Mollusk Assemblages as Records of Past and Present Ecological Status

Supplementary Material

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SECTION 1: Datasets

TABLE S1.1 | Live-only benthic community data sets

Source	Water Body	Station	Data Group[1]		# Benthic Invertebrate Species	# Benthic Invertebrate Individuals	# Mollusk Species	# Mollusk Individuals	% Mollusk Individuals
			AMBI	Bentix					
Borja et al. (2009)	Bay of Biscay								
		41	B	—	62	18,274	11	333	1.8%
		42	A	A, B	93	118,379	19	10,462	8.8%
Bouchet and Sauriau (2008)	Bay of Biscay								
		Y1	B	A	32	1,534	10	226	14.7%
CEFAS (2004)	United Kingdom coastal waters								
		55	A	A	209	3,214	38	596	10.8%
		70	A	B	99	1,482	16	283.33	19.1%
		175	A	A	131	2,929	26	298	10.2%
		270	B	B	51	1,040	18	608	58.5%
		295	B	B	83	1,178	27	334	28.4%
		325	B	B	59	29,672	12	6,751	18.5%
		345	B	A	74	749.33	15	67.33	9.0%
		536	A	B	141	3,222	26	1,168	36.3%
		565	B	A	80	98,842	16	574	0.6%
		566	A	A	49	68,272	10	930	1.4%
		576	A	A	138	12,255	32	520	4.2%
		605	B	A	122	3,114	20	795	25.5%
		646	A	B	138	4,871	21	156	3.2%
		655	A	A	39	618	10	146	23.6%
		768	A	A	62	5,756	13	2,980	51.8%
		805	A	B	128	1,650	32	492	29.8%
		809	B	B	168	27,098	31	13,978	5.2%
		825	A	B	81	800	12	101	12.6%
		845	A	B	135	10,494	20	2,713	25.9%
		865	B	A	166	919	23	47	5.1%
Cinar et al. (2012)	Izmir Bay								
		Sta. 4	A	A	90	2,540	16	600	23.6%
		Sta. 6	B	B	106	3,720	18	380	10.2%
		Sta. 11	A	A	115	4,530	20	1,330	29.4%
		Sta. 17	B	B	234	9,710	43	1,030	10.6%
		Sta. 20	A	B	153	7,817	37	1,387	17.7%
		Sta. 22	B	B	136	7,908	31	1,468	18.6%
		Sta. 24	A	A	78	9,320	30	1,540	16.5%
		Sta. 26	A	A	198	8,180	53	1,390	17.0%

Dashfield and McNeill (2013)	English Channel								
		Cawsand (18/07/2008)	A	A, B	115	5,184	29	560	10.8%
		Cawsand (3/09/2008)	B	A, B	126	5,553	25	536	9.7%
		Cawsand (18/11/2008)	B	A, B	108	5,707	27	414	7.3%
		Cawsand (14/01/2009)	A	B	110	5,417	27	475	8.8%
		Cawsand (4/03/2009)	A	A, B	103	4,395	25	327	7.4%
		Cawsand (16/09/2009)	A	A	88	2,372	15	222	9.4%
		Cawsand (19/05/2010)	B	A	72	1,217	15	84	6.9%
		Cawsand (7/07/2010)	B	A	83	1,173	13	89	7.6%
		Cawsand (9/09/2010)	A	B	76	810	11	46	5.7%
		Eddystone (21/05/2008)	A	A	83	503	13	24	4.8%
		Eddystone (23/07/2008)	B	A, B	172	2,404	29	140	5.8%
		L4 (Hilmars Box - 17/07/2008))	B	A, B	152	1,848	27	115	6.2%
		L4 (Hilmars Box - 17/09/2008)	A	A	164	1,767	24	96	5.4%
		L4 (Hilmars Box - 5/11/2008)	B	B	142	2,172	22	102	4.7%
		L4 (Hilmars Box - 18/03/2009)	B	—	108	710	13	32	4.5%
		L4 (Hilmars Box - 11/06/2009)	A	A, B	170	1,808	22	204	11.3%
		Rame (4/06/2008)	B	—	56	1,132	11	321	28.4%
		Rame (28/01/2009)	B	—	50	831	13	170	20.5%
		Rame (19/03/2009)	A	—	58	705	10	113	16.0%
Gittenberger and van Loon (2013)	North Sea								
		North Sea	A	A	54	14,481	14	3,970	27.4%
		The Delta	B	A	148	61,521	16	7,234	11.8%
Gremare et al. (1998)	Bay of Banyuls-sur-mer								
		19	A	B	55	458	11	44	9.6%
		26	A	B	58	884	14	204	23.1%
		31	A	A	62	1,770	17	74	4.2%
		43	A	B	55	3,448	17	172	5.0%
		178	A	B	68	1,000	10	78	7.8%
		183	A	A	56	718	11	94	13.1%
Husa et al. (2014)	Hardangerfjord								
		Herand	B	—	41	322	12	119	37.0%
		Husnes	A	—	48	574	13	117	20.4%
		Varaldsoy	B	A	50	556	14	194	34.9%
Makra and Nicolaidou (2000)	Argolikos Bay								
		1	A	B	57	789	10	82	10.4%
		3	B	B	94	878	16	52	5.9%

