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Supplementary information

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Supplementary Information

Half of global methane emissions come from highly variable aquatic ecosystem sources

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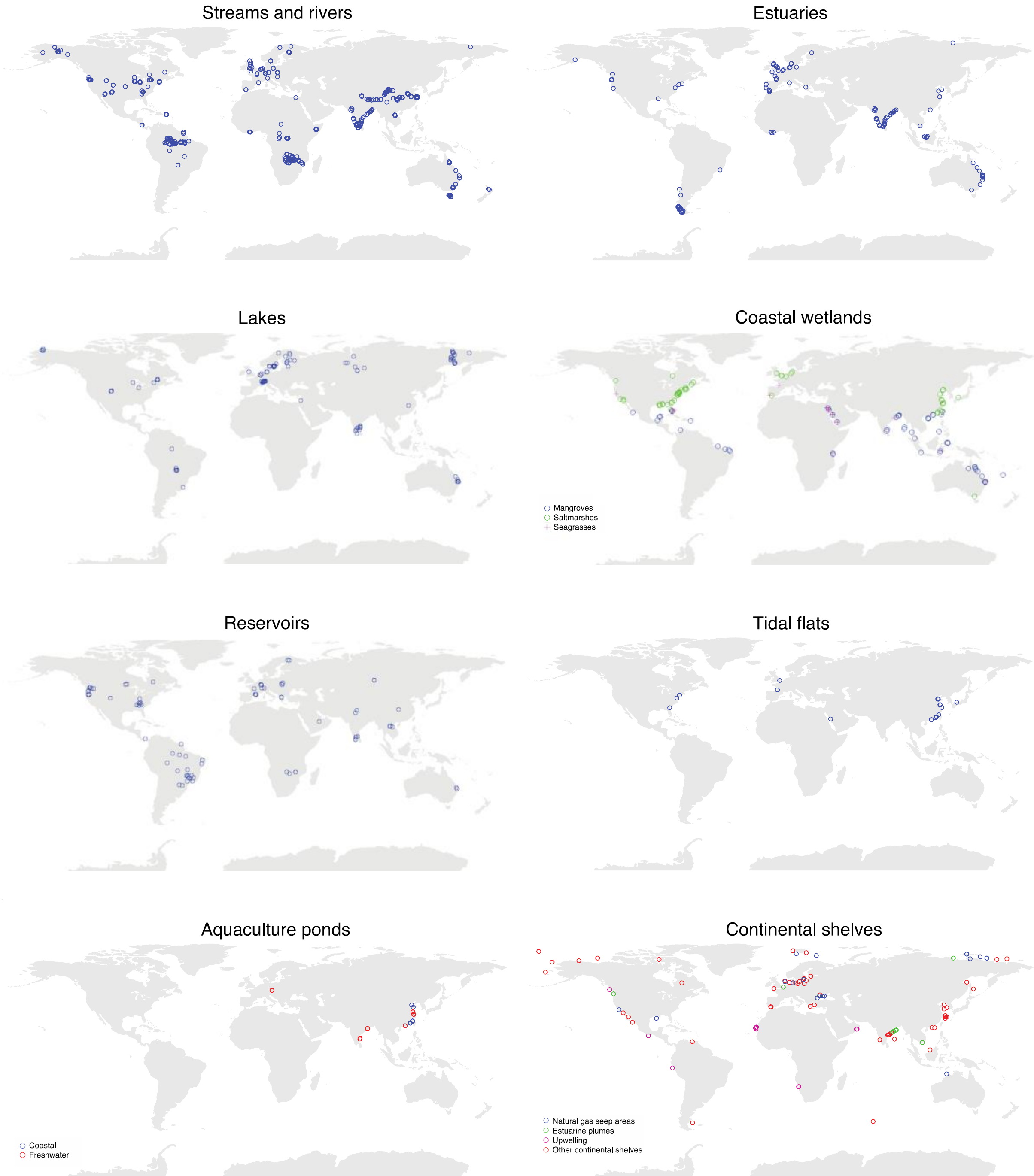
Supplementary Figure 1



Global distribution of methane flux study sites from streams and rivers, lakes, reservoirs, aquaculture ponds, estuaries, coastal wetlands, tidal flats and continental shelves.

