

Supplementary Information for

Global patterns and drivers of coupling between anammox and denitrification processes across inland aquatic ecosystems

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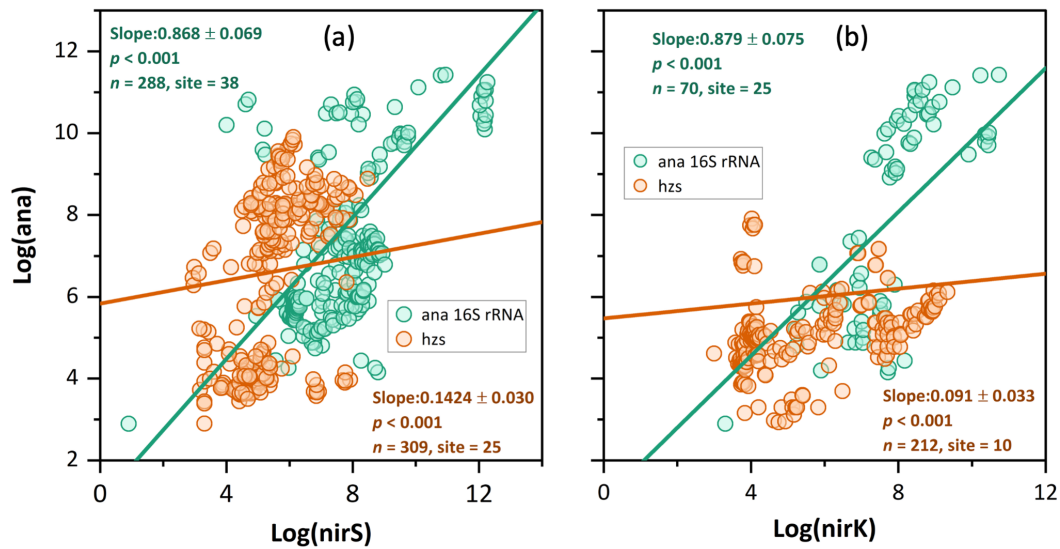


Figure 1 Relationships between the functional genes for anammox and denitrification at the global scale. The relationship is characterized via the linear mixed-effects model.

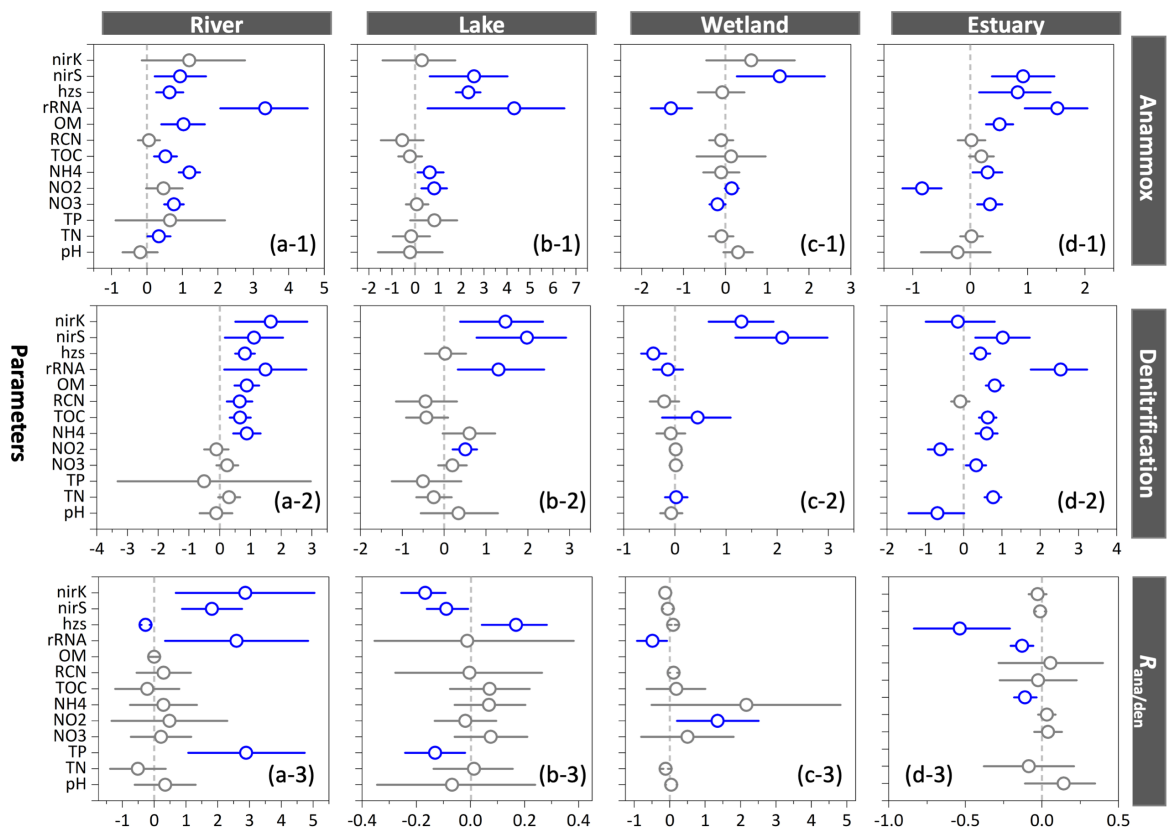


Figure 2 Effects of various variables on the anammox and denitrification processes across specific aquatic ecosystems. The error bars represent 95% confidence intervals (CIs). The slope is significant when the 95% CI does not overlap with zero.