Warwick and Clarke (1993)	NE Atlantic Ocean								
		CR	A	A	56	4,230	13	294	6.9%
		E63	B	B	74	902	13	346	38.4%
		E64	B	A	66	1,355	11	311	23.0%
		E65	A	A	59	2,072	10	348	16.8%
		E67	B	A	49	2,001	11	634	31.7%
		E68	B	B	47	2,964	10	848	28.6%
		K	B	A	50	15,643	17	3,281	21.0%
		M77	B	A	131	129,503	27	507	0.4%
		M78	B	A	110	8,249	19	274	3.3%
		M79	A	A	158	15,913	22	2,555	16.1%
		M80	B	A	175	18,097	29	3,169	17.5%
		M81	B	A	175	21,598	36	1,207	5.6%
		S1	A	B	106	5,019	22	204	4.1%
		S3	A	A	78	4,645	19	1,210	26.1%
Zenetos et al. (1996)	Atalanti Bay								
		12	B	—	27	1,998	10	426	21.3%
Zettler (2001)	Baltic Sea								
		Mecklenburger Bucht (Dameshöved)	A	B	39	208	13	65	31.3%
		Mecklenburger Bucht (Kadetrinne, KM G 26)	B	—	58	144	10	25	17.4%
		Mecklenburger Bucht (Kaltenhof, Poel, KM B 5)	B	A	52	164	14	60	36.6%
		Mecklenburger Bucht (Kaltenhof, Poel, KM B 10)	B	B	60	229	13	60	26.2%
		Mecklenburger Bucht (Kaltenhof, Poel, KM B 15)	B	A, B	69	246	16	72	29.3%
		Mecklenburger Bucht (Kaltenhof, Poel, KM B 22)	B	A	59	131	13	34	26.0%
		Mecklenburger Bucht (Klein Klützhöved, KM A 10)	A	A, B	70	248	17	62	25.0%
		Mecklenburger Bucht (Klein Klützhöved, KM A 15)	B	A, B	84	261	22	82	31.4%
		Mecklenburger Bucht (Klein Klützhöved, KM A 20)	A	A, B	71	180	17	55	30.6%
		Mecklenburger Bucht (Kühlungsborn, KM C 10)	A	—	56	194	13	45	23.2%
		Mecklenburger Bucht (Kühlungsborn, KM C 15)	B	A, B	68	244	16	60	24.6%

	Mecklenburger Bucht (Kühlungsborn, KM C 20)	B	A, B	63	193	13	53	27.5%
	Mecklenburger Bucht (MB1)	A	A, B	86	699	20	207	29.6%

[1]The AMBI software calculates index scores based on stations. Hence, AMBI Data Groups are either A or B. The Bentix Excel script calculates index scores for each replicate at each station. Hence, Bentix Data Groups are A, B, or both (A, B). A Bentix Data Group of "A, B" indicates that replicates from the same station were assigned to different groups.

