of the 1960's the upwelling season started by Julian day 68 ± 8 (around 10th march) and ended by Julian day 321 ± 7 (around 17th November) whereas in the early 2000's it starts at day 95 ± 14 (around 5th April) and ends by Julian day 261 ± 14

(around 20th September). The upwelling season has reduced by 85 ± 22 days over the last 40 years.

The inverse of the offshore Ekman transport, $1/I_W$ (in s m^{-2}), can be used as a proxy to the renewal time of a coastal upwelling system, specially in the case of the Rías Baixas (Rosón et al. 1997; Álvarez-Salgado et al. 2000; Piedracoba et al. 2005; Gilcoto et al. 2007). Figure 3d show the long-term trend of $1/I_W$ for the coastal upwelling system off NW Spain during the upwelling season, which increased from $2.2\pm 0.5 \text{ s m}^{-2}$ in the early 1960's to $5.1\pm 0.9 \text{ s m}^{-2}$ in the early 2000's. Interestingly, over the short period between 1998 and 2006, renewal rates ranged from 3.8 to 7.5 s m^{-2} , increasing at the extremely high rate of $10\%\text{y}^{-1}$. Therefore, this period can be very useful to test the influence of the renewal rate of upwelled waters off NW Spain on the occurrence of HABs.

Figure 4a shows the maximum number of days that the mussel rafts areas were closed to extraction in the inner and outer Ría de Vigo from 1998 to 2006. A 3-year running mean was applied to be coherent with the analysis of the time evolution of the seasonal cycle of the offshore Ekman transport. In both the inner and outer Ría de Vigo, a significant ($p < 0.001$) positive correlation was observed between the number of days that mussels cannot be extracted and $1/I_W$, with $r^2 = 0.85$ for the inner and $r^2 = 0.96$ for the outer Ría de Vigo. The same trend was observed in the Ría de Pontevedra ($r^2 = 0.68$, $p < 0.02$), the inner ($r^2 = 0.70$, $p < 0.02$) and outer ($r^2 = 0.70$, $p < 0.02$) Ría de Arousa and the Ría de Muros-Noia ($r^2 = 0.51$, $p < 0.07$). Significant differences has been observed in the maximum number of days per year that the different zones of the four Rías Baixas are closed to extraction, with the Ría de Pontevedra (closed 227 ± 57 days per year in the period 1998–2006) and outer Ría de Vigo (closed 198 ± 53 days per year)

representing the upper end and the outer Ría de Arousa (closed $67 \pm$ days per year) representing the lower end (see Table 1). The abscissa of Figure 4a can be converted into true renewal rates (τ) by multiplying $1/I_w$ times the volume of the embayment (V) and dividing by the length of its open end to the shelf (L; Rosón et al. 1997; Álvarez-Salgado et al. 2000; Piedracoba et al. 2005; Gilcoto et al. 2007):

$$\tau = \frac{1}{I_w} \cdot \frac{V}{L} \quad (3)$$

Lengths and volumes were estimated from digitalised charts published by the Hydrographic Institute of the Spanish Navy processed with the programme Surfer 8 of Golden Software. Figure 4b shows how the maximum number of days that the inner and outer Ría de Vigo have been closed to mussel extraction distribute once the specific volume and length of the inner and outer ría have been considered (see Table 2). Applying the same concepts to the other three Rías Baixas —Pontevedra, Arousa and Muros-Noia (Fig. 1)— the distribution of Figure 4c is obtained, which can be adjusted to the equation:

$$D = 365 \cdot \left(1 - \exp\left(-\frac{\tau}{c_1}\right) \right) \quad (4)$$

where D is the maximum number of days that the mussel rafts are closed to extraction during a year, and c_1 , 37 ± 2 days, is the coefficients of the non linear regression equation ($r^2 = 0.79$, $n = 42$, $p < 0.001$). According to this equation, the mussels rafts of a given area will be closed to extraction a maximum of 50% and 75% of the days per year if the renewal time is over 25 ± 1 and 50 ± 3 days, respectively.

