

Supplementary materials

Association between gross domestic product and spatial distribution of denitrifying anaerobic methane-oxidizing archaea along the Yangtze River

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Text S1 Physicochemical analyses

Ammonia nitrogen ($\text{NH}_4^+\text{-N}$), nitrite nitrogen ($\text{NO}_2^-\text{-N}$), and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) were extracted by KCl (2mol/L) solution for 1 h and then determined by a spectrophotometer (Shimadzu, Japan). Dissolved organic carbon (DOC) was quantified by a TOC analyzer (Elementar, Germany) after extracted by ultrapure water. The metals (Cu, Zn, Cr, Mn, Fe) were digested by combined acids ($\text{HNO}_3\text{-HClO}_4$) and then quantified by an ICP-OES instrument (PerkinElmer, USA). The pH was measured using a pH meter (Mettler Toledo, Switzerland) with a sediment-to-ultrapure water ratio of 1:2.5. All reagents were of analytical grade, purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

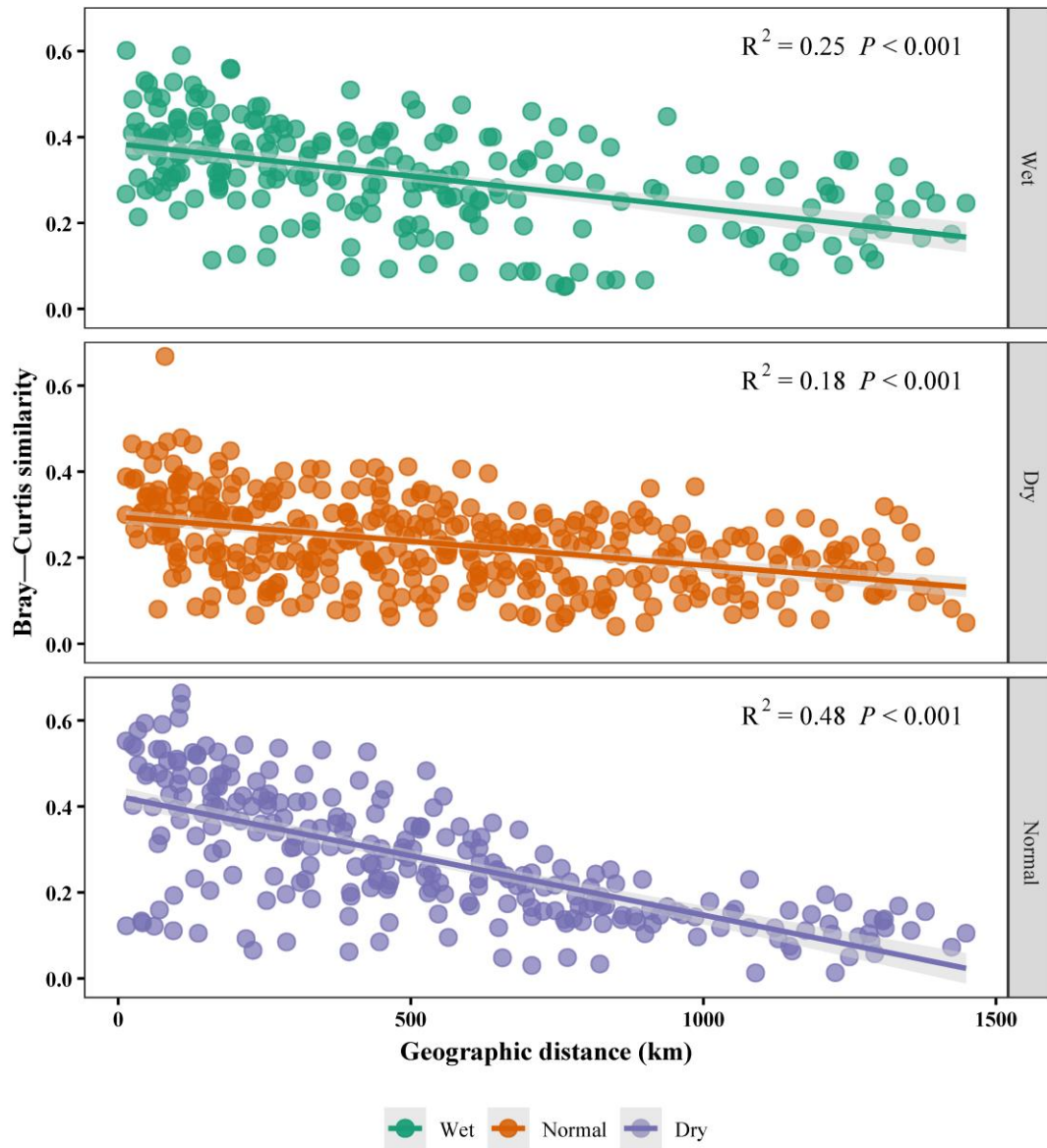


Fig. S1 Distance decay patterns of DAMO archaea based on Bray-Curtis similarity (1-“Bray-Curtis”distance) and geographic distance.

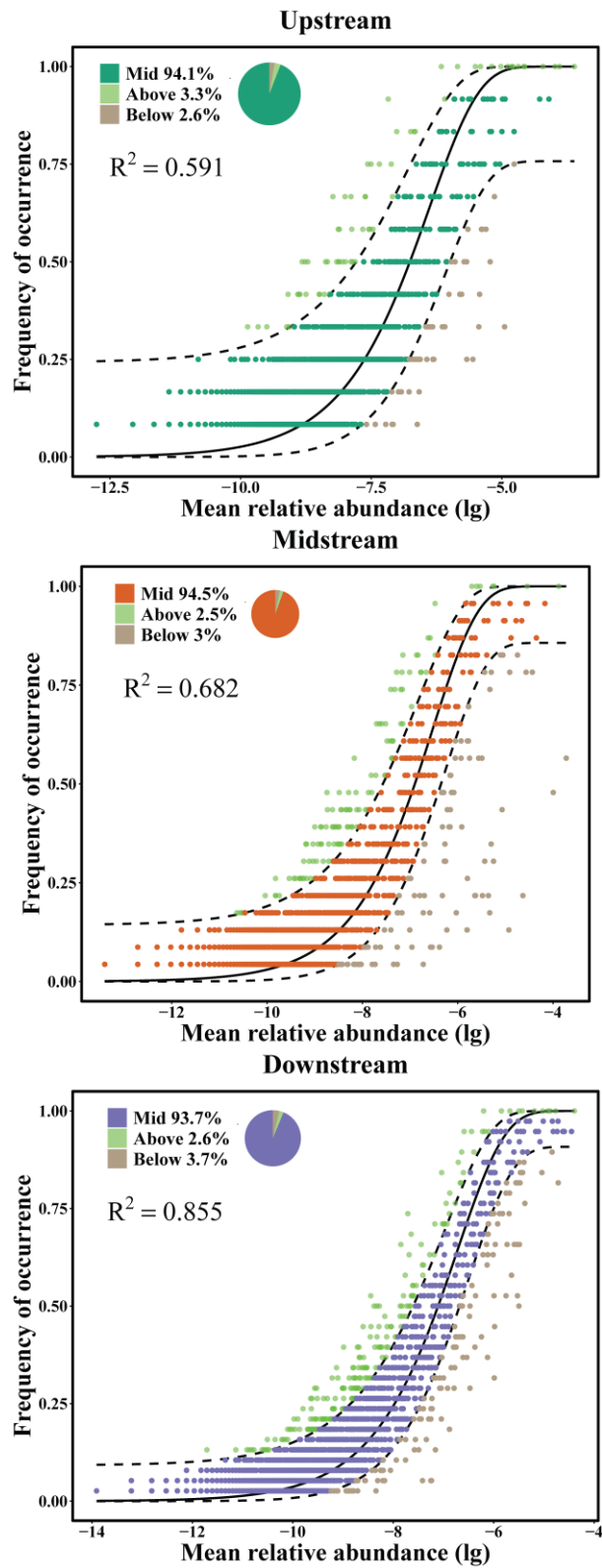


Fig. S2 Neutral community model fitting of DAMO archaeal communities in different regions.