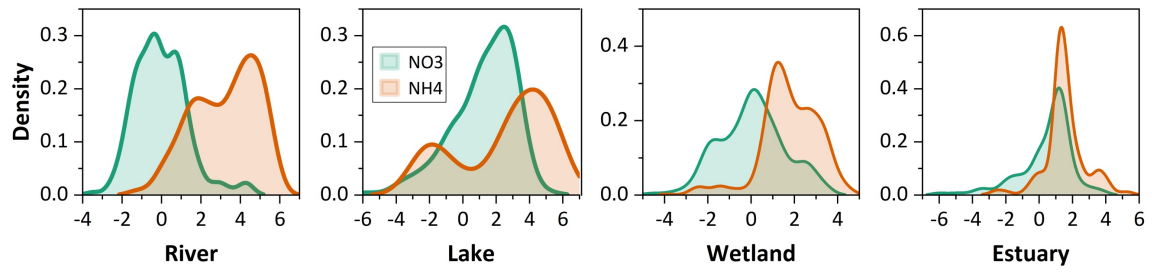


Figure 3 Distribution of NH_4^+ and NO_3^- concentrations in specific aquatic ecosystems. The concentration value is logarithmically transformed.

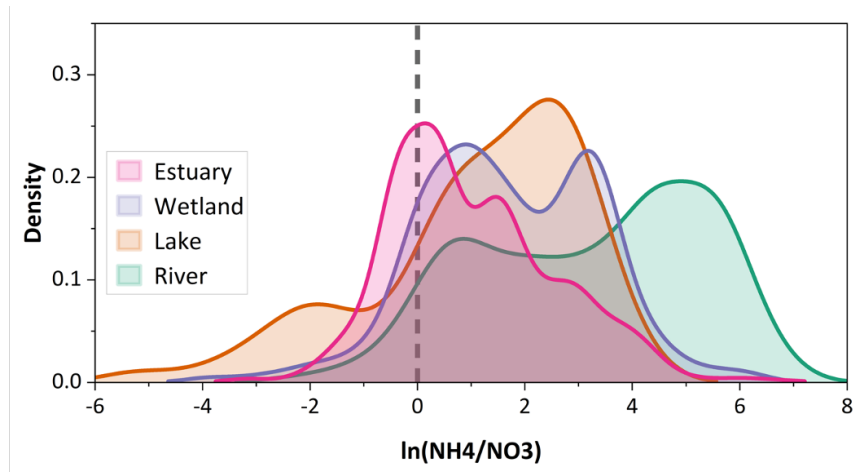


Figure 4 Density plot of $\ln(\text{NH}_4/\text{NO}_3)$ across specific aquatic ecosystems.

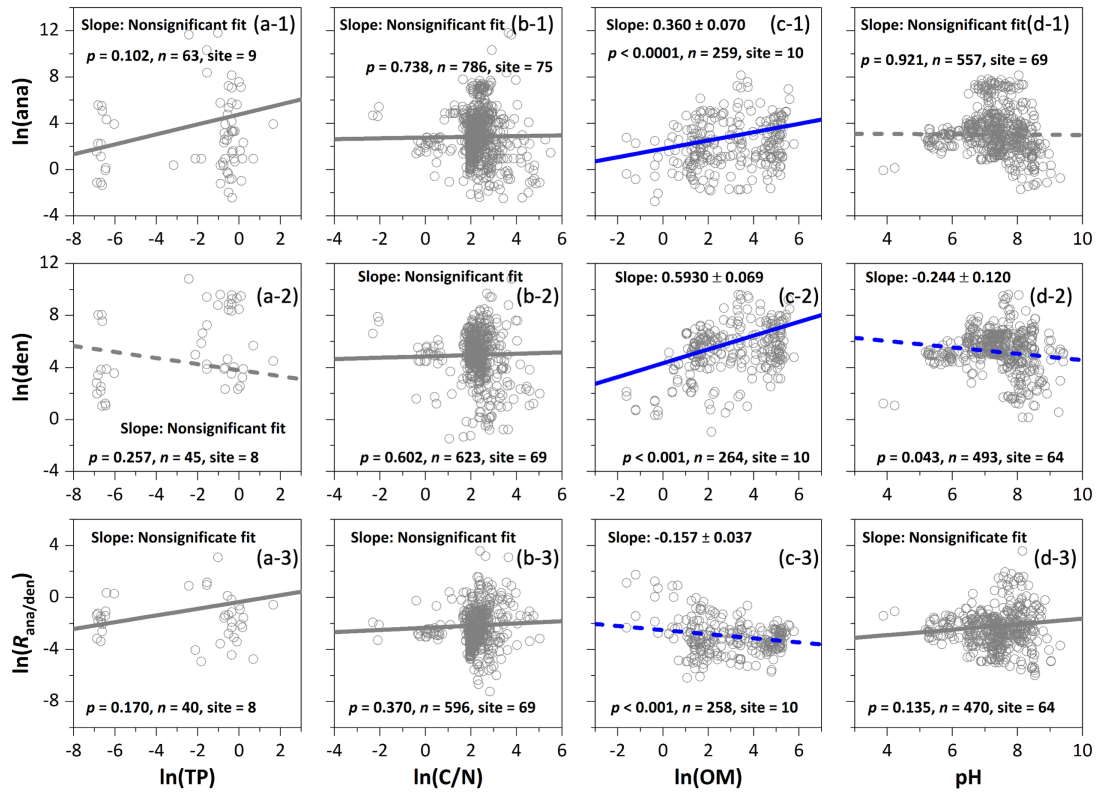


Figure 5 Variables driving anammox and denitrification variation at the global scale. The solid and dashed blue lines represent positive and negative significant fits, respectively, according to the linear mixed-effects model. The gray lines represent nonsignificant fits.