4. Discussion and Conclusions

The seasonality of coastal winds off NW Spain over the last 40 years is consistent with previous descriptions of the Iberian upwelling system (Wooster et al., 1976; Fiúza, 1983; Álvarez Salgado et al., 2002; Cabanas and Álvarez, 2006) and it is a common feature of coastal upwelling systems at temperate latitudes world wide (Bakun and Nelson, 1991). The dramatic decrease of coastal upwelling intensity during the second half of the XX century, switching from average upwelling favourable conditions in the early 1960's to average downwelling favourable conditions in the early 2000's, is not exclusive of the Galician coast, but a common feature of the Atlantic coast of the Iberian Peninsula. Lemos and Sansó (2006) obtained the same result from the records of the coastal meteorological stations along the Portuguese coast from 37°N to 41 °N. These observations contradicts Bakun's (1990) hypothesis on the progressive intensification of coastal winds in the major coastal upwelling systems of the world as a consequence of the differential warming of land and the adjacent ocean masses in the context of climate change. Bakun's (1990) hypothesis has been invoked by Gregg et al. (2005) to explain the significant increase in satellite derived chlorophyll fluorescence in the coastal upwelling systems of SW Africa, Peru– Chile, California–Oregon or Somalia. Interestingly, no significant increases were observed by these authors in the coastal upwelling systems of the Western Iberian Peninsula and NW Africa. On the contrary, studies of these coastal upwelling systems using the International Comprehensive Ocean–Atmosphere Data Set Project wind data base (<http://www.ncdc.noaa.gov/oa/climate/coads/>), recorded by ship–based meteorological stations, suggest a long–term increase in wind intensity (Guisande et al., 2004;

McGregor et al., 2007). This apparent contradiction between land and ship based meteorological stations has not been solved yet.

The original analysis applied in this work to the time series of offshore Ekman transports allows going deeply on the structure of the switch from upwelling to downwelling favourable conditions over the last 40 years off NW Spain: the extension of the upwelling season has reduced by 30% and upwelling intensity by 45% over the study period. However, the final causes of the changes in the wind structure, which according to Bakun's (1990) hypothesis should be related to a decrease of the temperature gradient between the land and ocean masses off the Western Iberian Peninsula, remain also unresolved.

This dramatic change in the wind regime should have a direct influence on the recruitment of commercial species with life cycles adapted to the seasonality of coastal winds along the Western Iberian Peninsula such as Sardina pilchardus (Guisande et al., 2004) or Octopus vulgaris (Otero et al., 2008). Barth et al. (2007) have recently shown the dramatic consequences of a 1-month delay in the spring transition to the upwelling-favourable season in the northern California Current Large Marine Ecosystem on the low recruitment of rocky intertidal organisms, specifically blue mussels. In this sense, the upwelling season off NW Spain has delayed 27 ± 15 days over the last 40 years.

For the case of the occurrence of HABs, microplankton succession in the Rías Baixas progress from the supremacy of large diatoms in spring, when the water column is still weakly stratified, to an increasing importance of dinoflagellates in late summer when stratification is stronger (Margalef, 1958; Figueiras et al., 2002). This seasonal change can be altered by strong summer upwelling events, which reset the succession to earlier stages characterised by the dominance of diatoms. The dynamics of the system

also promotes the spatial segregation between diatoms and dinoflagellates, with the former being more abundant in the interior of the Rías Baixas, where upwelling is stronger. Later stages of succession, typified by a higher importance of dinoflagellates, are usually found in the outer parts of the Rías Baixas, where the water column is stratified. Upwelling and relaxation events modify this structure along the longitudinal axis of these embayments (Tilstone et al., 1994; 2000). Thus, upwelling enhances positive residual circulation and transports dinoflagellates to the shelf, leaving the Rías Baixas dominated by diatoms. Conversely, during relaxation events the spatial structure contracts and dinoflagellates are advected to the inner part of these coastal inlets. Therefore, the residual circulation determines the microplankton composition in the Rías Baixas during the upwelling season. Since harmful dinoflagellates are habitual components of the summer microplankton community in these embayments (Margalef, 1958; Figueiras and Ríos, 1993; Figueiras et al., 2002), a decrease of the offshore Ekman transport, which produces an increase of the renewal time of the upwelled waters, favours the selection of these species adapted to increased stability – reduced turbulence. The selected species could take advantage from their swimming ability to perform vertical migrations (Villarino et al., 1995) and to obtain inorganic nutrients from the nutricline (Fraga et al., 1992; Álvarez-Salgado et al., 1998) or to maintain in the photic layer counteracting the downward vertical velocity imposed by physical conditions during downwelling (Figueiras et al., 1995, Fermín et al., 1996). The increasing recurrence of harmful microalgae in the Rías Baixas of NW Spain, specially of the genus Dynophysis, over the last decade has been a serious handicap for the exploitation of the blue mussel Mytilus galloprovincialis cultured on hanging ropes (ECOHARM, 2003). It has been shown in this work that the renewal time of water is