TABLE S1.2 | Molluscan live-dead data sets

Source	Water Body	Station	# Live Mollusk Species	# Live Mollusk Individuals	# Dead Mollusk Species	# Dead Mollusk Individuals
Giacobbe and Leonardi (1985)	Milazzo Gulf					
		Intermediate	15	96	44	789
		Deep	10	33	77	1,465
		Total	22	129	93	2,254
Leshno et al. (2015)	Levantine Margin, Mediterranean Sea					
		Total	19	3,764	77	7,516
Peharda et al. (2002)	Malo Jezero					
		2	6	19	13	95
		21	4	19	12	21
		22	6	26	20	413
		23	4	25	20	449
		Total	14	165	31	5,023
Weber and Zuschin (2013)	Adriatic Sea					
		Intertidal_Inner Flat	5	254	10	1,587
		Intertidal_Outer Flat	7	108	10	1,280
		Intertidal_Sandbar	7	360	9	929
		Intertidal_Channel	5	68	9	1,011
		Sublittoral_Shallow	8	395	8	522
		Sublittoral_Seagrass	7	95	11	1,254
		Sublittoral_Delta Sand	6	756	11	546
		Total	11	2,036	11	7,129
Zenetos and Van Aartsen (1995)	Aegean Sea					
		Total	83	603	119	617

SECTION 2 | Preliminary analysis of mollusk-only and whole-community relationship

We conducted a preliminary, exploratory analysis of the effects of 12 variables on the relationship between mollusk-only and whole-community calculations of AMBI and Bentix (expressed as the difference of whole-community values - mollusk-only values; **Figures S2.1, S2.2**). This analysis was conducted using the statistical software JMP 11.0.0 (SAS Institute Inc.) and used only the data set from Warwick and Clarke (1993). The analysis included data from all stations in the data set that had at least four mollusk species (the minimum number of species recommended for calculating a reliable Bentix value). Our analysis suggests that the "whole-community - mollusk-only" difference tends to approach zero (i.e., the accuracy of mollusk-only index calculations increases) when the ecological group of the most abundant mollusk species in the community increases, when the proportion of individuals in the whole community that are mollusks increases (particularly ~15% and higher), and when the evenness — estimated using Hurlbert's PIE (Probability of Interspecific Encounter; Hurlbert, 1971) — of the whole community is relatively high (at least ~0.7-0.8; **Figure S2.1**). Whole-community AMBI also shows negative correlations with the number of species in the whole community (r=-0.56) and with PIE (r=-0.50) that are much weaker for mollusk-only AMBI (r=-0.33 and r=0.01 for number of species and PIE, respectively). These factors have a similar pattern of relationships with whole-community and mollusk-only Bentix, but the correlations tend to be weaker (r=0.22 and r=0.44 for the relationship between whole-community Bentix and number of species and PIE, respectively, while the correlation coefficients for the relationship of mollusk-only Bentix to number of species and PIE were r=0.16 and r=0.18).

When the number of mollusk species, "whole-community - mollusk-only" difference, whole-community index values, and the proportion of individuals at each station that are mollusks are plotted together and grouped by the average AMBI ecological group for each station (**Figure S2.2**), several patterns are evident. First, the "whole-community - mollusk-only" differences tend to approach zero as the number of mollusk species increases (primary y-axis in **Figure S2.2**) and as the proportion of mollusk individuals increases (size of plotted points in **Figure S2.2**), although there does not appear to be a strong interaction between these variables (r=-0.16; **Figure S2.1**). The concordance between whole-community and mollusk-only index values also improves with increasing whole-community ecological status (color of plotted points in **Figure S2.2**). Finally, although there are stations with low "whole-community - mollusk-only" differences in index values in all average AMBI ecological group bins, the variance in the difference decreases and the values are closer to zero as the average AMBI ecological group increases (secondary y-axis in **Figure S2.2**). This pattern is analogous to the relationship between "whole-community - mollusk-only" differences and the AMBI ecological group of the most abundant mollusk species in **Figure S2.1** because the ecological groups of the most abundant species are likely to influence the resulting index value.