Supplementary Table 1. Global aquatic methane emission estimates from previous studies

System	Mean emission (Tg CH_4 yr^{-1})	Median emission (Tg CH_4 yr^{-1})	n= sites	n =flux	Surface area (x 10^6 km^2)	Surface area reference	Global estimate reference	Notes
Rivers	1.5		21		0.36	Downing and Duarte [1]	Bastviken et al. .[2]	Upscaled based on arithmetic means, for tropical rivers uses values from temperate rivers
Rivers	26.8	2.85	385		0.65	Raymond et al. [3]	Stanley et al.[4]	Diffusive only fluxes, stream area method
Lakes, reservoirs, ponds	199 - 331		166		3.23 - 5.36	Messager et al. [5], Verpoorter et al. [6]	DelSontro et al.[7]	Diffusive and ebullitive fluxes, upscaled based on arithmetic means, database does not report location
Lakes, reservoirs, ponds	104 - 185		166		3.23 - 5.36	Messager et al. [5], Verpoorter et al. [6]	DelSontro et al.[7]	Diffusive and ebullitive fluxes, upscaled based on relationship to chlorophyll a, database does not report location
Ponds (<0.001 km2)	8.49	5.56	50		0.15 - 0.86	Verpoorter extrapolation (sensu Holgerson & Raymond [8])	Holgerson & Raymond [8]	Diffusive only flux, Monte Carlo approach
Lakes	71.6		66		3.74	Downing and Duarte [1]	Bastviken et al.[2]	Diffusive and ebullitive fluxes, and stored methane, upscaled based on arithmetic means
Reservoirs	20		35		0.5	Downing and Duarte [1]	Bastviken et al. .[2]	Diffusive and ebullitive fluxes, and stored methane, upscaled based on arithmetic means
Reservoirs	17.7	4.1	75		0.31	Lehner et al.[9]	Deemer et al. [10]	Diffusive and ebullitive fluxes, upscaled based on arithmetic means
Fresh. aquaculture ponds	6.0			33	0.111970	Yuan et al. [11]	Yuan et al. [11]	Does not include coastal aquaculture ponds, upscaled based on arithmetic means
Salt marshes	1.1			85	0.055	Mcowen et al. [12]	Al-Haj & Fulweiler [13]	Upscaled based on arithmetic means, Rosentreter and Williamson [14]
Mangroves	0.03 - 1.7		23	31	0.137760	Giri et al.[15]	Rosentreter et al. [16]	Water-air and sediment-air fluxes, upscaled based on arithmetic means, does not report medians
Mangroves	3.68 - 4			110	0.137760 - 0.152361	Mcleod [17]	Al-Haj & Fulweiler [13]	Upscaled based on arithmetic means, Rosentreter and Williamson [14]
Seagrasses	0.09 - 2.7			13	0.15 - 4.32	Duarte [18]	Garcias-Bonet & Duarte [19]	Flux per species
Seagrasses	0.5 - 1.0			28	0.788 - 1.646788	Jayathilake & Costello[20], Davidson & Finlayson [21]	Al-Haj & Fulweiler [13]	Upscaled based on arithmetic means, Rosentreter and Williamson [14]
Estuaries	0.8 - 1.32				1.4	Woodwell [22]	Bange et al. [23]	Literature compilation, applied global exchange coefficient