the key environmental variable that better explains the constrictions to the efficient exploitation of blue mussels in the Rías Baixas. The significant differences observed in the number of days per year that the cultivation zones of the four Rías Baixas are closed to extraction by the Galician Government for health safety reasons can be explained by the simple geomorphology index V/L , involving the volume of the mussel raft cultivation area (V) and the length of its open end to the shelf (L). Renewal times of more than 25 and 50 days reduce mussel extraction to 50% and 25% of the year, respectively. Predictions in the context of global warming indicate that the intensity of coastal winds off the Rías Baixas will continue to decrease at least up to the horizon 2070–2100 (Moreno Rodríguez, 2005), leading to an increase of the renewal time of these embayments and, consequently, a probable increase in the number of days that the cultivation areas will be closed to extraction.

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Table 1. Number of days that the different areas of the Rías Baixas were closed to mussel extraction during the years 1998 to 2006. See the location of the areas in Figure 1.

Ría	Area	year									
		98	99	00	01	02	03	04	05	06	
Arousa	1.1. Ribeira	18	76	47	51	67	79	71		160	62
	1.2. Ribeira	22	69	44	52	71	83	77		166	57
	2.1. Pobra	22	5	34	26	46	69	46		150	56
	2.2. Pobra	21	5	18	3	39			21	0	79
	3.1. Pobra	21	30	17	3	28		23	0	48	0
	3.2. Pobra	21	17	26	3	26		41	0	125	16
	3.3. Pobra	22	35	23	3	39		48	0	116	11
	4.1. Pobra	22	31	30	7	53		65	28	144	13
	4.2. Pobra	25	5	19	7	46		70	19	98	19
	4.3. Pobra	7	6	0	3			46	0	0	64
	5.1. Vilagarcía	25	38	8	3	45	45	9	98		11
	5.2. Vilagarcía	7	17	39	4	58		57	2	126	13
	6.1. Cambados	34	62	9	3	41	7		0	69	5
	6.2. Cambados	21	65	42	12	60	68	41		155	17
	6.3. Cambados	27	83	37	24	61	84	55		165	45
	7.1. Cambados	21	82	50	40	88	97	73		173	68
	7.2. Cambados	16	42	46	48	82		109	80	186	65
	8.1. Cambados	21	55	13	3	50		45	0	138	0
	8.2. Grove	27	6	90	15	77	50	12		147	18
	8.3. Grove	38	94	0	0	43	0		0	65	11
	9.1. Grove	96	138	39	51	125	109	115	181	118	
	9.2. Grove	36	107	81	109	157	134	173	257	159	
	9.3. Grove	74	139	123	47	115	97	117	185	112	
	9.4. Grove	140	122	79	104	141	139	173	255	145	
Muros-Noia	1 Muros	97	105	192	129	159	162	169	245	156	
	2 Muros	72	88	164	85	123	125	75	213	125	
	3 Noia	39	164	119	51	121	109	60	181	125	
Pontevedra	1.1. Cangas	199	141	183	117	168	208	286	270	174	
	1.2. Cangas	180	160	249	138	175	222	275	285	189	
	2.1. Bueu	184	174	278	124	160	271	304	266	167	
	2.2. Bueu	184	187	249	129	170	261	292	260	173	
	2.3. Bueu	157	133	278	151	169	271	290	274	168	
	3.1. Portonovo	183	151	107	89	141	212	148	197	98	
	3.2. Portonovo	163	158	151	91	152	223	208	219	123	
	3.3. Portonovo	14	73	164	88	142	218	225	238	126	

