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Supplementary material

Biodiversity, trait composition and ecological functioning: impacts of coastal urbanisation on subtropical mudflats

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The subtropical mudflat macrofaunal assemblages were sampled in selected 24 mudflats along south-east Queensland, Australia (Table S1). Anthropogenic activities have a profound impact on biodiversity and ecosystem functioning, and therefore, the coastal sub-catchments were categorised in to 4 urban land-uses (Fig. S1).

Geographic locations of the study site

Table S1. The geographic coordinates of the 24 subtropical mudflats along the south-east Queensland coast (negative latitudes indicate S of the equator) (Fig. 1)

H_ind, high industry; L_ind, low industry; R, residential; P, peri-urban

Site number	Latitude (°)	Longitude (°)	Sub-catchment & (classification)	Sub-catchment size (km^2)
1	–27.8222	153.0464	Cooboulture River Northern catchment (P)	12.59
2	–27.1747	153.0319	Deception Bay coastal drainage (R)	2.54
3	–27.1956	153.0431	Redcliffe Deception Bay (L_ind)	17.23
4	–27.2597	153.0747	Hays inlet (P)	78.81
5	–27.2775	153.0369	Pine River Northern catchment (P)	9.56
6	–27.3436	153.0933	Kedron Brook (H_ind)	59.23
7	–27.3425	153.1000	Kedron Brook (H_ind)	59.23
8	–27.3947	153.1391	Inter catchment (H_ind)	14.21
9	–27.3950	153.1583	Brisbane port (H_ind)	9.84
10	–27.3933	153.1689	Brisbane port (H_ind)	9.84
11	–27.4222	153.1706	Crab Creek (H_ind)	3.65
12	–27.4764	153.2033	Tarradarrapin creek (R)	14.22
13	–27.4808	153.2422	Hillard Creek (L_ind)	27.57
14	–27.5158	153.2622	Cleveland (R)	10.58
15	–27.5739	153.3056	Eprapah Creek (R)	38.70
16	–27.5622	153.3003	Eprapah Creek (R)	38.70
17	–27.6019	153.3019	Moogurrapum Creek (L_ind)	15.90
18	–27.6436	153.3119	Southern Redland coastal drainage (P)	8.62
19	–27.6589	153.3092	Southern Redland coastal drainage (P)	8.62
20	–27.7053	153.3239	Logan River lower catchment (L_ind)	192.35
21	–27.7178	153.3539	Logan River lower catchment (L_ind)	192.35
22	–27.7503	153.3511	Behm Creek (L_ind)	21.10
23	–27.8222	153.3781	McCoy’s Creek (P)	10.06
24	–28.1069	153.4464	Tallebudgera Creek (R)	24.11

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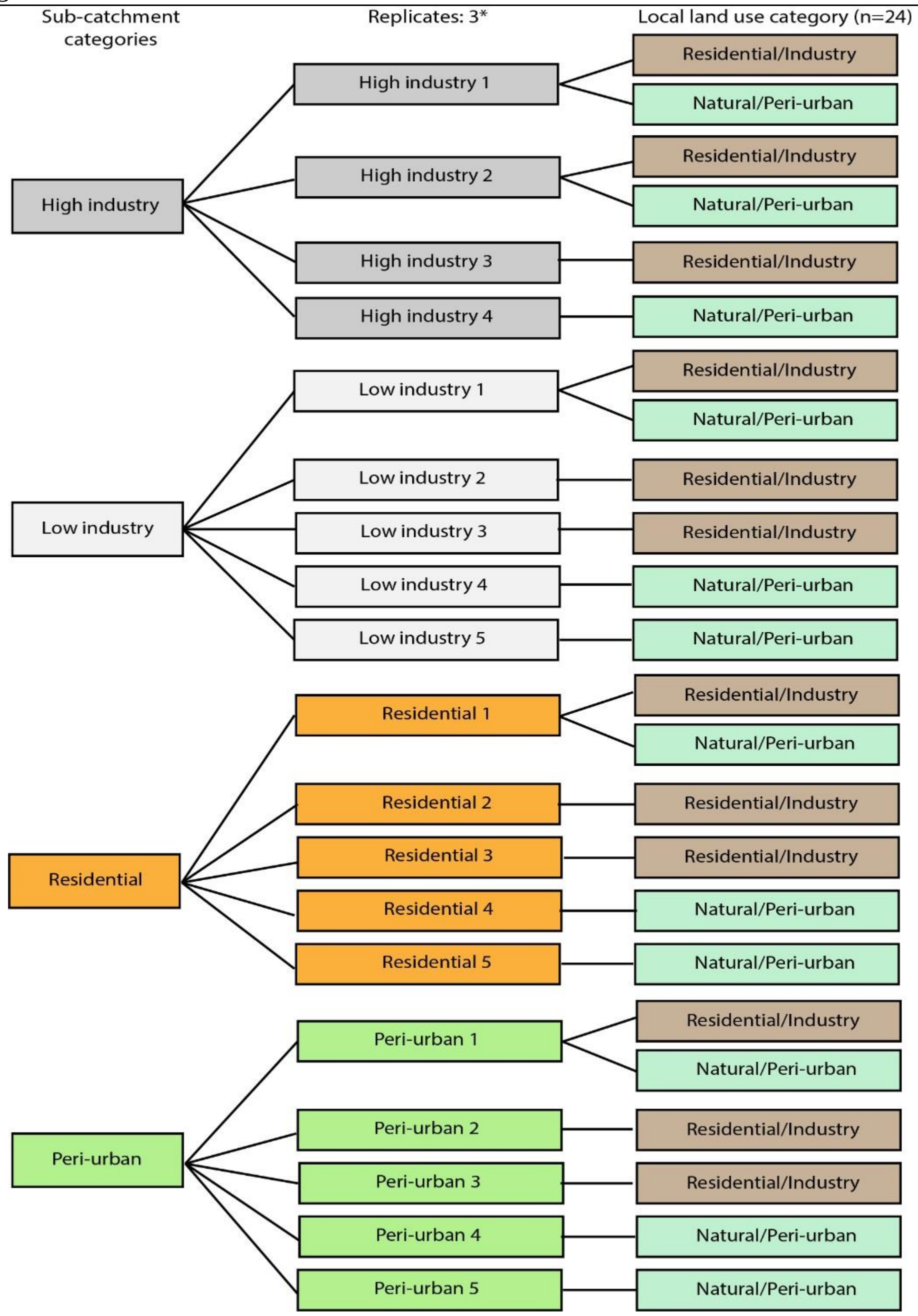