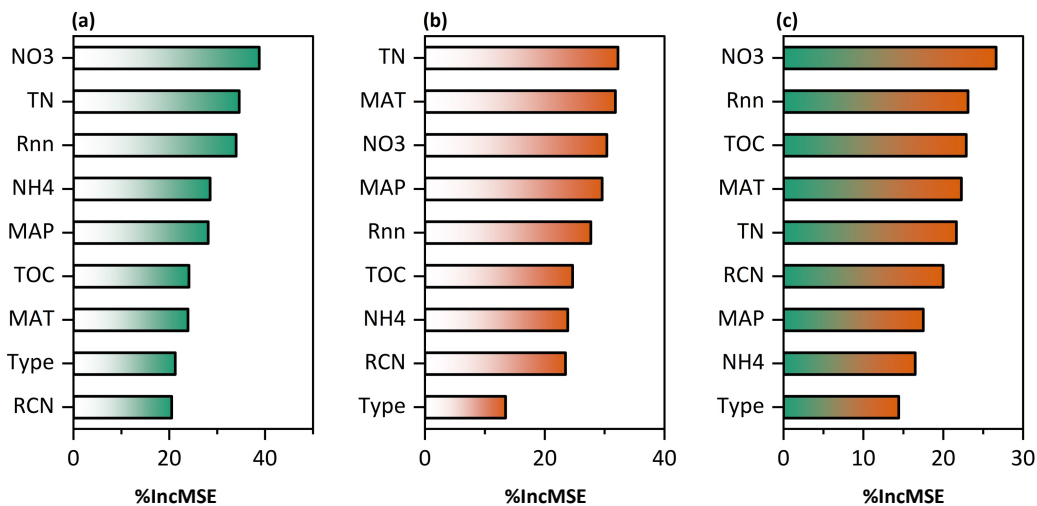


Figure 6 The importance (increase in mean squared error, %IncMSE) of variables for explaining the anammox rate (a) and denitrification rate (b) as well as $R_{\text{ana/den}}$ (c) based on the random forest model. Rnn and RCN represent the ratio of NH_4^+ to NO_3^- and the ratio of TOC to TN, respectively.

Table 1 Global anammox and denitrification rates as well as the ratio of annamox to denitrification ($R_{\text{ana/den}}$) across specific aquatic ecosystems on the basis of observations.

Aquatic ecosystems	Anammox rates (nmol-N g ⁻¹ day ⁻¹)		Denitrification rates (nmol-N g ⁻¹ day ⁻¹)		$R_{\text{ana/den}}$	
	Median (Q1-Q3)	Mean ($\pm$ SE)	Median (Q1-Q3)	Mean ($\pm$ SE)	Median (Q1-Q3)	Mean ($\pm$ SE)
River	17.75 (7.47-51.84)	1471.38 $\pm$ 1366.09	99.13 (29.42-573.48)	968.67 $\pm$ 419.42	0.215 (0.074-0.481)	0.622 $\pm$ 0.219
Lake	26.89 (11.36-64.04)	89.94 $\pm$ 56.40	185.06 (83.58-601.26)	778.91 $\pm$ 497.31	0.118 (0.040-0.164)	0.133 $\pm$ 0.035
Wetland	21.55 (10.62-47.45)	159.37 $\pm$ 56.41	200.02(110.37-337.07)	284.93 $\pm$ 55.24	0.161 (0.067-0.706)	1.825 $\pm$ 1.030
Estuary	23.24 (6.41-61.91)	92.06 $\pm$ 44.77	227.45(115.80-747.72)	685.62 $\pm$ 177.95	0.129 (0.046-0.277)	0.241 $\pm$ 0.055
Global	21.55 (8.21-58.90)	604.55 $\pm$ 490.25	171.76 (65.40-519.25)	690.58 $\pm$ 164.21	0.129 (0.060-0.374)	0.758 $\pm$ 0.272

List of references for our dataset

1. Bagnoud A, Guye-Humbert S, Schlöter-Hai B, Schlöter M, Zopfi J. Environmental factors determining distribution and activity of anammox bacteria in minerotrophic fen soils. *FEMS microbiology ecology* **96**, (2020).
2. Bernard RJ, Mortazavi B, Kleinhuizen AA. Dissimilatory nitrate reduction to ammonium (DNRA) seasonally dominates NO_3^- reduction pathways in an anthropogenically impacted sub-tropical coastal lagoon. *Biogeochemistry* **125**, 47-64 (2015).
3. Bonaglia S, Deutsch B, Bartoli M, Marchant HK, Brückert V. Seasonal oxygen, nitrogen and phosphorus benthic cycling along an impacted Baltic Sea estuary: regulation and spatial patterns. *Biogeochemistry* **119**, 139-160 (2014).
4. Brin LD, Giblin AE, Rich JJ. Environmental controls of anammox and denitrification in southern New England estuarine and shelf sediments. *Limnology and Oceanography* **59**, 851-860 (2014).
5. Cai M, *et al.* Nitrate Addition Increases the Activity of Microbial Nitrogen Removal in Freshwater Sediment. *Microorganisms* **10**, (2022).
6. Cao W, Guan Q, Li Y, Wang M, Liu B. The contribution of denitrification and anaerobic ammonium oxidation to N_2 production in mangrove sediments in Southeast China. *Journal of Soils and Sediments* **17**, 1767-1776 (2017).
7. Cao W, Yang J, Li Y, Liu B, Wang F, Chang C. Dissimilatory nitrate reduction to ammonium conserves nitrogen in anthropogenically affected subtropical mangrove sediments in Southeast China. *Marine pollution bulletin* **110**, 155-161 (2016).
8. Chen J, Gu JD. Faunal Burrows Alter the Diversity, Abundance, and Structure of AOA, AOB, Anammox and n-Damo Communities in Coastal Mangrove Sediments. *Microbial ecology* **74**, 140-156 (2017).
9. Chen L, *et al.* Anammox response to natural and anthropogenic impacts over the Yangtze River. *The Science of the total environment* **665**, 171-180 (2019).
10. Chen L, *et al.* Dispersal limitation drives biogeographical patterns of anammox bacterial communities across the Yangtze River. *Applied microbiology and biotechnology* **104**, 5535-5546 (2020).
11. Chen S, *et al.* Gross nitrogen transformations in intertidal sediments of the Yangtze Estuary: Distribution patterns and environmental controls. *Geoderma* **429**, 116233 (2023).