Estuaries	0.9 - 1.7				1.4	Woodwell et al. [24]	Upstill-Goddard et al. [25]	Upscaled based on mean river CH_4 concentration and 90% estuarine CH_4 removal
Estuaries	1.8 - 3.0		8		1.4	Woodwell et al. [24]	Middelburg et al. [26]	Literature compilation, applied global exchange coefficient
Estuaries	6.6		32		1.1	Dürr et al. [27]	Borges & Abril [28]	Estuaries and some coastal wetlands combined, upscaled based on arithmetic means
Shelf region	0.7 - 14				1.4	Sverdrup et al. [29]	Ehhalt [30]	Area of shelf at less than 10m depth, speculation
Coastal	6.3				25	Lambert & Schmidt [31]	Lambert & Schmidt [31]	Speculation
Shelf region	7.3 - 12.1				55.376	Menard & Smith [32]	Bange et al. [23]	Applied global exchange coefficient
Coastal region and upwelling zone	1.9 - 3.8				48.7	Rhee et al. [33]	Rhee et al. [33]	Based on 6-12 mg CH_4 m^{-2} yr^{-1}, estimated based on data from the Atlantic
Open ocean	4 - 6.7				361	Sverdrup et al. [29]	Ehhalt [30]	Refers to work of Swinnerton and Linnenbom (1967) and Lamontagne et al. (1973), data not traceable
Open ocean and coastal	0.4 - 6.1				361	Sverdrup et al. [29]	Conrad and Seiler [34]	Basin-wide observation, based on 1-17 mg CH_4 yr^{-1}, data from the Atlantic
Open ocean	3.6				360	Lambert & Schmidt [31]	Lambert & Schmidt [31]	Literature compilation
Open ocean	2.8 - 4.4				306.609	Bange et al. [23]	Bange et al. [23]	Literature compilation, applied global exchange coefficient
Open ocean	0.2 - 0.4				340	Levitus [35]	Bates et al. [36]	Basin-wide observation, estimated based on data from the Pacific
Open ocean	0.3 - 0.6				313.3	Rhee et al. [33]	Rhee et al. [33]	Based on 1-2 mg CH_4 m^{-2} yr^{-1}, estimated based on data from the Atlantic
Near-shore (0-50m)	2.04	1.49			9.95	Weber et al. [37]	Weber et al. [37]	Diffusive only flux, unclear what type of coastal ecosystems are included in near-shore estimate
Outer shelf (50-200m)	0.65	0.57			13.7	Weber et al. [37]	Weber et al. [37]	Diffusive only flux
Slope (200-2000m)	0.36	0.30			31.2	Weber et al. [37]	Weber et al. [37]	Diffusive only flux
Open ocean (>2000m)	1.01	0.91			303	Weber et al. [37]	Weber et al. [37]	Diffusive only flux
Total ocean	2 - 8				303	Weber et al. [37]	Weber et al. [37]	Diffusive and ebullitive fluxes, ebullitive flux based on 11-17% seafloor ebullition

Supplementary Table 2. River total methane emissions over latitudinal bands A) using river and stream surface area (RSSA), B) using ice-corrected river and stream surface area, C) sample size of total methane emissions (without differentiation of diffusion or ebullition), diffusive and ebullitive fluxes, where n refers to the number of sites (details see methods), D) total, diffusive and ebullitive areal flux. No ebullitive or total methane flux measurements were available for the 60-90º latitude bands. For this area, we assumed the same water surface evasion rates as in the lower 40-60º band. The C.I.95% in A) and B) is therefore calculated using the sample size of the 40-60º latitude band.

A)

Latitude band	RSSA (km^2)	Total emission ($Tg\ CH_4\ yr^{-1}$) mean ± C.I.95%	Total emission ($Tg\ CH_4\ yr^{-1}$) median (IQR)	Diffusive emission ($Tg\ CH_4\ yr^{-1}$) mean ± C.I.95%	Diffusive emission ($Tg\ CH_4\ yr^{-1}$) median (IQR)	Ebullitive emission ($Tg\ CH_4\ yr^{-1}$) mean ± C.I.95%	Ebullitive emission ($Tg\ CH_4\ yr^{-1}$) median (IQR)
0-10˚	210829	9.0 ± 10.8	1.5 (5.2)	6.0 ± 4.0	1.3 (3.8)	3.6 ± 5.5	0.4 (1.7)
10-25˚	120535	6.9 ± 6.1	1.1 (4.0)	19.7 ± 51.6	0.2 (1.5)	3.5 ± 5.2	0.4 (1.5)
25-40˚	114521	2.3 ± 2.8	1.6 (1.9)	2.6 ± 1.4	0.5 (1.6)	1.2 ± 2.0	0.7 (1.0)
40-60˚	159458	6.2 ± 4.9	2.4 (5.3)	8.3 ± 7.6	1.1 (4.0)	4.8 ± 18.4	0.5 (2.1)
60-90˚	167657	6.5 ± 5.1	2.5 (5.5)	4.8 ± 9.3	0.8 (2.6)	5.0 ± 19.3	0.6 (2.2)
Global	773000	37.6 ± 21.1	7.2 (23.8)	40.1 ± 21.9	3.2 (13.9)	17.0 ± 15.9	2.2 (8.0)

B)