Fig. S1. A schematic of the experimental design. Four sub-catchment categories were used, replicated at least 3 times with two sites of differing land use selected within each replicate sub-catchment. In total 24 field sites were used. (Note: it was not always possible to select both the residential–industry and natural–peri-urban sites within the same sub-catchment so overall 4–5 sub-catchments were used in each of the 4 categories). The four sub-catchment categories were: low-intensity Industrial (4–12% land use coverage), high-intensity industrial (>35% land use coverage), residential (53–90% land use coverage) and peri-urban (54–70% land use coverage). The replicated sub-catchments for each land use category were selected so that they were spatially distributed along the coast and not immediately adjacent to each other (except high industry which was unavoidable) maximising the spatial separation of replicates.

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Macrofaunal assemblages of subtropical mudflats in south-east Queensland

A preliminary survey of macrofaunal assemblage was conducted at Tallebudgera Creek was used to determine the minimum number of box core samples that would best represent the assemblage of a given subtropical mudflat in south-east Queensland (Fig. S2).

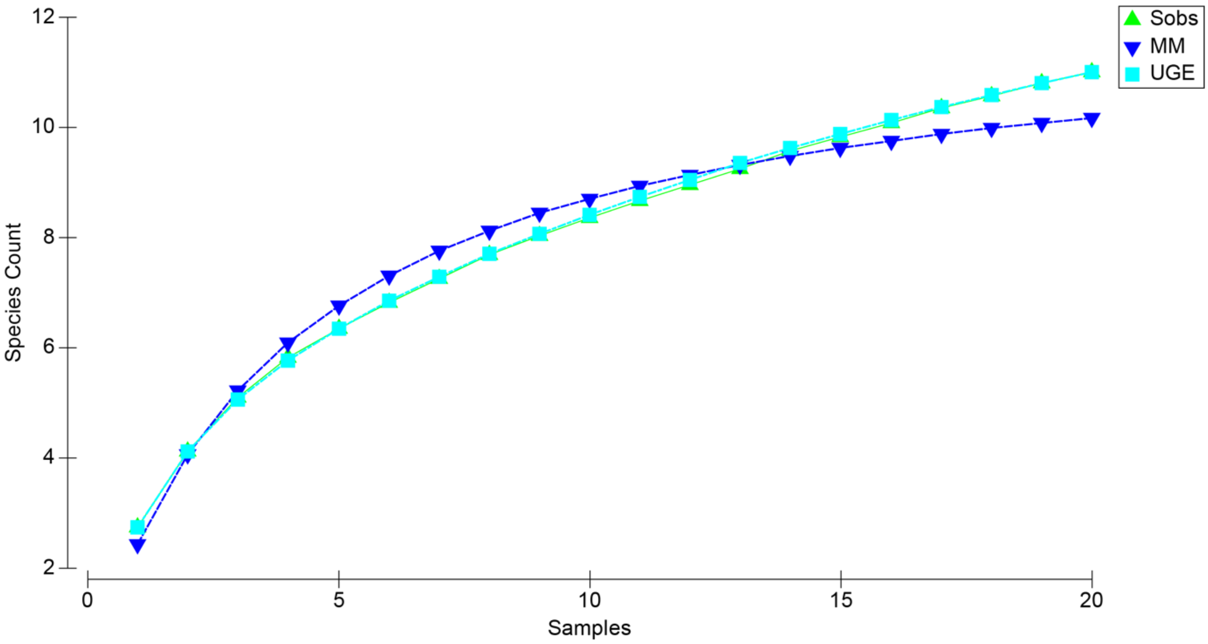

Fig. S2. Species accumulation plot for macrofaunal benthos collected in 20 core samples (0.018 cm^2 × 11-cm sediment depth) from the mid-intertidal mudflats at Tallebudgera Creek, south-east Queensland (January 2016). The observed species count (Sobs; green) plateaus after the 5th sample, thus a minimum of five box cores are required to represent the benthic macrofaunal assemblage. UGE, Ugland, Gray and Ellingsen (Ugland *et al*. 2003); MM, Michaelis-Menton.