12. Cheng L, *et al.* Dissimilatory nitrate reduction processes in sediments of urban river networks: Spatiotemporal variations and environmental implications. *Environmental pollution* **219**, 545-554 (2016).
13. Chu J, Zhang J, Zhou X, Liu B, Li Y. A Comparison of Anammox Bacterial Abundance and Community Structures in Three Different Emerged Plants-Related Sediments. *Current microbiology* **71**, 421-427 (2015).
14. Dale OR, Tobias CR, Song B. Biogeographical distribution of diverse anaerobic ammonium oxidizing (anammox) bacteria in Cape Fear River Estuary. *Environmental microbiology* **11**, 1194-1207 (2009).
15. Deng F, *et al.* Dissimilatory nitrate reduction processes and associated contribution to nitrogen removal in sediments of the Yangtze Estuary. *Journal of Geophysical Research: Biogeosciences* **120**, 1521-1531 (2015).
16. Diao M, Balkema C, Suarez-Munoz M, Huisman J, Muyzer G. Succession of bacteria and archaea involved in the nitrogen cycle of a seasonally stratified lake. *FEMS microbiology letters* **370**, (2023).
17. Ding B, Chen Z, Li Z, Qin Y, Chen S. Nitrogen loss through anaerobic ammonium oxidation coupled to Iron reduction from ecosystem habitats in the Taihu estuary region. *The Science of the total environment* **662**, 600-606 (2019).
18. Dong LF, Smith CJ, Papaspyrou S, Stott A, Osborn AM, Nedwell DB. Changes in benthic denitrification, nitrate ammonification, and anammox process rates and nitrate and nitrite reductase gene abundances along an estuarine nutrient gradient (the Colne estuary, United Kingdom). *Applied and environmental microbiology* **75**, 3171-3179 (2009).
19. Fernandes SO, Javanaud C, Michotey VD, Guasco S, Anschutz P, Bonin P. Coupling of bacterial nitrification with denitrification and anammox supports N removal in intertidal sediments (Arcachon Bay, France). *Estuarine, Coastal and Shelf Science* **179**, 39-50 (2016).
20. Fernandes SO, Michotey VD, Guasco S, Bonin PC, Bharathi PA. Denitrification prevails over anammox in tropical mangrove sediments (Goa, India). *Marine environmental research* **74**, 9-19 (2012).
21. Fortin SG, Song B, Anderson IC. Microbially mediated nitrogen removal and retention in the York River Estuary. *FEMS microbiology ecology* **97**, (2021).
22. Fozia, *et al.* Anaerobic ammonium oxidation (anammox) bacterial diversity, abundance, and activity in sediments of the Indus Estuary. *Estuarine, Coastal and Shelf Science* **243**, 106925 (2020).

23. Fu B, *et al.* Shift of anammox bacterial community structure along the Pearl Estuary and the impact of environmental factors. *Journal of Geophysical Research: Oceans* **120**, 2869-2883 (2015).
24. Gao D, *et al.* Soil dissimilatory nitrate reduction processes in the *Spartina alterniflora* invasion chronosequences of a coastal wetland of southeastern China: Dynamics and environmental implications. *Plant and Soil* **421**, 383-399 (2017).
25. Gao D, *et al.* Effects of shrimp-aquaculture reclamation on sediment nitrate dissimilatory reduction processes in a coastal wetland of southeastern China. *Environmental pollution* **255**, 113219 (2019).
26. Gao J, *et al.* Organic carbon quantity and composition jointly modulate the differentiation of nitrate reduction pathways in sediments of the Chinese eutrophic lake, Lake Chaohu. *Water research* **220**, 118720 (2022).
27. Han B, *et al.* Rates and microbial communities of denitrification and anammox across coastal tidal flat lands and inland paddy soils in East China. *Applied Soil Ecology* **157**, 103768 (2021).
28. Han H, Lu X, Burger DF, Joshi UM, Zhang L. Nitrogen dynamics at the sediment–water interface in a tropical reservoir. *Ecological Engineering* **73**, 146-153 (2014).
29. Han P, Li M, Gu JD. Biases in community structures of ammonia/ammonium-oxidizing microorganisms caused by insufficient DNA extractions from Baijiang soil revealed by comparative analysis of coastal wetland sediment and rice paddy soil. *Applied microbiology and biotechnology* **97**, 8741-8756 (2013).
30. Hietanen S. Anaerobic ammonium oxidation (anammox) in sediments of the Gulf of Finland. *AQUATIC MICROBIAL ECOLOGY*, (2007).
31. Hou L, *et al.* Anaerobic ammonium oxidation (anammox) bacterial diversity, abundance, and activity in marsh sediments of the Yangtze Estuary. *Journal of Geophysical Research: Biogeosciences* **118**, 1237-1246 (2013).
32. Hou L, *et al.* Anaerobic ammonium oxidation and its contribution to nitrogen removal in China's coastal wetlands. *Scientific reports* **5**, 15621 (2015).
33. Hu J, *et al.* The coexistence and diversity of *Candidatus methyloiridis* oxyfera-like and anammox bacteria in sediments of an urban eutrophic lake. *International microbiology : the official journal of the Spanish Society for Microbiology* **25**, 457-469 (2022).
34. Huang F, Lin X, Yin K. Effects of marine produced organic matter on the potential estuarine capacity of NO(x)(-) removal. *The Science of the total environment* **812**, 151471 (2022).