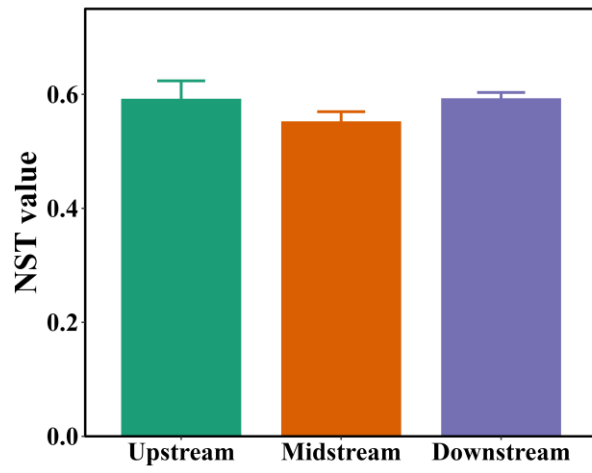


Fig. S3 NST model visualization of DAMO archaeal communities in different spatial regions.

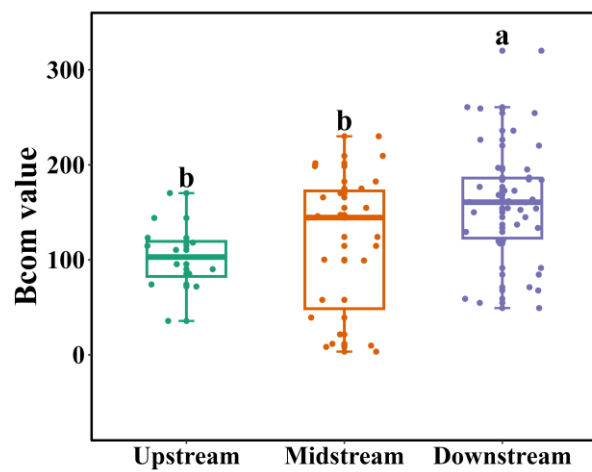


Fig. S4 Niche analysis of DAMO archaeal communities in different spatial regions.

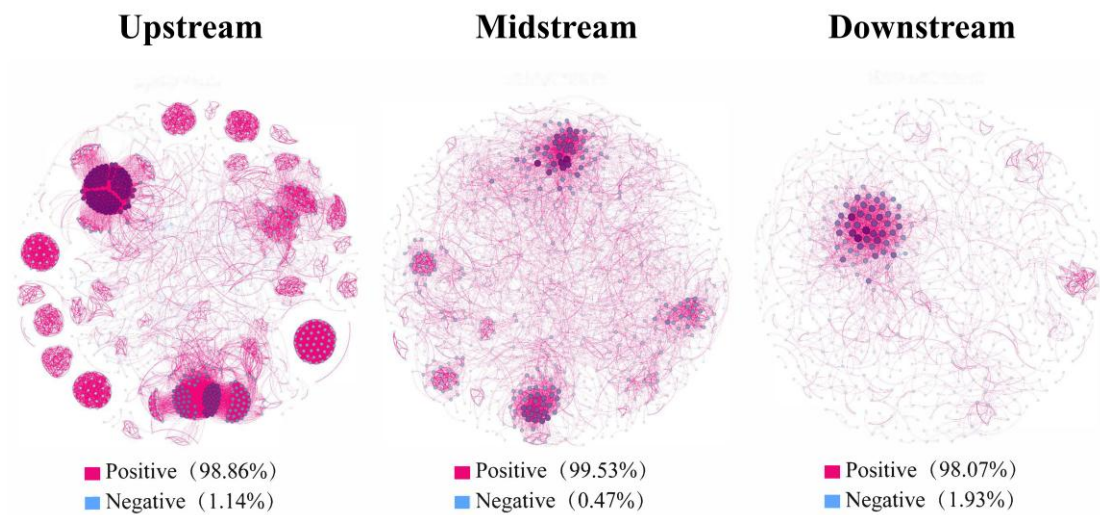


Fig. S5 Co-occurrence networks of DAMO archaeal communities in different spatial regions. The size and color of the node were determined by its degree, with larger degrees corresponding to larger node sizes and darker color.