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Table S2. The results of SIMPER to compare macrofaunal species composition between winter 2016 and summer 2017 across the 24 mudflats in south-east Queensland

Species that contributed more that >90% to the cumulative dissimilarity between the two seasons are shown.

Species	Mean abundance (individuals m^{-2})		Individual contribution (%)	Cumulative contribution (%)
	Winter 2016	Summer 2017		
Hiatula alba	2.06	2.7	5.25	5.25
Barantolla lepte	2.47	2.6	4.69	9.94
Magelona dakini	2.02	1.99	4.00	13.95
Nematoda	1.36	2.06	3.96	17.90
Marcia hiantina	1.21	1.8	3.94	21.84
Haminoea fusca	1.03	1.38	3.45	25.29
Notomastus torquatus	1.80	2.16	3.39	28.68
Aglaophamus australiensis	2.92	2.89	3.19	31.87
Victoriopisa australiensis	0.70	1.1	3.18	35.06
Armandia intermedia	0.91	1.42	3.09	38.15
Mactra maculata	1.02	1.11	3.07	41.22
Phyllodoce novaehollandiae	1.07	1.19	2.89	44.11
Owenia australis	2.04	2.24	2.79	46.91
Macrophthalmus setosus	1.51	1.98	2.78	49.69
Elphidium discoidale	0.32	1.1	2.69	52.38
Acetes sibogae	0.39	0.96	2.65	55.03
Mictyris longicarpus	1.50	1.62	2.62	57.65
Lumbrineris tetraura	0.36	0.96	2.50	60.15
Australonereis ehlersi	0.42	0.8	2.22	62.37
Myrianida australiensis	0.39	0.78	2.10	64.47
Pyrazus ebeninus	1.27	1.44	2.00	66.46
Glycera americana	0.28	0.77	1.99	68.46
Leitoscoloplos bifurcatus	0.48	0.72	1.99	70.45
Australoplax tridentata	0.53	0.61	1.96	72.41
Uca vomeris	0.44	0.7	1.94	74.35
Metapenaeus endeavouri	0.24	0.61	1.72	76.07
Nemertea	0.26	0.7	1.72	77.80
Conuber sordidum	0.74	0.98	1.65	79.45
Prionospio queenslandica	0.32	0.5	1.53	80.98
Stenothoe miersi	0.06	0.62	1.4	82.38
Alpheus richardsoni	0.24	0.48	1.38	83.76
Sternaspis scutata	0.18	0.5	1.37	85.13
Chaenostoma punctulatum	0.41	0.39	1.37	86.50
Laternula anatina	0.18	0.4	1.22	87.72
Lutraria impar	0.19	0.43	1.21	88.93
Eurysyllis tuberculata	0.18	0.33	1.05	89.98
Marphysa mullawa	0.30	0.24	1.05	91.03