35. Humbert S, Zopfi J, Tarnawski SE. Abundance of anammox bacteria in different wetland soils. *Environmental microbiology reports* **4**, 484-490 (2012).
36. Ji G, Wang R, Zhi W, Liu X, Kong Y, Tan Y. Distribution patterns of denitrification functional genes and microbial floras in multimedia constructed wetlands. *Ecological Engineering* **44**, 179-188 (2012).
37. Jiang Y, *et al.* Variations of dissimilatory nitrate reduction processes along reclamation chronosequences in Chongming Island, China. *Soil and Tillage Research* **206**, 104815 (2021).
38. Kim H, Bae HS, Reddy KR, Ogram A. Distributions, abundances and activities of microbes associated with the nitrogen cycle in riparian and stream sediments of a river tributary. *Water research* **106**, 51-61 (2016).
39. Lansdown K, *et al.* Importance and controls of anaerobic ammonium oxidation influenced by riverbed geology. *Nature Geoscience* **9**, 357-360 (2016).
40. Li J, Han Y, Liao J, *et al.* Characteristics of anaerobic ammonia-oxidizing bacteria in mangrove wetland effluent dissipation. *Journal of Environmental Science* **39(2)**, 509-517(2019). (In Chinese)
41. Li J, Yu S, Qin S. Removal Capacities and Environmental Constrains of Denitrification and Anammox Processes in Eutrophic Riverine Sediments. *Water, Air, & Soil Pollution* **231**, (2020).
42. Li M, Cao H, Hong Y, Gu JD. Spatial distribution and abundances of ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) in mangrove sediments. *Applied microbiology and biotechnology* **89**, 1243-1254 (2011).
43. Li M, Gu JD. Community structure and transcript responses of anammox bacteria, AOA, and AOB in mangrove sediment microcosms amended with ammonium and nitrite. *Applied microbiology and biotechnology* **97**, 9859-9874 (2013).
44. Li M, Hong YG, Cao HL, Gu JD. Mangrove trees affect the community structure and distribution of anammox bacteria at an anthropogenic-polluted mangrove in the Pearl River Delta reflected by 16S rRNA and hydrazine oxidoreductase (HZO) encoding gene analyses. *Ecotoxicology* **20**, 1780-1790 (2011).
45. Li M, Wei G, Liu J, Wang X, Hou L, Gao Z. Effects of Nitrate Exposure on Nitrate Reduction Processes in the Wetland Sediments from the Yellow River Estuary. *Estuaries and Coasts* **45**, 315-330 (2021).
46. Li N, Li B, Nie M, Wu J. Effects of exotic *Spartina alterniflora* on saltmarsh nitrogen removal in the Yangtze River Estuary, China. *Journal of Cleaner Production* **271**, 122557 (2020).

47. Li P, *et al.* Seasonal variation of anaerobic ammonium oxidizing bacterial community and abundance in tropical mangrove wetland sediments with depth. *Applied Soil Ecology* **130**, 149-158 (2018).
48. Li S, Twilley RR. Nitrogen Dynamics of Inundated Sediments in an Emerging Coastal Deltaic Floodplain in Mississippi River Delta Using Isotope Pairing Technique to Test Response to Nitrate Enrichment and Sediment Organic Matter. *Estuaries and Coasts* **44**, 1899-1915 (2021).
49. Li X, *et al.* Nitrogen loads alter the N(2) production between denitrification and anammox in Min River Estuary, a highly impacted estuary in southeast China. *Environmental pollution* **277**, 116757 (2021).
50. Li X, Lai DYF, Gao D. Anaerobic oxidation of methane with denitrification in sediments of a subtropical estuary: Rates, controlling factors and environmental implications. *J Environ Manage* **273**, 111151 (2020).
51. Li X, Qian W, Hou L, Liu M, Chen Z, Tong C. Human activity intensity controls the relative importance of denitrification and anaerobic ammonium oxidation across subtropical estuaries. *Catena* **202**, 105260 (2021).
52. Li X, *et al.* High Incidence Hypoxia Increases Benthic Nitrogen Retention but Decreases Nitrogen Removal in Seasonally Hypoxic Areas off the Changjiang Estuary. *Journal of Geophysical Research: Biogeosciences* **126**, (2021).
53. Li X, Sardans J, Hou L, Gao D, Liu M, Peñuelas J. Dissimilatory Nitrate/Nitrite Reduction Processes in River Sediments Across Climatic Gradient: Influences of Biogeochemical Controls and Climatic Temperature Regime. *Journal of Geophysical Research: Biogeosciences* **124**, 2305-2320 (2019).
54. Li Y, Hong Y, Wu J, Wang Y, Ye F. Spatial variability pattern of the anaerobic ammonia-oxidizing bacterial community across a salinity gradient from river to ocean. *Ecotoxicology* **30**, 1743-1753 (2021).
55. Li Y, *et al.* Anaerobic ammonium oxidation (anammox) is the main microbial N loss pathway in alpine wetland soils of the Qinghai-Tibet Plateau. *Science of The Total Environment* **787**, 147714 (2021).
56. Lin J, Chen N, Yuan X, Tian Q, Hu A, Zheng Y. Impacts of human disturbance on the biogeochemical nitrogen cycle in a subtropical river system revealed by nitrifier and denitrifier genes. *The Science of the total environment* **746**, 141139 (2020).