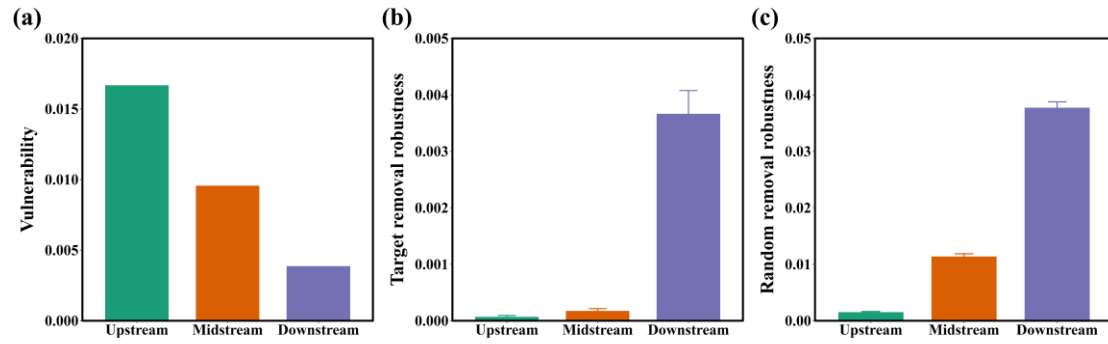


Fig. S6 Co-occurrence network stability of DAMO archaeal communities. (a) Vulnerability, (b) target removal robustness and (c) random removal robustness of co-occurrence networks across different spatial regions.

Table S1 Sampling sites in the main stream of the Yangtze River.

Sample	Region	City	Dry	Wet	Normal	Latitude (°W)	Longitude (°N)
S1	Upstream	Chongqing	+	+	+	106.58	29.58
S2	Upstream	Chongqing	+	-	-	107.42	29.74
S3	Upstream	Chongqing	+	+	+	106.84	29.58
S4	Upstream	Chongqing	+	+	+	108.07	30.32
S5	Upstream	Chongqing	+	-	-	108.96	30.93
S6	Upstream	Chongqing	+	-	-	109.92	31.06
S7	Midstream	Yichang	+	-	+	110.75	30.96
S8	Midstream	Yichang	+	-	+	111.51	30.41
S9	Midstream	Jingzhou	+	+	+	112.21	30.32
S10	Midstream	Yueyang	+	-	+	113.20	29.49
S11	Midstream	Jingzhou	+	+	+	113.87	30.18
S12	Midstream	Wuhan	+	+	-	114.30	30.57
S13	Midstream	Huanggang	+	+	+	114.84	30.53
S14	Midstream	Huangshi	+	+	+	115.27	30.15
S15	Midstream	Jiujiang	+	+	+	116.28	29.78
S16	Downstream	Anqing	+	+	+	117.02	30.50
S17	Downstream	Chizhou	+	+	+	117.71	30.78
S18	Downstream	Wuhu	+	+	+	118.36	31.34
S19	Downstream	Nanjing	+	+	+	118.87	32.20
S20	Downstream	Yangzhou	+	+	+	119.18	32.25
S21	Downstream	Yangzhou	+	+	+	119.71	32.31
S22	Downstream	Zhenjiang	+	+	+	119.31	32.19
S23	Downstream	Changzhou	+	+	+	120.01	31.97
S24	Downstream	Wuxi	+	+	+	120.26	31.93
S25	Downstream	Suzhou	+	+	+	120.74	31.98
S26	Downstream	Shanghai	+	+	+	121.55	31.38
S27	Downstream	Taizhou	+	+	+	119.95	32.08
S28	Downstream	Nantong	+	+	-	120.96	31.81

+: Sampling; -: No Sampling

Table S2 Physicochemical attributes of each sample.