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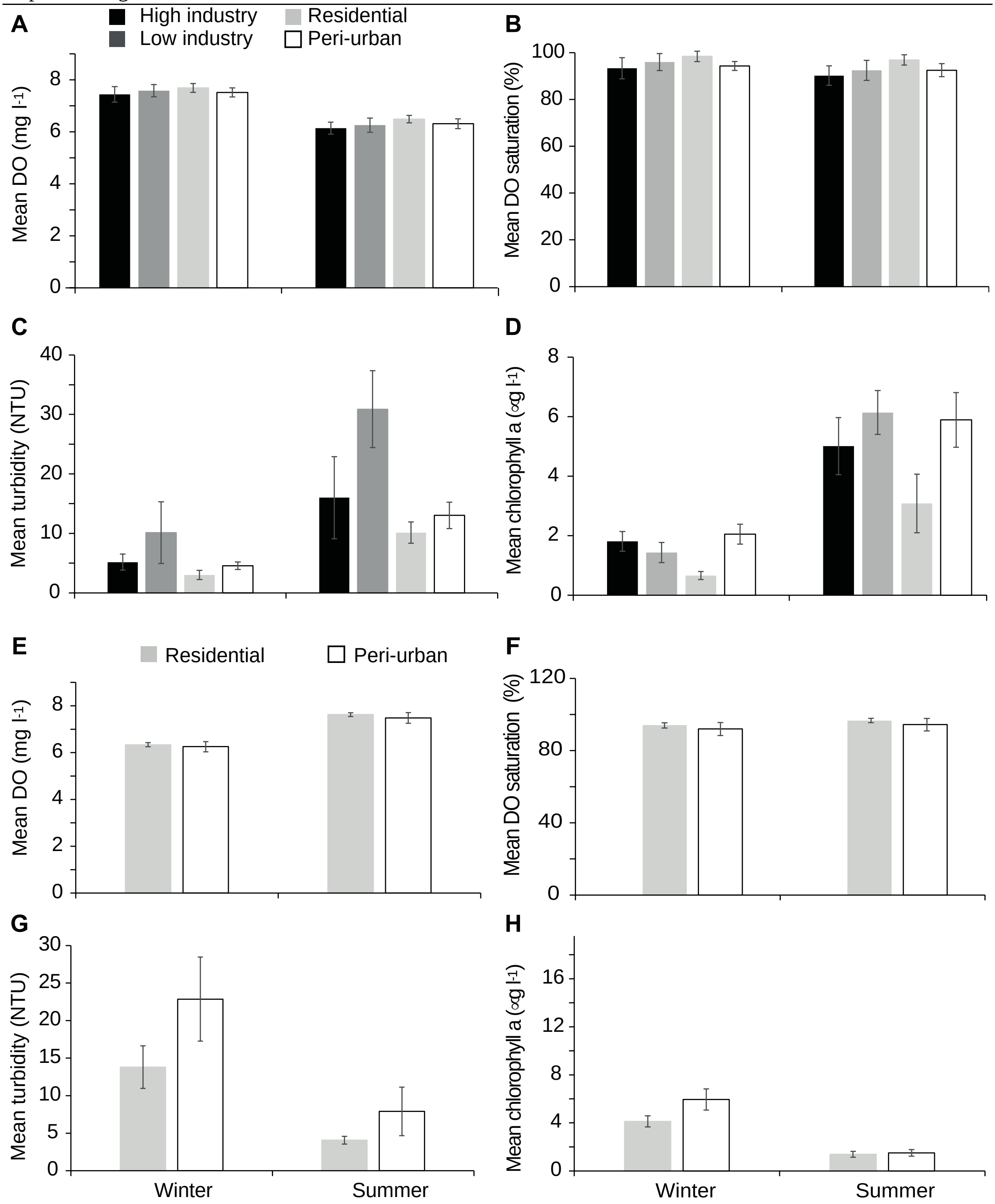

Fig. S3. Mean (±s.e.m.) water quality parameters (data from Ecosystem Health Monitoring Program 2017) between the four sub-catchment land-use categories in winter 2016 and summer 2017 (A) dissolved oxygen (DO) content, (B) dissolved oxygen (DO) saturation (at 17°C winter, 26°C in summer) (C) mean turbidity, and (D) mean chlorophyll-*a* content. Mean (±s.e.m.) water quality parameters (data from Ecosystem Health Monitoring Program 2017) between the two different local land-use categories (peri-urban and industrial–residential) (E) dissolved oxygen (DO) content, (F) dissolved oxygen (DO) saturation (Temperature in winter = 17°C, summer = 26°C), (G) turbidity and (H) chlorophyll-*a* concentration in winter 2016 and summer 2017. NTU, Nephelometric Turbidity Units.

Table S3. Results from one-way ANOVA to compare sediment parameters of the 24 mudflats and water quality parameters (measured adjacent, <4 km, to the 22 of the sites) (Ecosystem Health Monitoring Program 2017) between the four sub-catchment land-use categories, local land-use categories and 5 urban pressures in winter and summer

The water quality data were collected monthly from 2006 to 2015 (Ecosystem Health Monitoring Program 2017). Data were only available for 22 sites (data was not available for 2 sites belonging to peri-urban sub-catchment category). Bonferroni *P*-value in parentheses. OM, organic matter