57. Lin X, Li X, Gao D, Liu M, Cheng L. Ammonium Production and Removal in the Sediments of Shanghai River Networks: Spatiotemporal Variations, Controlling Factors, and Environmental Implications. *Journal of Geophysical Research: Biogeosciences* **122**, 2461-2478 (2017).
58. Ling X, Lu G, Xue C. Environmental and anthropogenic factors affect bacterial community and nitrogen removal in the Yarlung Zangbo River. *Environmental science and pollution research international* **29**, 84590-84599 (2022).
59. Lisa JA, Song B, Semedo M, Duernberger KA, Tobias CR. Determining geochemical and microbial parameters underlying geographic patterns of denitrification and anammox rates in the New River Estuary, North Carolina, USA. *Estuarine, Coastal and Shelf Science* **275**, 107973 (2022).
60. Lisa JA, Song B, Tobias CR, Duernberger KA. Impacts of freshwater flushing on anammox community structure and activities in the New River Estuary, USA. *Aquatic Microbial Ecology* **72**, 17-31 (2014).
61. Lisa JA, Song B, Tobias CR, Hines DE. Genetic and biogeochemical investigation of sedimentary nitrogen cycling communities responding to tidal and seasonal dynamics in Cape Fear River Estuary. *Estuarine, Coastal and Shelf Science* **167**, A313-A323 (2015).
62. Liu C, *et al.* Coupling of denitrification and anaerobic ammonium oxidation with nitrification in sediments of the Yangtze Estuary: Importance and controlling factors. *Estuarine, Coastal and Shelf Science* **220**, 64-72 (2019).
63. Liu XG, Wang J, Wu ZF, Cheng GF, Gu ZJ. Anaerobic Ammonium Oxidation Bacteria in a Freshwater Recirculating Pond Aquaculture System. *International journal of environmental research and public health* **18**, (2021).
64. Mao C, *et al.* Patterns and drivers of anaerobic nitrogen transformations in sediments of thermokarst lakes. *Global change biology* **29**, 2697-2713 (2023).
65. Mara P, *et al.* Comparison of Oyster Aquaculture Methods and Their Potential to Enhance Microbial Nitrogen Removal From Coastal Ecosystems. *Frontiers in Marine Science* **8**, (2021).
66. Marshall AJ, *et al.* Nitrogen cycling in coastal sediment microbial communities with seasonally variable benthic nutrient fluxes. *Aquatic Microbial Ecology* **86**, 1-19 (2021).
67. Meyer RL, Risgaard-Petersen N, Allen DE. Correlation between anammox activity and microscale distribution of nitrite in a subtropical mangrove sediment. *Applied and environmental microbiology* **71**, 6142-6149 (2005).

68. Naeher S, *et al.* Molecular and geochemical constraints on anaerobic ammonium oxidation (anammox) in a riparian zone of the Seine Estuary (France). *Biogeochemistry* **123**, 237-250 (2015).
69. Nair RR, Rangaswamy B, Sarojini BSI, Joseph V. Anaerobic ammonia-oxidizing bacteria in tropical bioaugmented zero water exchange aquaculture ponds. *Environmental science and pollution research international* **27**, 10541-10552 (2020).
70. Pang Y, Wang J, Li S, Ji G. Long-term sulfide input enhances chemoautotrophic denitrification rather than DNRA in freshwater lake sediments. *Environmental pollution* **270**, 116201 (2021).
71. Qi M, Qian W, Chen Z, Tong C, Li X. Disproportionate variations in denitrification and anaerobic ammonium oxidation across freshwater-oligohaline wetlands in Min River Estuary, Southeast China. *Environmental science and pollution research international* **29**, 6678-6687 (2022).
72. Qin H, *et al.* Vertical distribution and community composition of anammox bacteria in sediments of a eutrophic shallow lake. *Journal of applied microbiology* **125**, 121-132 (2018).
73. Qin Y, Chen Z, Ding B, Li Z. Impact of sand mining on the carbon sequestration and nitrogen removal ability of soil in the riparian area of Lijiang River, China. *Environmental pollution* **261**, 114220 (2020).
74. Qu M, *et al.* Distribution and quantity discrepancy of anammox and N-DAMO bacteria in lakeshore sediments with or without emergent macrophytes. *International Journal of Environmental Science and Technology* **19**, 11867-11877 (2022).
75. Ribeiro H, *et al.* Differential effects of crude oil on denitrification and anammox, and the impact on N₂O production. *Environmental pollution* **216**, 391-399 (2016).
76. Rissanen AJ, Tirola M, Hietanen S, Ojala A. Interlake variation and environmental controls of denitrification across different geographical scales. *Aquatic Microbial Ecology* **69**, 1-16 (2013).
77. Ruifei W, Xinkuan H, Peili L, Qingxiang Y. CO-OCCURRENCE AND DIVERSITY OF NITRITE-DEPENDENT ANAEROBIC METHANE OXIDIZING AND ANAEROBIC AMMONIUM OXIDIZING BACTERIA IN THE WATER-LEVEL FLUCTUATION ZONE OF THE THREE GORGES RESERVOIR, CHINA. *Fresenius Environmental Bulletin*, (2016).
78. Salk KR, Bullerjahn GS, McKay RML, Chaffin JD, Ostrom NE. Nitrogen cycling in Sandusky Bay, Lake Erie: oscillations between strong and weak export and implications for harmful algal blooms. *Biogeosciences* **15**, 2891-2907 (2018).
79. She Y, Qi X, Xin X, He Y, Wang W, Li Z. Insights into microbial interactive mechanism regulating dissimilatory nitrate reduction processes in riparian freshwater aquaculture sediments. *Environmental research* **216**, 114593 (2023).

80. Shen LD, Cheng HX, Liu X, Li JH, Liu Y. Potential role of anammox in nitrogen removal in a freshwater reservoir, Jiulonghu Reservoir (China). *Environmental science and pollution research international* **24**, 3890-3899 (2017).
81. Shen LD, Liu X, Wu HS. Importance of anaerobic ammonium oxidation as a nitrogen removal pathway in freshwater marsh sediments. *Journal of applied microbiology* **125**, 1423-1434 (2018).
82. Shen LD, *et al.* Distribution and activity of anaerobic ammonium-oxidising bacteria in natural freshwater wetland soils. *Applied microbiology and biotechnology* **100**, 3291-3300 (2016).
83. Shen LD, *et al.* Evidence for anaerobic ammonium oxidation process in freshwater sediments of aquaculture ponds. *Environmental science and pollution research international* **23**, 1344-1352 (2016).
84. Shen L-d, *et al.* Depth-specific distribution and importance of nitrite-dependent anaerobic ammonium and methane-oxidising bacteria in an urban wetland. *Soil Biology and Biochemistry* **83**, 43-51 (2015).
85. Sun W, *et al.* Molecular diversity and distribution of anammox community in sediments of the Dongjiang River, a drinking water source of Hong Kong. *Journal of applied microbiology* **116**, 464-476 (2014).
86. Tan E, *et al.* Quantitatively deciphering the roles of sediment nitrogen removal in environmental and climatic feedbacks in two subtropical estuaries. *Water research* **224**, 119121 (2022).
87. Tan E, *et al.* Organic matter decomposition sustains sedimentary nitrogen loss in the Pearl River Estuary, China. *The Science of the total environment* **648**, 508-517 (2019).
88. Tan E, *et al.* Warming stimulates sediment denitrification at the expense of anaerobic ammonium oxidation. *Nature Climate Change* **10**, 349-355 (2020).
89. Teixeira C, Magalhães C, Joye SB, Bordalo AA. Potential rates and environmental controls of anaerobic ammonium oxidation in estuarine sediments. *Aquatic Microbial Ecology* **66**, 23-32 (2012).
90. Teixeira C, Magalhães C, Joye SB, Bordalo AA. The contribution of anaerobic ammonium oxidation to nitrogen loss in two temperate eutrophic estuaries. *Estuarine, Coastal and Shelf Science* **143**, 41-47 (2014).
91. Teng Z, Zhen Y, Yu Z, Mi T, Cai T. Nitrogen-loss and associated microbial communities in sediments from the Yangtze Estuary and adjacent sea. *Frontiers in Marine Science* **9**, (2022).