Season	Sample	NO ₃ ⁻ -N (µg/g)	NO ₂ ⁻ -N (µg/g)	NH ₄ ⁺ -N (µg/g)	TN (mg/g)	TP (mg/g)	Cu (µg/g)	Zn (µg/g)	Cr (µg/g)	Mn (µg/g)	Fe (mg/g)	DOC (µg/g)
	S1	3.613	/	3.913	4.667	0.492	5.088	45.905	19.195	272.866	47.471	/
	S3	1.238	/	6.960	18.133	0.215	17.801	78.312	34.345	749.307	69.746	19.336
	S4	5.572	0.020	18.239	14.267	0.189	18.471	121.986	27.614	703.635	68.710	20.510
	S9	10.430	0.010	3.440	8.462	0.141	11.210	42.882	21.314	311.441	43.764	11.250
	S11	3.297	0.010	4.981	/	0.081	111.392	53.972	/	63.097	17.931	18.986
	S12	4.720	0.610	27.700	1.244	0.287	24.088	90.795	34.443	707.769	71.693	28.025
	S13	5.844	0.010	5.388	18.318	0.144	109.858	48.877	12.944	244.263	38.829	20.528
	S14	11.184	/	7.170	11.966	0.064	1.049	36.209	16.490	313.314	47.439	24.682
	S15	2.375	/	4.452	58.463	0.024	4.221	53.823	19.119	391.204	51.252	22.540
	S16	3.315	0.010	24.165	99.321	0.254	21.817	88.139	35.551	833.410	73.777	20.698
Wet	S17	4.663	0.010	9.865	7.853	0.416	34.857	94.036	38.512	917.419	84.080	17.281
	S18	18.408	0.010	15.522	3.071	0.036	11.468	58.364	26.705	556.970	53.207	30.950
	S19	18.627	1.062	11.316	4.581	0.427	47.291	110.426	38.396	853.559	83.805	38.462
	S20	0.977	/	10.557	66.535	0.390	19.751	86.970	32.718	651.423	67.830	35.230
	S21	1.250	0.060	38.700	8.053	0.290	21.628	97.270	43.690	996.533	82.967	31.523
	S22	3.093	3.356	9.573	3.838	0.330	11.100	63.921	24.639	544.904	58.715	30.254
	S23	1.181	0.010	7.565	4.819	0.242	36.256	135.938	40.144	587.613	74.716	22.142
	S24	17.211	0.010	17.110	8.091	0.070	32.103	104.199	28.638	709.823	63.202	35.284
	S25	2.381	/	11.260	3.711	0.334	22.635	105.031	31.322	658.134	65.458	36.214
	S26	1.639	0.010	9.873	29.333	0.283	11.734	64.571	25.450	581.639	56.918	31.023
	S27	1.405	0.070	5.881	5.899	0.147	11.973	44.937	14.459	258.900	45.169	20.586