Latitude band	Ice-corrected RSSA (km^2)	Total emission ($Tg\ CH_4\ yr^{-1}$) mean ± C.I.95%	Total emission ($Tg\ CH_4\ yr^{-1}$) median (IQR)	Diffusive emission ($Tg\ CH_4\ yr^{-1}$) mean ± C.I.95%	Diffusive emission ($Tg\ CH_4\ yr^{-1}$) median (IQR)	Ebullitive emission ($Tg\ CH_4\ yr^{-1}$) mean ± C.I.95%	Ebullitive emission ($Tg\ CH_4\ yr^{-1}$) median (IQR)
0-10˚	210829	9.0 ± 10.8	1.5 (5.2)	6.0 ± 4.0	1.3 (3.8)	3.6 ± 5.5	0.4 (1.7)
10-25˚	120535	6.9 ± 6.1	1.1 (4.0)	19.7 ± 51.6	0.2 (1.5)	3.5 ± 5.2	0.4 (1.5)
25-40˚	111139	2.2 ± 2.7	1.5 (1.9)	2.5 ± 1.3	0.5 (1.5)	1.1 ± 1.9	0.6 (1.0)
40-60˚	108499	4.2 ± 3.3	1.6 (3.6)	5.7 ± 5.2	0.7 (2.7)	3.3 ± 12.5	0.4 (1.4)
60-90˚	75421	2.9 ± 2.3	1.1 (2.5)	2.1 ± 4.2	0.4 (1.2)	2.3 ± 8.7	0.2 (1.0)
Global	626423	30.5 ± 17.1	5.8 (19.3)	32.5 ± 17.8	2.6 (11.3)	13.8 ± 12.9	1.7 (6.5)

C)

Latitude band	Total emissions	Diffusive emission	Ebullitive emission
0-10˚	53	116	48
10-25˚	99	130	57
25-40˚	5	199	5
40-60˚	30	124	11
60-90˚	0	22	1
Global	187	591	122

D)

Latitude band	Total areal flux ($mg\ CH_4\ m^{-2}\ d^{-1}$) mean ± C.I.95%	Total areal flux ($mg\ CH_4\ m^{-2}\ d^{-1}$) median (IQR)	Diffusive areal flux ($mg\ CH_4\ m^{-2}\ d^{-1}$) mean ± C.I.95%	Diffusive areal flux ($mg\ CH_4\ m^{-2}\ d^{-1}$) median (IQR)	Ebullitive areal flux ($mg\ CH_4\ m^{-2}\ d^{-1}$) mean ± C.I.95%	Ebullitive areal flux ($mg\ CH_4\ m^{-2}\ d^{-1}$) median (IQR)
0-10˚	177.9 ±217.3	20.8 (78.4)	136.7 ± 96.4	14.1 (38.6)	65.9 ± 65.2	3.5 (28.8)
10-25˚	200.7 ± 127.8	16.2 (89.7)	90.2 ± 67.3	7.4 (30.0)	74.2 ± 45.4	5.1 (33.9)
25-40˚	47.2 ± 35.7	57.4 (46.3)	52.8 ± 22.0	12.5 (28.1)	22.8 ± 21.7	23.6 (28.8)
40-60˚	152.2 ± 155.3	34.7 (48.6)	118.9 ± 63.1	19.4 (46.0)	23.4 ± 16.6	15.2 (33.3)
60-90˚	NA	NA	42.0 ± 32.0	11.3 (34. 1)	10.2 ± NA	10.2 (NA)
Global	182.4 ± 93.2	21.6 (73.2)	90.9 ± 28.3	12.7 (33.5)	63.8 ± 32.8	5.6 (30.3)

Supplementary Table 3. Upscaling information for lakes and reservoirs by size and typology class. Upscaling was based on the *ln* mean and standard deviation of total (diffusive + ebullitive) areal fluxes for a given class, but we present the mean areal flux (mg CH_4 m^{-2} d^{-1}) from the database given that these units are more easily interpretable. Median fluxes are also presented for comparison. Interquartile ranges (IQR) are given in parentheses for median values and C.I.95% are given for means. Annual emissions are adjusted based on an effective proportion of lake and reservoir surface area that is not under ice cover and an ice melt emission pulse correction factor.

