Diel Fluctuation of Carbon Dioxide Emission Affected By Eutrophication and Dissolved Organic Matter in China’s Largest Urban Lake

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Outlines

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03 **Results & discussion**

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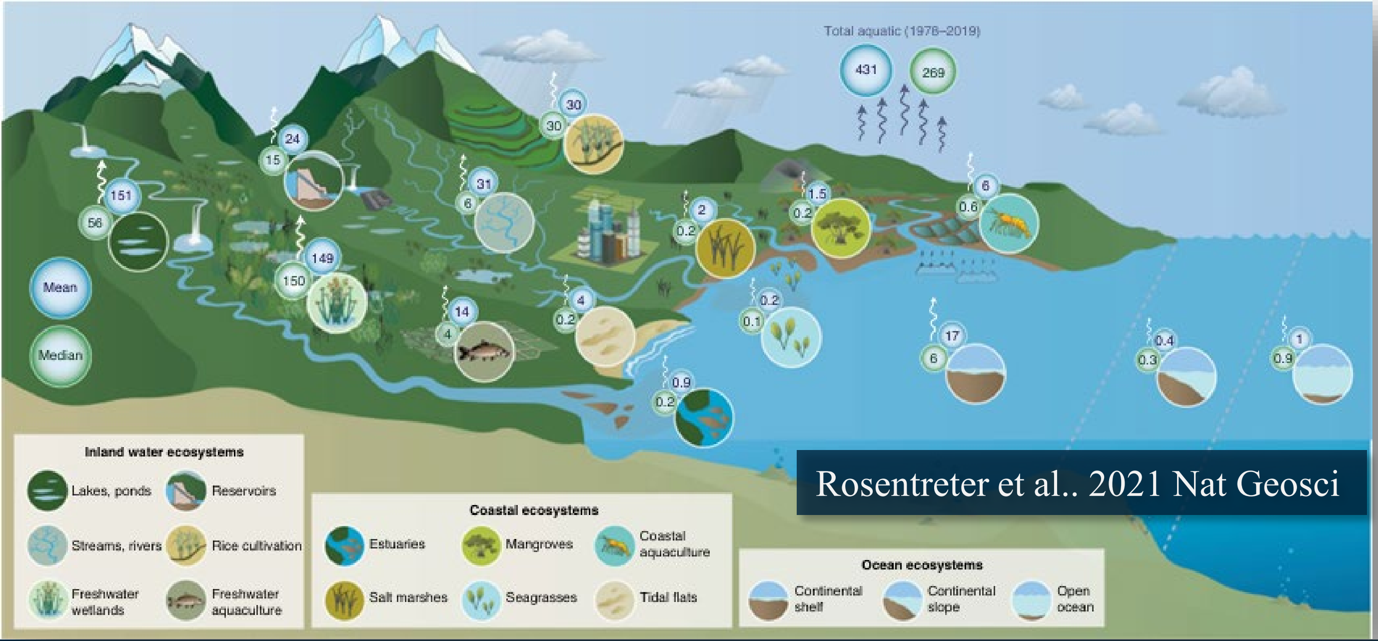
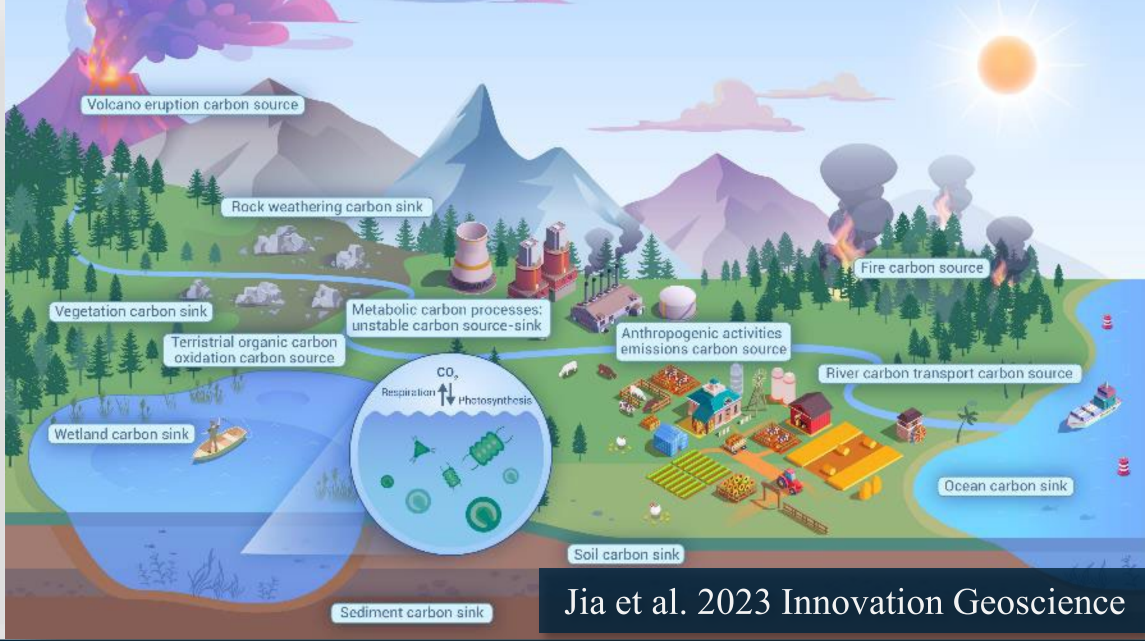
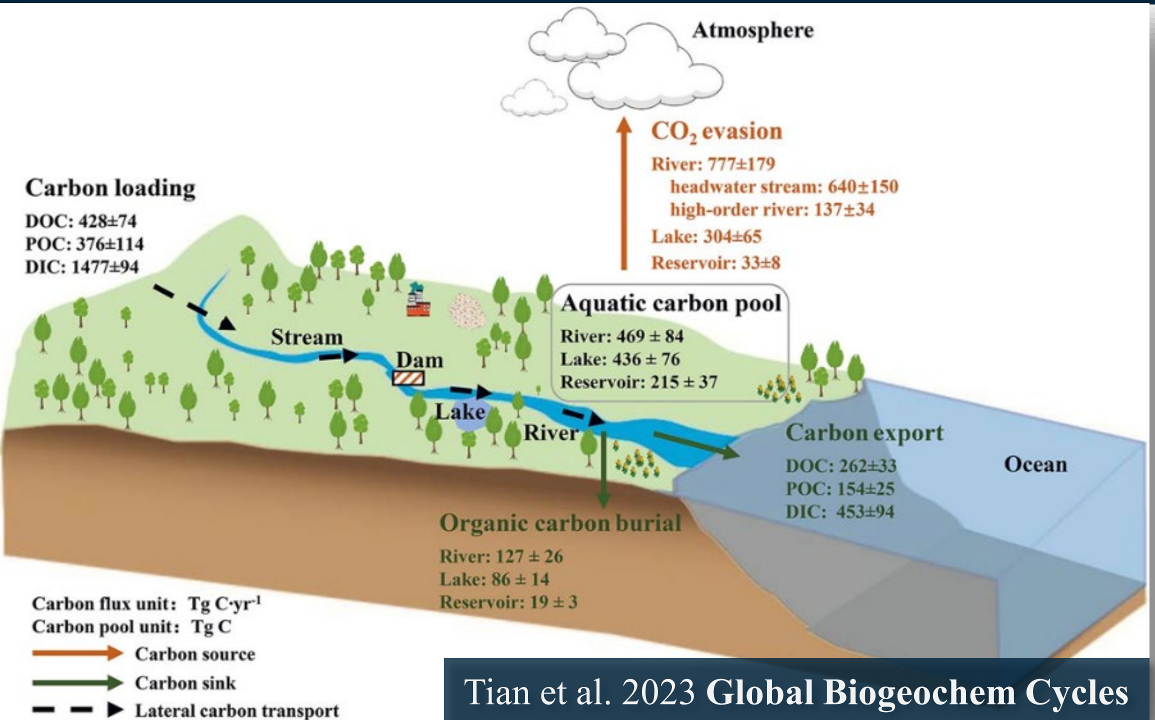
Inland waters are crucial for carbon exchanges (potential GHG emitters)