	S28	1.597	0.070	8.958	20.792	0.235	15.456	78.491	27.770	597.224	70.594	36.140
	S1	2.417	0.060	17.675	3.656	0.445	16.801	58.993	35.642	705.043	79.272	17.728
	S3	1.980	0.040	17.800	13.085	0.139	21.613	85.498	35.011	722.668	104.660	32.928
	S4	0.310	0.040	11.991	3.751	0.728	35.391	125.579	62.328	1035.320	119.127	71.520
	S7	0.813	0.127	2.957	6.665	0.142	23.429	/	29.406	728.165	100.863	64.040
	S8	1.034	0.040	5.520	4.845	0.065	4.322	/	10.136	318.831	64.486	24.840
	S9	2.694	0.030	2.654	0.711	0.002	6.419	/	15.567	339.097	47.594	16.472
	S10	0.301	0.040	3.047	15.297	1.100	38.391	25.462	46.541	937.906	65.898	25.220
	S11	0.382	0.050	11.248	11.764	0.049	21.050	1.133	29.880	574.614	76.691	28.852
	S13	/	0.030	4.723	21.275	0.078	5.956	/	20.280	342.153	56.354	28.388
	S14	0.962	0.030	11.926	8.346	0.521	40.017	49.360	42.573	858.768	95.935	35.044
	S15	0.923	0.010	39.240	11.004	0.461	28.390	95.236	38.659	983.951	93.490	38.280
Normal	S16	1.435	0.030	15.046	97.333	0.458	26.089	32.713	34.654	804.350	88.410	30.184
	S17	2.826	0.070	38.683	13.424	0.359	21.052	12.118	30.295	830.295	77.078	37.512
	S18	1.557	0.030	14.362	6.152	0.246	7.317	/	19.745	466.082	61.692	45.760
	S19	0.788	0.020	5.229	9.787	0.331	183.894	120.855	102.208	1344.620	75.096	49.320
	S20	/	0.086	15.806	5.836	0.350	111.068	90.818	86.543	902.484	51.001	27.852
	S21	/	0.052	47.664	7.963	0.255	141.410	145.007	143.604	1850.220	89.711	77.680
	S22	/	0.048	14.479	14.232	0.629	123.880	117.317	136.301	1736.790	77.746	34.240
	S23	/	0.040	2.078	3.218	0.015	86.435	77.346	74.312	639.209	41.519	29.852
	S24	0.781	/	5.034	1.016	0.275	118.318	109.431	95.687	1090.280	56.413	38.884
	S25	/	0.035	28.354	8.302	0.440	132.375	137.990	111.516	1478.950	78.504	29.664
	S26	/	0.028	3.334	3.592	0.298	103.999	97.779	89.406	1092.940	59.441	42.984
	S27	0.779	0.010	11.592	11.266	0.242	102.824	90.036	90.706	1017.890	55.471	61.320
Dry	S1	2.160	0.050	3.470	4.900	0.083	7.645	72.335	31.498	336.914	62.806	21.962

S2	1.025	0.020	6.026	6.598	0.307	15.964	69.666	24.583	469.457	56.939	104.487
S3	1.292	0.010	3.554	6.650	0.141	13.333	89.009	28.118	433.370	51.424	42.881
S4	1.688	0.010	22.837	25.623	0.766	30.729	149.734	53.937	896.179	76.221	96.048
S5	0.887	0.315	4.101	10.627	0.031	19.345	86.575	65.491	761.644	87.305	78.039
S6	0.970	0.560	9.030	15.663	0.316	21.941	60.825	67.723	877.324	90.805	36.743
S7	1.110	0.021	20.222	20.058	0.727	31.960	89.197	39.070	968.062	90.696	77.495
S8	0.423	/	/	5.504	0.158	14.170	76.547	27.910	480.990	65.339	29.530
S9	1.263	0.010	1.576	1.079	0.005	3.460	29.974	23.963	262.579	43.046	18.409
S10	8.640	0.020	1.901	1.346	0.244	4.097	38.651	33.460	395.837	45.652	31.019
S11	124.632	0.040	1.180	13.728	0.172	7.577	31.116	29.327	251.073	41.425	31.739
S12	24.131	0.040	4.493	5.894	0.152	5.863	46.369	45.057	417.247	49.471	75.286
S13	69.018	0.030	2.169	9.024	0.227	5.855	67.245	22.504	390.944	43.741	34.749
S14	9.840	0.030	3.312	3.117	0.127	6.429	35.267	24.718	397.577	48.162	38.227
S15	26.519	0.030	5.207	4.854	0.019	203.410	717.200	123.546	3147.810	466.655	54.038
S16	5.849	/	/	6.161	0.096	18.511	165.952	19.461	846.231	47.621	42.223
S17	61.807	/	/	62.580	0.021	34.486	91.081	46.888	670.677	90.992	53.647
S18	9.477	/	/	13.723	0.347	13.020	82.521	23.233	667.140	49.972	61.133
S19	7.797	0.030	22.754	31.920	0.694	44.040	106.810	45.509	1587.440	109.777	57.997
S20	1.683	0.040	7.758	16.583	0.292	17.918	59.025	34.016	607.722	59.332	38.452
S21	6.366	0.030	29.045	9.681	0.276	18.958	93.694	42.764	714.564	74.945	88.443
S22	1.895	0.030	10.122	17.096	0.328	18.287	109.099	33.041	713.943	62.945	59.898
S23	9.672	0.040	5.066	11.022	0.187	17.498	82.606	38.221	564.988	58.610	42.846
S24	10.954	0.030	3.077	25.146	0.268	36.208	81.189	30.839	582.924	55.917	49.720
S25	7.608	0.030	5.800	9.427	0.262	0.317	39.298	17.024	310.913	45.692	37.995
S26	6.551	0.030	3.896	16.447	0.524	6.225	72.786	16.871	455.023	44.970	56.992