Type	Size class (km^2)	n	Total areal flux (mg CH_4 m^{-2} d^{-1}) mean ± C.I.95%	Total areal flux (mg CH_4 m^{-2} d^{-1}) median (IQR)	Surface area (km^2)	Ice cover and ice melt correction factor	Annual emission (Tg CH_4 yr^{-1}) mean ± C.I.95%	Annual emission (Tg CH_4 yr^{-1}) median (IQR)
Lake	< 0.001	24	407.6 ± 238.0	265.3 (277.8)	143,863 - 861,568	0.60	54.5 ± 48.5	21.2 (44.3)
Lake	0.001 - 0.01	27	228.8 ± 114.6	112.2 (151.9)	400,076 - 692,600	0.60	31.1 ± 23.7	13.2 (27.5)
Lake	0.01 - 0.1	69	98.3 ± 39.3	40.7 (82.3)	602,100 - 664,534	0.60	22.4 ± 18.4	4.4 (15.4)
Lake	0.1 - 1	58	62.5 ± 37.8	20.8 (50.1)	523,400 - 966,851	0.60	9.9 ± 7.0	3.0 (6.8)
Lake	> 1	20	144.8 ± 191.6	13.7 (83.6)	2,042,784 - 2,501,979	0.79	33.0 ± 45.0	14.0 (25.0) (C)
Reservoir	< 1	16	119.6 ± 116.5 (A)	26.1 (74.9)	28,470 - 68,400	0.98	2.4 ± 4.7	0.4 (1.2)
Reservoir	> 1	62	188.9 ± 105.6 (B)	46.4 (144.8) (B)	230,100 - 515,000	0.86	22.0 ± 6.4	14.7 (18.4)

(A) For small reservoirs, 89 out of 1000 Monte Carlo simulations resulted in negative methane flux estimates; these values were forced to zero
(B) For large reservoirs we report the mean and median per area fluxes calculated via upscaling based on chlorophyll *a* distribution
(C) Our large lake estimate does not include the Caspian Sea given its large size and its saline status; including its surface area would elevate our median annual flux estimate to 16.64

Supplementary Table 4. Surface areas of coastal ocean ecosystems and freshwater aquaculture ponds that were used for upscaling to global annual methane emissions

Ecosystem	Surface area (km^2)	Reference	Note
Estuaries	1,020,000	Woodwell et al. [24], Dürr et al. [27]	Average of 940,000 [24], and 1,100,000 [27]
Coastal wetlands			
Salt marshes	54,951	Mcowen et al. [12]	Most recent
Mangroves	137,600	Bunting et al. [38]	Most recent
Seagrasses	266,582	Mckenzie et al. [39],	Most recent, lower confidence
Tidal flats	127,921	Murray et al. [40]	Most recent
Freshwater aquaculture ponds	87,500	Verdegem & Bosma [41]	Most recent
Coastal aquaculture ponds	23,330	Verdegem & Bosma [41]	Most recent
Continental shelves			
Estuarine plumes	4,280,000	Cai et al. [42] and C.T.A.	Sum of largest rivers (C.T.A., pers.comm)
Seep areas	61,910	Laruelle et al. [43]	Arbitrarily assuming 0.5% of continental shelves shallower than 50 m (13.382 x 10^6 km^2, Laruelle et al. [43])
Upwelling areas	3,600,000	Schlesinger et al. [44]	
East Siberian Arctic shelf	2,100,000	Shakhova et al. [45]	
Residual continental shelf	16,346,090	Laruelle et al. [43]	Calculated as the total surface of continental shelves of 26.39 x 10^6 km^2 (Laruelle et al. [43]) minus estuarine plumes, shallow seep areas, upwelling areas, and East Siberian Arctic shelf
Total continental shelf	26,388,000		Sum of estuarine plumes, seep and upwelling areas, East Siberian Arctic shelf and residual shelf

Supplementary Table 5. Methane transport pathways and physical interfaces in aquatic ecosystems where fluxes from the literature were measured.

Aquatic ecosystem	Transport pathway	Interface
Rivers and streams	Diffusive Ebullitive	Water-air
Lakes	Diffusive Ebullitive (A)	Water-air
Reservoirs	Diffusive Ebullitive (A)	Water-air
Freshwater aquaculture ponds	Diffusive Ebullitive	Water-air
Estuaries	Diffusive Ebullitive	Water-air
Salt marshes	Diffusive Ebullitive Plant-mediated	Sediment-air Sediment-water Water-air
Mangroves	Diffusive Plant-mediated	Sediment-air Sediment-water Water-air Stem/leaf-air
Seagrasses	Diffusive Plant-mediated	Sediment-water Water-air
Tidal flats	Diffusive Ebullitive	Sediment-air Water-air
Coastal aquaculture ponds	Diffusive Ebullitive	Water-air
Continental shelves	Diffusive Ebullitive	Water-air

(A) Only sites where both diffusive and ebullitive methane emission were available were considered

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