Environmental parameters	Winter 2016		Summer 2017	
	F	*P*	*F*	*P*
Sub-catchment land-use categories				
Sediment parameters				
RDL depth	1.242	0.321	1.880	0.166
Chlorophyll-*a*	1.746	0.190	1.201	0.335
Organic matter	1.436	0.262	3.035	0.053
Silt and clay	2.598	0.081	1.540	0.235
Water quality parameters				
Dissolved oxygen content	0.207	0.890	0.463	0.712
Dissolved oxygen saturation	0.435	0.730	0.635	0.602
Turbidity	1.135	0.362	3.156	0.050 (0.062)
Chlorophyll-*a*	4.143	0.021 (0.058)	2.382	0.103
Local land-use categories				
Sediment parameters				
RDL depth	1.732	0.202	2.082	0.163
Chlorophyll-*a*	0.662	0.425	1.004	0.327
Organic matter	0.107	0.747	0.660	0.425
Silt and clay	0.795	0.382	1.858	0.187
Water quality parameters				
Dissolved oxygen content	0.392	0.538	0.144	0.708
Dissolved oxygen saturation	0.458	0.506	0.299	0.590
Turbidity	1.643	0.215	2.302	0.145
Chlorophyll-*a*	0.101	0.754	3.695	0.065
Agriculture urban pressure				
Sediment parameters				
RDL depth	0.963	0.398	0.988	0.389
Chlorophyll-*a*	0.716	0.500	0.298	0.746
Organic matter	1.297	0.294	0.335	0.719
Silt and clay	0.385	0.685	0.188	0.830
Water quality parameters				
Dissolved oxygen content	0.755	0.484	0.480	0.626
Dissolved oxygen saturation	1.068	0.363	0.711	0.504
Turbidity	0.858	0.440	2.003	0.162
Chlorophyll-*a*	1.622	0.224	3.090	0.069
OM enrichment urban pressure				
Sediment parameters				
RDL depth	0.260	0.773	0.104	0.902
Chlorophyll-*a*	0.883	0.428	0.402	0.674
Organic matter	1.995	0.161	3.770	0.040 (0.056)
Silt and clay	0.475	0.629	0.028	0.972
Water quality parameters				
Dissolved oxygen content	0.327	0.725	0.292	0.750
Dissolved oxygen saturation	0.153	0.859	0.061	0.941
Turbidity	1.330	0.288	0.654	0.531
Chlorophyll-*a*	0.600	0.559	0.576	0.572
Manufacturing urban pressure				
Sediment parameters				
RDL depth	0.103	0.903	0.016	0.985
Chlorophyll-*a*	0.330	0.723	0.709	0.504
Organic matter	0.512	0.606	1.703	0.206

Environmental parameters	Winter 2016		Summer 2017	
	F	*P*	*F*	*P*
Silt and clay	0.581	0.568	0.661	0.527
Water quality parameters				
Dissolved oxygen content	0.413	0.668	0.083	0.920
Dissolved oxygen saturation	0.223	0.802	0.051	0.951
Turbidity	0.316	0.733	0.049	0.952
Chlorophyll-*a*	0.559	0.581	0.224	0.803
Residential urban pressure				
Sediment parameters				
RDL depth	0.380	0.688	0.690	0.513
Chlorophyll-*a*	0.599	0.559	0.205	0.816
Organic matter	0.417	0.664	0.893	0.424
Silt and clay	0.239	0.790	0.114	0.893
Water quality parameters				
Dissolved oxygen content	0.950	0.404	0.891	0.427
Dissolved oxygen saturation	1.182	0.328	1.099	0.353
Turbidity	0.595	0.562	0.882	0.430
Chlorophyll-*a*	2.009	0.162	0.427	0.658
Utility urban pressure				
Sediment parameters				
RDL depth	0.287	0.753	0.342	0.714
Chlorophyll-*a*	1.098	0.352	0.719	0.499
Organic matter	0.053	0.948	0.157	0.856
Silt and clay	0.746	0.486	0.513	0.606
Water quality parameters				
Dissolved oxygen content	0.650	0.533	0.069	0.934
Dissolved oxygen saturation	0.546	0.588	0.144	0.867
Turbidity	0.123	0.885	0.111	0.896
Chlorophyll-*a*	1.885	0.179	1.018	0.380

Table S4. Results of two-way ANOVA to compare the number of individuals, species richness, Shannon–Weiner diversity and evenness of mudflat macrofaunal assemblages between the four sub-catchment land-use categories, local land-use categories or the interaction between sub-catchment and local land-use in winter or summer

Metric		Winter			Summer	
	F	df (*n*)	*P*	*F*	df (*n*)	*P*
Individuals m^{-2}						
Main effect: Sub-catchment land use categories	0.637	3 (6)	0.602	0.508	3 (6)	0.682
Main effect: local land use	1.184	1 (12)	0.293	0.147	1 (12)	0.707
Interaction: sub-catchment *v*. local land use	1.112	3 (24)	0.373	1.889	3 (24)	0.172
Species richness						
Main effect: Sub-catchment land use categories	1.067	3 (6)	0.391	1.005	3 (6)	0.416
Main effect: local land use	2.527	1 (12)	0.131	1.246	1 (12)	0.281
Interaction: sub-catchment *v*. local land use	0.720	3 (24)	0.554	2.195	3 (24)	0.128
Shannon–Weiner						
Main effect: Sub-catchment land use categories	1.195	3 (6)	0.343	1.082	3 (6)	0.385
Main effect: local land use	1.878	1 (12)	0.189	1.156	1 (12)	0.298
Interaction: sub-catchment *v*. local land use	0.480	3 (24)	0.701	1.524	3 (24)	0.246
Pielou's evenness						
Main effect: Sub-catchment land use categories	0.020	3 (6)	0.996	0.914	3 (6)	0.456
Main effect: local land use	0.050	1 (12)	0.826	0.004	1 (12)	0.950
Interaction: sub-catchment *v*. local land use	2.348	3 (24)	0.111	2.535	3 (24)	0.093