S27	6.663	0.080	8.190	24.602	0.218	5.700	61.999	26.602	412.940	47.297	74.691
S28	16.796	0.030	2.363	6.265	0.245	7.660	61.703	28.600	413.747	50.522	48.082

Table S3 Information on statistical methods in R language (version 4.4.0).

Statistical methods	Main package	Version
Alpha diversity		
Beta diversity		
PERMANOVA	vegan	2.6.10
RDA		
CPCoA	amplicon	1.19.0
Distance-decay patterns	geosphere	1.5.20
Bcom	spaa	0.2.5
One-way ANOVA		
Duncan's multiple comparison test	agricolae	1.3.7
	Hmisc	5.1.3
Neutral community model	minpack.lm	1.2.4
	stats4	4.4.0
NST	NST	3.1.10
Hierarchical partitioning analysis	rdacca.hp	1.1.1
Mantel test	linkET	0.0.7.4
Spearman correlation	WGCNA	1.73
Topological index		
Modularity	igraph	2.1.4

Table S4 Socio-economic, factors (GDP, urbanization rate, and population density) of each sampling city.

City	GDP (yuan/person)	Urbanization rate (%)	Population density (person/km ²)
Chongqing	94135	71.67	275.30
Yichang	146847	65.32	149.37
Jingzhou	61313	58.18	318.40
Yueyang	96450	62.39	292.92
Wuhan	145471	84.79	891.16
Huanggang	49822	50.50	277.42
Huangshi	86434	68.24	422.14
Jiujiang	84322	63.82	195.65
Anqing	69190	57.49	258.99
Chizhou	83624	61.39	131.91
Wuhu	127107	74.46	459.67
Nanjing	183576	87.20	937.63
Yangzhou	162081	72.79	517.52
Zhenjiang	163481	80.70	625.00
Changzhou	188387	78.51	813.47
Wuxi	206358	83.31	1077.76
Suzhou	190964	82.48	969.79
Shanghai	190783	89.46	2636.27
Taizhou	149262	70.08	616.30
Nantong	152627	72.57	623.07

Table S5 Climatic factors (average precipitation and daily temperature) of the sampling month.

Season	City	Average precipitation (mm/day)	Average temperature (°C)
Wet	Chongqing	222.4	28.4
	Jingzhou	157.7	29.6
	Wuhan	154.5	30.2
	Huanggang	199.7	29.2
	Huangshi	189.1	23.3
	Jiujiang	212.2	29.0
	Anqing	235.3	29.8
	Chizhou	297.4	18.2
	Wuhu	208.2	29.0
	Nanjing	181.8	28.8
	Yangzhou	266.4	29.4
	Zhenjiang	206.1	28.2
	Changzhou	187.0	30.7
	Wuxi	198.3	30.1
	Suzhou	208.5	29.7
	Shanghai	204.7	29.2
Taizhou	314.5	29.4	
Nantong	283.4	30.0	
Normal	Chongqing	53.9	14.8
	Yichang	46.8	13.8
	Jingzhou	52.3	14.1
	Yueyang	58.9	14.6
	Huanggang	54.3	14.0
	Huangshi	57.5	9.3
	Jiujiang	58.6	13.2
	Anqing	52.3	14.3
	Chizhou	59.4	5.7
	Wuhu	43.3	13.2
	Nanjing	29.3	12.6
	Yangzhou	30.2	12.7
	Zhenjiang	30.4	11.8
	Changzhou	31.7	13.6
	Wuxi	34.9	13.1
	Suzhou	41.2	12.4
Shanghai	39.7	11.8	
Taizhou	25.9	12.6	
Dry	Chongqing	51.2	15.0
	Yichang	47.4	13.0