6 **Table 1.** Continuation

7

Ría	Area	year									
		98	99	00	01	02	03	04	05	06	
Vigo	1.1. Cargas	179	123	193	144	170	209	272	281	187	
	1.2. Cargas	193	122	139	121	178	204	276	267	173	
	1.3. Cargas	98	24	149	112	171	202	265	263	180	
	2.1. Cargas	105	24	63	68	78		112	128	197	78
	2.2. Cargas	60	4	52	53	84	112	160	187	74	
	3.1. Cargas	47	4	41	47	60	90	79		128	32
	3.2. Redondela	30	4	26	36	61	83	37	62	18	
	4.1. Redondela	36	4	26	15	116	78	10	55		0
	4.2. Redondela	38	4	23		15	98	78	0	74	6
	5.1. Redondela	86	22	24	30		116	133	47	124	21
	5.2. Vigo	184	131	77	45	57	98		113	134	39

8

Table 2. Geometric characteristics of the mussel raft cultivation areas defined in the four Rías Baixas of NW Spain. V: Volume of the cultivation area (in 10^9 m^3); L: length of the open end of the cultivation area to the self (in 10^3 m). The areas are shown in Figure 1.

Ría	L (x 10 ³ m)			V (x 10 ⁹ m ³)		V/L (x 10 ⁶ m ²)
	ID	measured	corrected	ID	measured	
Muros–Noia	L1	5.69	5.69	V1	1.41	0.25
Arousa (inner)	L2	6.72	6.72	V2	1.11	0.17
Arousa (outer)	L3	9.55	8.62*	V2+V3	3.49	0.40
Pontevedra	L4	11.49	4.48†	V4	2.35	0.52
Vigo (inner)	L5	2.50	2.50	V5	0.53	0.21
Vigo (outer)	L6	7.62	3.32‡	V5+V6	1. 52	0.46

* L3 has been corrected to weight the blockage of the Salvora Island to the free exchange of the Ría de Arousa with the adjacent shelf. The 10% reduction applied is the ratio between the width of the Salvora island (1.19 km) compared with the total width of the mouth of the Ría de Arousa (12.24 Km).

† L4 has been corrected to weight the blockage of the Ons Islands to the free exchange of the Ría de Pontevedra with the adjacent shelf. The 61% reduction applied is the ratio between the width of the southern mouth (4.48 Km) compared with the total width of the mouth of the Ría de Pontevedra (11.49 Km).

‡ L6 has been corrected to weight the blockage of the Cíes Islands to the free exchange of the Ría de Vigo with the adjacent shelf. The 56% reduction applied is the ratio between the width of the southern mouth (6.57 Km) compared with the total width of the mouth of the Ría de Vigo (15.05 Km).

1 **Figure captions**

2 **Figure 1.** Map of the Galician Rías Baixas (NW Spain) showing the position of the
3 mussel raft cultivation areas and the volumes (V) and lengths (L) defined in this work.
4 V1, L1: Ría de Muros–Noia; V2, L2: Ría de Arousa (inner); V3, L3: Ría de Arousa
5 (outer); V4, L4: Ría de Pontevedra; V5, L5: Ría de Vigo (inner); V6, L6: Ría de Vigo
6 (outer).

7 **Figure 2.** Offshore Ekman transport off the Ría Baixas: average seasonal cycle for the
8 period 1966–2006 (solid line) and average seasonal cycles for consecutive groups of 3
9 years (dotted lines).

10 **Figure 3.** Time evolution of (a) A_0 , the constant of the harmonic analysis of the
11 offshore Ekman transport (in $\text{m}^2 \text{s}^{-1}$); (b) the onset (black dots) and offset (white dots)
12 of the upwelling season (in days); (c) upwelling (black dots) and downwelling (white
13 dots) seasons average offshore Ekman transport (in $\text{m}^2 \text{s}^{-1}$); renewal time, $1/I_w$ (in 10^3
14 s m^{-2}).

15 **Figure 4.** Relationship between the maximum number of days per year that a given
16 mussel raft cultivation area is closed to extraction and (a) $1/I_w$ for the inner and outer
17 Ría de Vigo; (b) the renewal time for the inner and outer Ría de Vigo; and (c) the
18 renewal time for the six study areas of the Rías Baixas. For symbols, please see legend
19 of panel b.

Longitude