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Table S5. Results of one-way ANOSIM to compare the species and trait compositional differences between the three varying intensities of the proportional coverage in each urban pressure e.g. agriculture, organic matter (OM) enrichment industries, manufacturing, residential and utilities

Significant differences are denoted by *, $P < 0.05$

Urban pressure	Winter 2016		Summer 2017	
	Global *R*	*P*	Global *R*	*P*
Species composition				
Agriculture	–0.155	0.928	–0.202	0.985
OM enrichment	0.247	0.006*	0.184	0.034*
Manufacturing	–0.027	0.569	0.039	0.350
Residential	–0.250	0.988	–0.072	0.696
Utility	–0.057	0.683	–0.096	0.773
Trait composition				
Agriculture	–0.142	0.962	0.05	0.298
OM enrichment	0.144	0.051	–0.026	0.579
Manufacturing	0.104	0.133	0.107	0.108
Residential	–0.057	0.681	0.054	0.283
Utility	0.04	0.33	0.153	0.084

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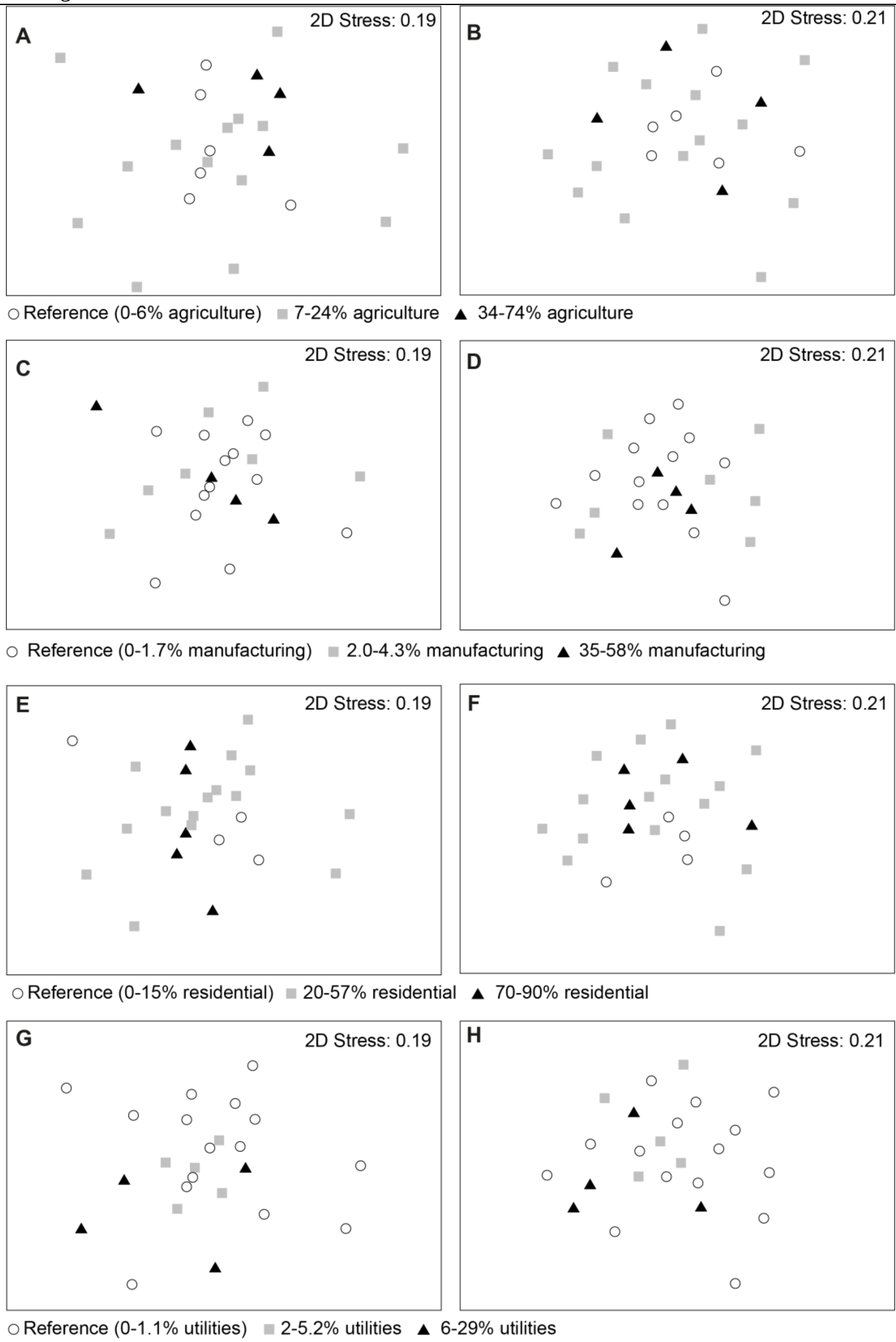