Jingzhou	69.8	13.3
Yueyang	114.9	15.1
Wuhan	67.0	12.9
Huanggang	63.9	12.7
Huangshi	98.1	10.0
Jiujiang	125.8	11.4
Anqing	75.9	14.7
Chizhou	94.4	6.3
Wuhu	77.2	13.1
Nanjing	56.9	11.9
Yangzhou	44.6	12.7
Yangzhou	44.6	12.7
Zhenjiang	60.1	11.7
Changzhou	69.2	14.7
Wuxi	67.8	15.0
Suzhou	68.2	13.9
Shanghai	72.0	14.6
Taizhou	42.3	14.4
Nantong	55.9	13.9

Table S6 The VIF value for each variable in RDA.

Variables	VIF
Mn	18.21
Fe	8.67
Zn	8.13
Cr	7.35
Urbanization rate	5.91
Temperature	5.81
Precipitation	5.19
Cu	4.15
GDP	4.08
Population density	2.52
NH ₄ ⁺ -N	1.8
DOC	1.72
TP	1.6
TN	1.27
NO ₃ ⁻ -N	1.25
NO ₂ ⁻ -N	1.17

Table S7 Comparison of representative ASVs with whole genome of DAMO archaea.

Representative ASVs	<i>Candidatus</i> Methanoperedens sp. BLZ1 (%)	<i>Candidatus</i> Methanoperedens sp. BLZ2 (%)	<i>Candidatus</i> Methanoperedens nitroreducens (%)	<i>Candidatus</i> Methanoperedens nitroreducens Vercelli (%)
ASV1	89.94	89.94	84.33	84.01
ASV2	90.91	90.91	82.45	83.44
ASV4	89.97	89.97	83.23	82.50
ASV3	92.16	92.16	81.96	81.88
ASV5	90.60	90.60	82.91	82.19
ASV6	90.60	90.60	82.76	83.13
ASV8	89.94	89.94	81.33	81.56
ASV7	89.62	89.62	83.39	83.13
ASV12	91.85	91.85	81.96	80.00
ASV9	91.20	91.20	80.70	81.25

Table S8 PERMANOVA analysis across different regions.

Metrics	F value	<i>P</i>
Richness index	5.314	0.0071
Bray-Curtis similarity	44.180	2E-16
NST	2.156	0.116
Bcom width	5.26	0.00744

Table S9 Hierarchical partitioning results of DAMO archaea.

Variable	Unique	Individual	R ² (%)
GDP	0.0206	0.0269	20.53
Population density	0.0124	0.0168	12.82
Cu	0.0096	0.0133	10.15
Cr	0.0097	0.0127	9.69
Urbanization rate	0.0093	0.0106	8.09
Fe	0.0094	0.0078	5.95
Zn	0.0088	0.0077	5.88
Temperature	0.0055	0.0075	5.73
NH ₄ ⁺ -N	0.0071	0.0068	5.19
Precipitation	0.0030	0.0068	5.19
TP	0.0071	0.0065	4.96
DOC	0.0012	0.0051	3.89
NO ₃ ⁻ -N	0.0029	0.0037	2.82
TN	0.0033	0.0024	1.83
NO ₂ ⁻ -N	<0	<0	0

Table S10 Topological properties of the co-occurrence networks of DAMO archaeal communities in different regions.

Topological parameters	Upstream	Midstream	Downstream
Nodes	1026	969	645
Edges	14756	5300	2282
Average degree	28.764	10.939	7.076
Graph density	0.028	0.011	0.011
Average path length	5.119	4.917	7.784
Average clustering coefficient	0.721	0.422	0.409
Random removal robustness (50% removed)	0.0015	0.0114	0.0377
Target removal robustness (5 hubs removed)	6.82E-05	1.75E-04	3.67E-03
Vulnerability	0.0167	0.0096	0.0039