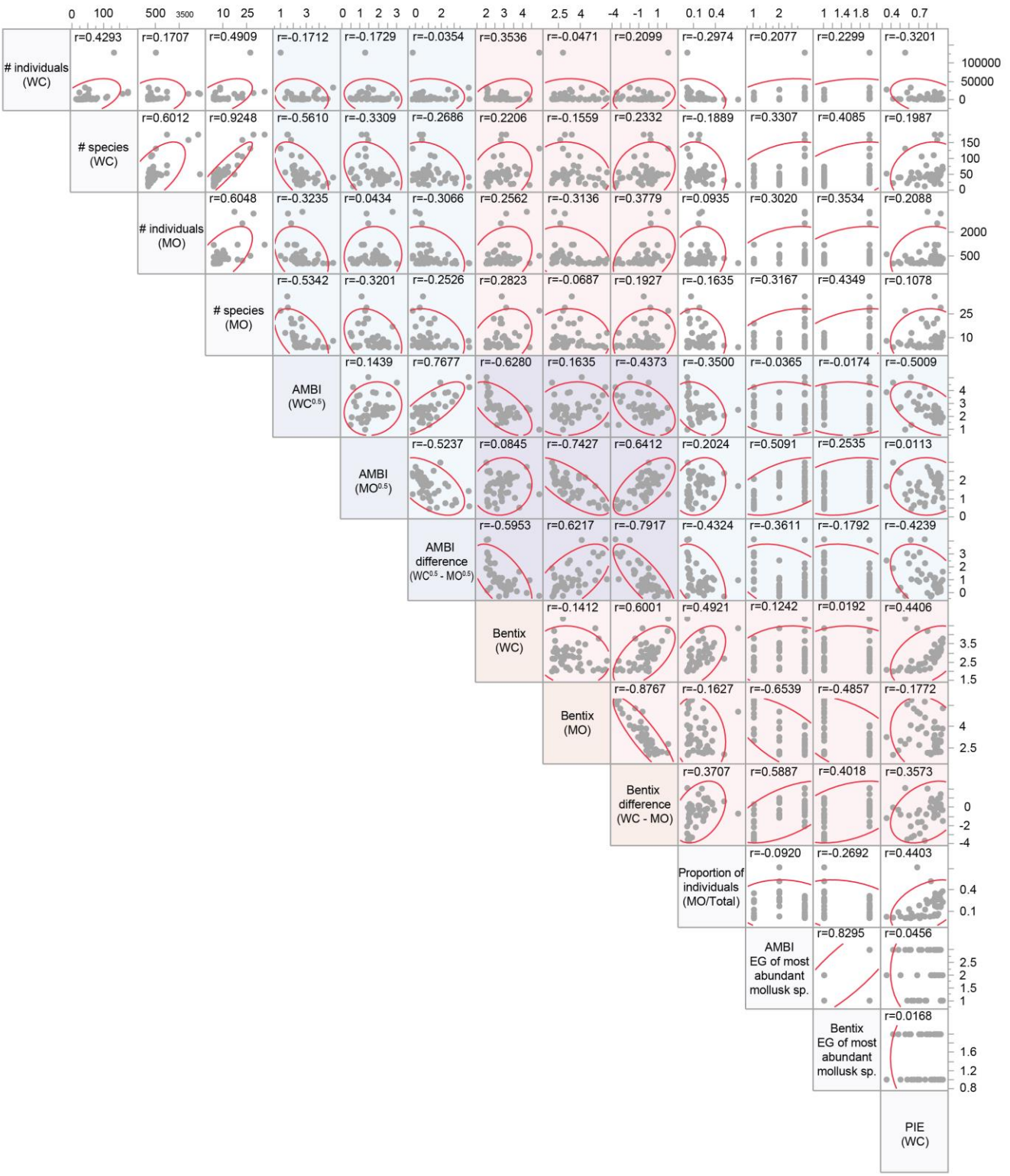

FIGURE S2.1 | Scatterplot matrix of 12 variables with the potential to impact the relationship between whole-community and mollusk-only calculations of AMBI and Bentix. Density ellipses for each scatterplot are shown in red. Cells showing AMBI calculations are shaded blue, while those showing

Bentix calculations are shaded red. WC = “whole-community”; MO = “mollusk-only”; EG = “ecological group”; PIE = “probability of interspecific encounter”.