92. Trimmer M, Nicholls JC, Deflandre B. Anaerobic ammonium oxidation measured in sediments along the Thames estuary, United Kingdom. *Applied and environmental microbiology* **69**, 6447-6454 (2003).
93. Wan Y, Ruan X, Wang J, Shi X. Spatial and Seasonal Variations in the Abundance of Nitrogen-Transforming Genes and the Microbial Community Structure in Freshwater Lakes with Different Trophic Statuses. *International journal of environmental research and public health* **16**, (2019).
94. Wang G, Xia X, Liu S, Wang J, Zhang S. Low diffusive nitrogen loss of urban inland waters with high nitrogen loading. *The Science of the total environment* **789**, 148023 (2021).
95. Wang J, *et al.* Denitrification and anammox: Understanding nitrogen loss from Yangtze Estuary to the east China sea (ECS). *Environmental pollution* **252**, 1659-1670 (2019).
96. Wang S, *et al.* Nitrate reduction in the reed rhizosphere of a riparian zone: From functional genes to activity and contribution. *Environmental research* **180**, 108867 (2020).
97. Wang S, *et al.* Hotspot of dissimilatory nitrate reduction to ammonium (DNRA) process in freshwater sediments of riparian zones. *Water research* **173**, 115539 (2020).
98. Wang S, *et al.* Abundance and Functional Importance of Complete Ammonia Oxidizers and Other Nitrifiers in a Riparian Ecosystem. *Environmental science & technology* **55**, 4573-4584 (2021).
99. Wang S, Zhu G, Peng Y, Jetten MS, Yin C. Anammox bacterial abundance, activity, and contribution in riparian sediments of the Pearl River estuary. *Environmental science & technology* **46**, 8834-8842 (2012).
100. Wang YF, Gu JD. Higher diversity of ammonia/ammonium-oxidizing prokaryotes in constructed freshwater wetland than natural coastal marine wetland. *Applied microbiology and biotechnology* **97**, 7015-7033 (2013).
101. Wang Y-F, Dick RP, Lorenz N, Lee N. Interactions and responses of n-damo archaea, n-damo bacteria and anammox bacteria to various electron acceptors in natural and constructed wetland sediments. *International Biodeterioration & Biodegradation* **144**, 104749 (2019).
102. Wei H, Gao D, Liu Y, Lin X. Sediment nitrate reduction processes in response to environmental gradients along an urban river-estuary-sea continuum. *The Science of the total environment* **718**, 137185 (2020).

103. Wu J, Hong Y, Wen X, Li Y, Wang Y, Chang X. Activity, Abundance, and Community Composition of Anaerobic Ammonia–Oxidizing (Anammox) Bacteria in Sediment Cores of the Pearl River Estuary. *Estuaries and Coasts* **43**, 73-85 (2019).
104. Wu J, Hong Y, Wilson SJ, Song B. Microbial nitrogen loss by coupled nitrification to denitrification and anammox in a permeable subterranean estuary at Gloucester Point, Virginia. *Marine pollution bulletin* **168**, 112440 (2021).
105. Xia C, Zhu G, Zou Y-X. Distribution patterns of anaerobic ammonia-oxidizing bacteria and denitrifying anaerobic methane-oxidizing bacteria in soil in the riparian zone. *Journal of Environmental Science*, 2015, 35(12): 3965-3975. (In Chinese)
106. Yang X-R, *et al.* An overlooked nitrogen loss linked to anaerobic ammonium oxidation in estuarine sediments in China. *Journal of Soils and Sediments* **17**, 2537-2546 (2017).
107. Yang Y, Dai Y, Li N, Li B, Xie S, Liu Y. Temporal and Spatial Dynamics of Sediment Anaerobic Ammonium Oxidation (Anammox) Bacteria in Freshwater Lakes. *Microbial ecology* **73**, 285-295 (2017).
108. Yang Z, *et al.* Dissimilatory nitrate reduction in urban lake ecosystems: A comparison study between closed and open lakes in Chengdu, China. *Water research* **214**, 118218 (2022).
109. Yao X, *et al.* Sediment organic matter properties facilitate understanding nitrogen transformation potentials in East African lakes. *The Science of the total environment* **841**, 156607 (2022).
110. Yao Z, Wang F, Wang C, Xu H, Jiang H. Anaerobic ammonium oxidation coupled to ferric iron reduction in the sediment of a eutrophic lake. *Environmental science and pollution research international* **26**, 15084-15094 (2019).
111. Yin X, *et al.* Seasonal and vertical variations in the characteristics of the nitrogen-related functional genes in sediments from urban eutrophic lakes. *Applied Soil Ecology* **143**, 80-88 (2019).
112. Yin X, *et al.* Microbial community of nitrogen cycle-related genes in aquatic plant rhizospheres of Lake Liangzi in winter. *Journal of basic microbiology* **58**, 998-1006 (2018).
113. Yongqiang Z, Yuguo W, Lvbing J. Nitrogen removal by denitrification and anammox processes in freshwater rivers of high nitrogen loading region of China. *Global NEST Journal*, (2017).
114. Yoshinaga I, *et al.* Distribution and diversity of anaerobic ammonium oxidation (anammox) bacteria in the sediment of a eutrophic freshwater lake, Lake Kitauro, Japan. *Microbes and environments* **26**, 189-197 (2011).