Fig. S4. nMDS ordination of the Bray-Curtis similarity (log(x+1) transformed) of the south-east Queensland macrofaunal mudflat assemblage taxonomic composition between sub-catchments with reference, medium and high cover of 4 urban pressures (of the total sub-catchment area) (A) agriculture in winter, (B) agriculture in summer, (C) manufacturing in winter, (D) manufacturing in summer, (E) residential in winter, (F) residential in summer, (G) utilities in winter and (H) utilities in summer.

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Table S6. The proportion of organic matter (OM) enriching industries of each sub-catchment area at three different levels of proportional cover of the OM enriching industries in each sub-catchment (reference <1.3ºC)

Site number	Sub-catchment (classification)	Sub-catchment with enriching industry (%)	Category
1	(a) Caboolture River Northern catchment (P)	0.00	<1.3% OM
2	(b) Deception Bay coastal drainage (R)	0.81	<1.3% OM
3	(c) Redcliffe Deception Bay (L_ind)	0.00	<1.3% OM
4	(d) Hays inlet (P)	1.25	<1.3% OM
5	(e) Pine River Northern catchment (P)	2.28	2–3% OM
6	(f) Kedron Brook (H_ind)	1.36	<1.3% OM
7	(f) Kedron Brook (H_ind)	1.36	<1.3% OM
8	(g) Inter catchment (H_ind)	1.24	<1.3% OM
9	(g) Brisbane port (H_ind)	0.00	<1.3% OM
10	(i) Brisbane port (H_ind)	0.00	<1.3% OM
11	(i) Crab Creek (H_ind)	3.55	3.5–7% OM
12	(j) Tarradarrapin creek (R)	2.59	2–3% OM
13	(k) Hillard Creek (L_ind)	4.51	3.5–7% OM
14	(l) Cleveland (R)	0.00	<1.3% OM
15	(m) Eprapah Creek (R)	3.52	3.5–7% OM
16	(m) Eprapah Creek (R)	3.52	3.5–7% OM
17	(n) Moogurrapum Creek (L_ind)	2.52	2–3% OM
18	(o) Southern Redland coastal drainage (P)	7.00	3.5–7% OM
19	(o) Southern Redland coastal drainage (P)	7.00	3.5–7% OM
20	(p) Logan River lower catchment (L_ind)	2.54	2–3% OM
21	(p) Logan River lower catchment (L_ind)	2.54	2–3% OM
22	(q) Behm Creek (L_ind)	5.02	3.5–7% OM
23	(r) McCoy's Creek (P)	0.27	<1.3% OM
24	(s) Tallebudgera Creek (R)	0.61	<1.3% OM

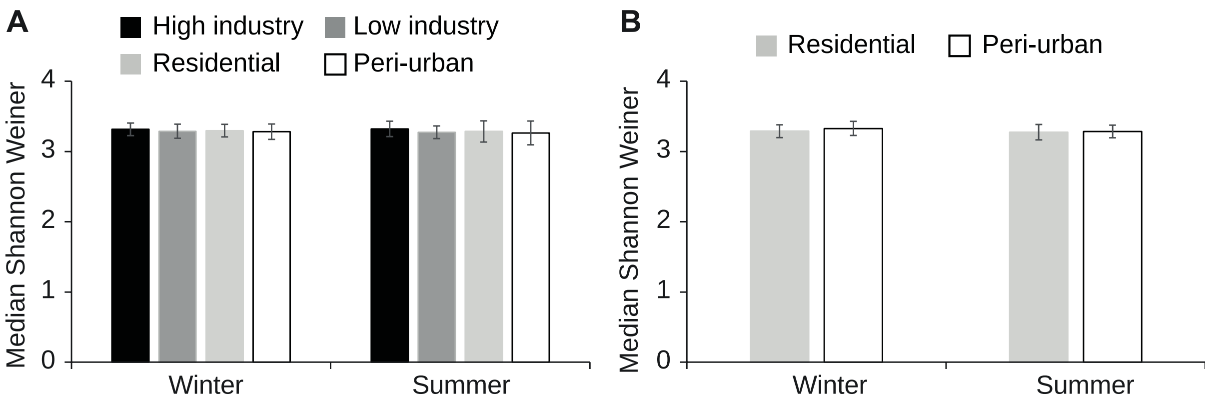

Fig S5. Median (±interquartile range) trait diversity for macrofaunal assemblages of mudflats in the (A) four different sub-catchment land-use categories and (B) local land-use categories in winter 2016 and summer 2017.