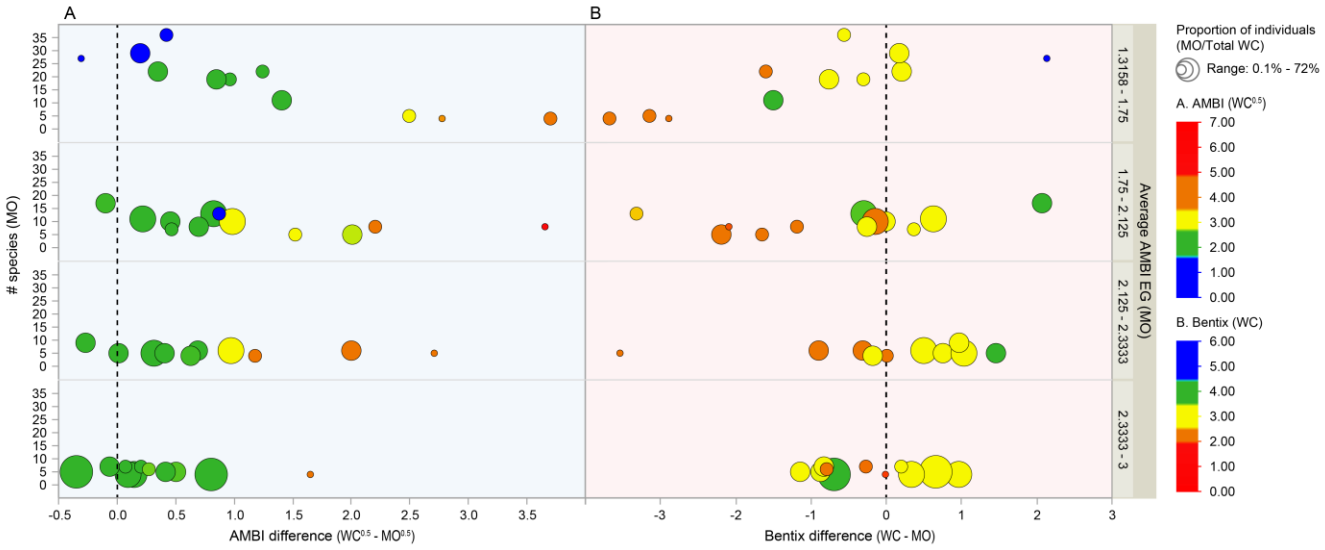

FIGURE S2.2 | The effects of four variables on the “mollusk-only - whole-community” difference for A) AMBI and B) Bentix. The primary y-axis and secondary y-axis show the number of mollusk species and average AMBI ecological group of the mollusk species, respectively. The color of the plotted points corresponds to the whole-community ecological status of each station, and the relative sizes of the points indicate the proportion of individuals at each station that are mollusks. Each point represents one station from the data set of Warwick and Clarke (1993). WC = “whole-community”; MO = “mollusk-only”; EG = “ecological group”.

REFERENCES

Borja, A., Muxika, I., and Rodríguez, J. G. (2009). Paradigmatic responses of marine benthic communities to different anthropogenic pressures, using M-AMBI, within the European Water Framework Directive. *Mar. Ecol.* 30, 214–227. doi:10.1111/j.1439-0485.2008.00272.x.