115. Yu L, Liu S, Jiang L, Wang X, Xiao L. Insight into the nitrogen accumulation in urban center river from functional genes and bacterial community. *PloS one* **15**, e0238531 (2020).
116. Zhang M, *et al.* Nitrogen loss by anaerobic ammonium oxidation in a mangrove wetland of the Zhangjiang Estuary, China. *The Science of the total environment* **698**, 134291 (2020).
117. Zhang M, Huang J-C, Sun S, Ur Rehman MM, He S, Zhou W. Dissimilatory nitrate reduction processes and corresponding nitrogen loss in tidal flow constructed wetlands. *Journal of Cleaner Production* **295**, 126429 (2021).
118. Zhang S, *et al.* Linkages between anammox and denitrifying bacterial communities and nitrogen loss rates in high-elevation rivers. *Limnology and Oceanography* **66**, 765-778 (2020).
119. Zhang S, *et al.* Potential roles of anaerobic ammonium oxidation (anammox) in overlying water of rivers with suspended sediments. *Biogeochemistry* **132**, 237-249 (2017).
120. Zhang T, Zhuang X, Ahmad S, Lee T, Cao C, Ni SQ. Investigation of dissimilatory nitrate reduction to ammonium (DNRA) in urban river network along the Huangpu River, China: rates, abundances, and microbial communities. *Environmental science and pollution research international* **29**, 23823-23833 (2022).
121. Zhang X, Agogu  H, Dupuy C, Gong J. Relative Abundance of Ammonia Oxidizers, Denitrifiers, and Anammox Bacteria in Sediments of Hyper-Nutriented Estuarine Tidal Flats and in Relation to Environmental Conditions. *CLEAN – Soil, Air, Water* **42**, 815-823 (2013).
122. Zhang X, *et al.* Diversity, abundance, and distribution of anammox bacteria in shipping channel sediment of Hong Kong by analysis of DNA and RNA. *Ecotoxicology* **30**, 1705-1718 (2021).
123. Zhao B, *et al.* Dissimilatory nitrate reduction and functional genes in two subtropical rivers, China. *Environmental science and pollution research international* **28**, 68155-68173 (2021).
124. Zhao J, *et al.* Diversity of anammox bacteria and abundance of functional genes for nitrogen cycling in the rhizosphere of submerged macrophytes in a freshwater lake in summer. *Journal of Soils and Sediments* **19**, 3648-3656 (2019).
125. Zhao S, Zhuang L, Wang C, Li Y, Wang S, Zhu G. High-throughput analysis of anammox bacteria in wetland and dryland soils along the altitudinal gradient in Qinghai-Tibet Plateau. *MicrobiologyOpen* **7**, e00556 (2018).
126. Zhao Y, Xia Y, Kana TM, Wu Y, Li X, Yan X. Seasonal variation and controlling factors of anaerobic ammonium oxidation in freshwater river sediments in the Taihu Lake region of China. *Chemosphere* **93**, 2124-2131 (2013).

127. Zhao Y, *et al.* Assembly mechanism and co-occurrence patterns of DNRA microbial communities and imprint of nitrate reduction in the Songhua River sediments of China's largest old industrial base. *Journal of Environmental Management* **322**, 116091 (2022).
128. Zheng L, *et al.* Abundance, diversity, and distribution patterns along with the salinity of four nitrogen transformation-related microbes in the Yangtze Estuary. *Annals of Microbiology* **70**, (2020).
129. Zheng Y, Hou L, Liu M, Yin G. Dynamics and environmental importance of anaerobic ammonium oxidation (anammox) bacteria in urban river networks. *Environmental pollution* **254**, 112998 (2019).
130. Zheng Y, *et al.* Community composition and activity of anaerobic ammonium oxidation bacteria in the rhizosphere of salt-marsh grass *Spartina alterniflora*. *Applied microbiology and biotechnology* **100**, 8203-8212 (2016).
131. Zheng Y, *et al.* Shifts in the community structure and activity of anaerobic ammonium oxidation bacteria along an estuarine salinity gradient. *Journal of Geophysical Research: Biogeosciences* **121**, 1632-1645 (2016).
132. Zhou S, Borjigin S, Riya S, Terada A, Hosomi M. The relationship between anammox and denitrification in the sediment of an inland river. *The Science of the total environment* **490**, 1029-1036 (2014).
133. Zhou X, Zhang J, Wen C. Community Composition and Abundance of Anammox Bacteria in Cattail Rhizosphere Sediments at Three Phenological Stages. *Current microbiology* **74**, 1349-1357 (2017).
134. Zhou Z, Ge L, Huang Y, Liu Y, Wang S. Coupled relationships among anammox, denitrification, and dissimilatory nitrate reduction to ammonium along salinity gradients in a Chinese estuarine wetland. *Journal of environmental sciences* **106**, 39-46 (2021).
135. Zhu G, *et al.* Hotspots of anaerobic ammonium oxidation at land–freshwater interfaces. *Nature Geoscience* **6**, 103-107 (2013).
136. Zhu G, Xia C, Shanyun W, Zhou L, Liu L, Zhao S. Occurrence, activity and contribution of anammox in some freshwater extreme environments. *Environmental microbiology reports* **7**, 961-969 (2015).