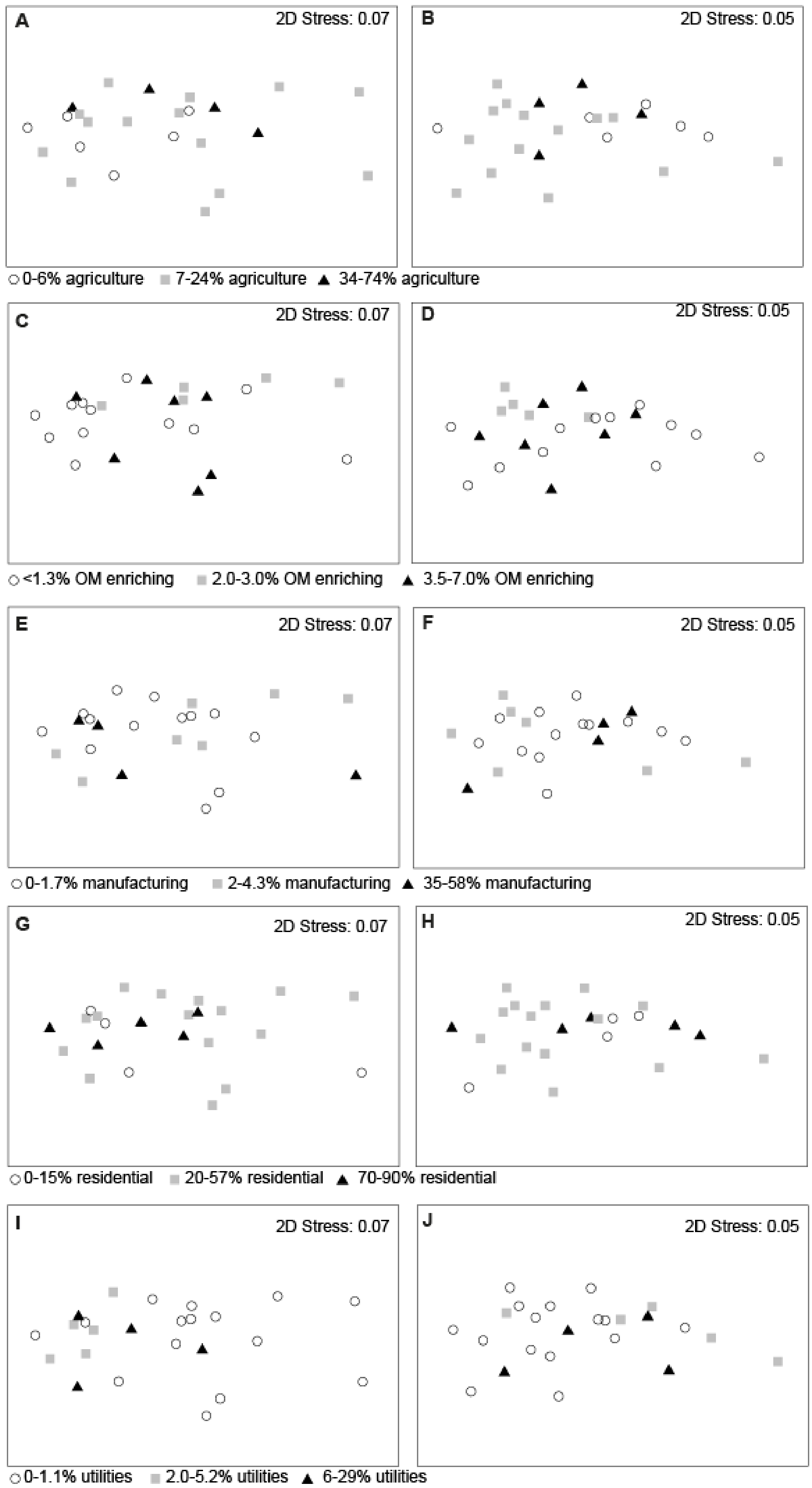

Fig. S6. nMDS ordination of the Bray–Curtis similarity of the south-east Queensland macrofaunal mudflat assemblage trait composition between sub-catchments with reference, medium and high cover of 5 urban pressures (of the total sub-catchment area) (A) agriculture in winter, (B) agriculture in summer, (C) organic matter enrichment in winter, (D) organic matter enrichment in summer, (E) manufacturing in winter, (F) manufacturing in summer, (G) residential in winter, (H) residential in summer, (I) utilities in winter and (J) utilities in summer.

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