Bouchet, V. M. P., and Sauriau, P.-G. (2008). Influence of oyster culture practices and environmental conditions on the ecological status of intertidal mudflats in the Pertuis Charentais (SW France): A multi-index approach. *Mar. Pollut. Bull.* 56, 1898–1912. doi:10.1016/j.marpolbul.2008.07.010.

CEFAS (2004). UK National Marine Monitoring Programme - Second Report (1999-2001).

Çinar, M. E., Katagan, T., Öztürk, B., Bakir, K., Dagli, E., Açik, S., et al. (2012). Spatio-temporal distributions of zoobenthos in soft substratum of Izmir Bay (Aegean Sea, eastern Mediterranean), with special emphasis on alien species and ecological quality status. *J. Mar. Biol. Assoc. U. K.* 92, 1457–1477. doi:10.1017/S0025315412000264.

Dashfield, S., and Mc Neill, L. (2013). Plymouth Marine Laboratory Benthic Survey macrofauna abundance and biomass data set from four sites in the Western English Channel surveyed bimonthly from 2008 to 2010 containing the data from the samples analysed as at December 2012. Plymouth Marine Laboratory, UK.

Giacobbe, S., and Leonardi, M. (1985). Caratteristiche dei sedimenti e bionomia bentonica in un'area campione del Golfo di Milazzo. *Mem. Biol. Mar. E Oceanogr.* 15, 165–189.

Gittenberger, A., and van Loon, W. (2013). Sensitivities of marine macrozoobenthos to environmental pressures in The Netherlands. *Ned. Faun. Meded.* 41, 79–112.

Grémare, A., Amouroux, J. M., and Vétion, G. (1998). Long-term comparison of macrobenthos within the soft bottoms of the Bay of Banyuls-sur-mer (northwestern Mediterranean Sea). *J. Sea Res.* 40, 281–302.

Hurlbert, S. H. (1971). The nonconcept of species diversity: A critique and alternative parameters. *Ecology* 52, 577–586. doi:10.2307/1934145.

Husa, V., Kutti, T., Ervik, A., Sjøtun, K., Hansen, P. K., and Aure, J. (2014). Regional impact from fin-fish farming in an intensive production area (Hardangerfjord, Norway). *Mar. Biol. Res.* 10, 241–252. doi:10.1080/17451000.2013.810754.

Leshno, Y., Edelman-Furstenberg, Y., Mienis, H., and Benjamini, C. (2015). Molluscan live and dead assemblages in an anthropogenically stressed shallow-shelf: Levantine margin of Israel. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 433, 49–59. doi:10.1016/j.palaeo.2015.05.008.

Makra, A., and Nicolaidou, A. (2000). Benthic communities of the inner Argolikos Bay. *Belg. J. Zool.* 130, 61–67.

Peharda, M., Hrs-Brenko, M., Bogner, D., Lucic, D., Onofri, V., and Benovic, A. (2002). Spatial distribution of live and dead bivalves in saltwater lake Malo Jezero (Mljet National Park). *Period. Biol.* 104, 115–122.

Warwick, R. M., and Clarke, K. R. (1993). Comparing the severity of disturbance: a metaanalysis of marine macrobenthic community data. *Mar. Ecol. Prog. Ser.* 92, 221–231.

Weber, K., and Zuschin, M. (2013). Delta-associated molluscan life and death assemblages in the northern Adriatic Sea: Implications for paleoecology, regional diversity and conservation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 370, 77–91. doi:10.1016/j.palaeo.2012.11.021.

Zenetos, A. (1996). Classification and Interpretation of the Established Mediterranean Biocoenoses Based Solely on Bivalve Molluscs. *J. Mar. Biol. Assoc. U. K.* 76, 403. doi:10.1017/S0025315400030630.

Zenetos, A., and Van Aartsen, J. J. (1995). The deep sea molluscan fauna of the S.E. Aegean Sea and its relation to the neighbouring faunas. *Boll. Malacol.* 30, 253–268.

Zettler, M. L. (2001). Historical benthic data from the southern Baltic Sea (1839-2001). Baltic Sea Research Institute Warnemünde (IOW), Germany.