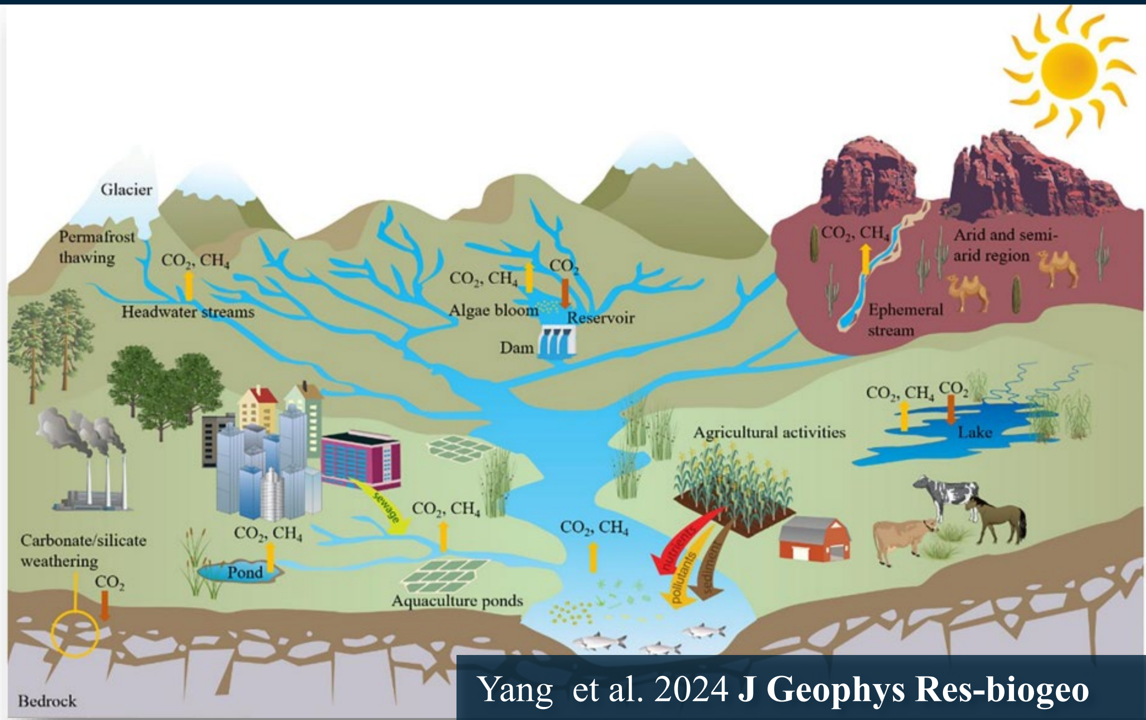
Rosentreter et al.. 2021 Nat Geosci



Jia et al. 2023 Innovation Geoscience



Tian et al. 2023 **Global Biogeochem Cycles**



Yang et al. 2024 **J Geophys Res-biogeo**

01

Upscaling of CO_2 emissions from lakes

Table1 Estimates of CO_2 –C emissions(Tg C yr^{-1}) from global lakes

References	Tg CO_2–C yr^{-1}	Improvements for upscaling
Cole et al. (2007)	109.09	Early global estimate
Duarte et al. (2008)	79.09	Including saline lakes
Marotta et al. (2009)	439.09	Including tropical lakes
Raymond et al. (2013)	319.09	Including reservoirs
Holgerson and Raymond (2016)	570	Including small ponds
DelSontro et al. (2018)	242.73-501.82	Based on remote sensing techniques

Table 2 Estimates of CO_2–C emissions(Tg C yr^{-1}) from China's lakes

References	Tg CO_2–C yr^{-1}	Improvements for upscaling
Li et al. (2018)	15.98	Early estimates in China
Ran et al. (2021)	7.3/8.4	Estimates in 1980s/2010s
Wang et al. (2023)	6.8	Including saline lakes, reservoirs
Sun et al. (2023)	6.78	Estimates by machine learning based on real-time water parameters
Wen et al. (2024)	8.07	Including saline lakes and lakes with different trophic states
Xiao et al. (2024)	2.75/-0.41	Estimates during 1988-1992 and 2007-2010

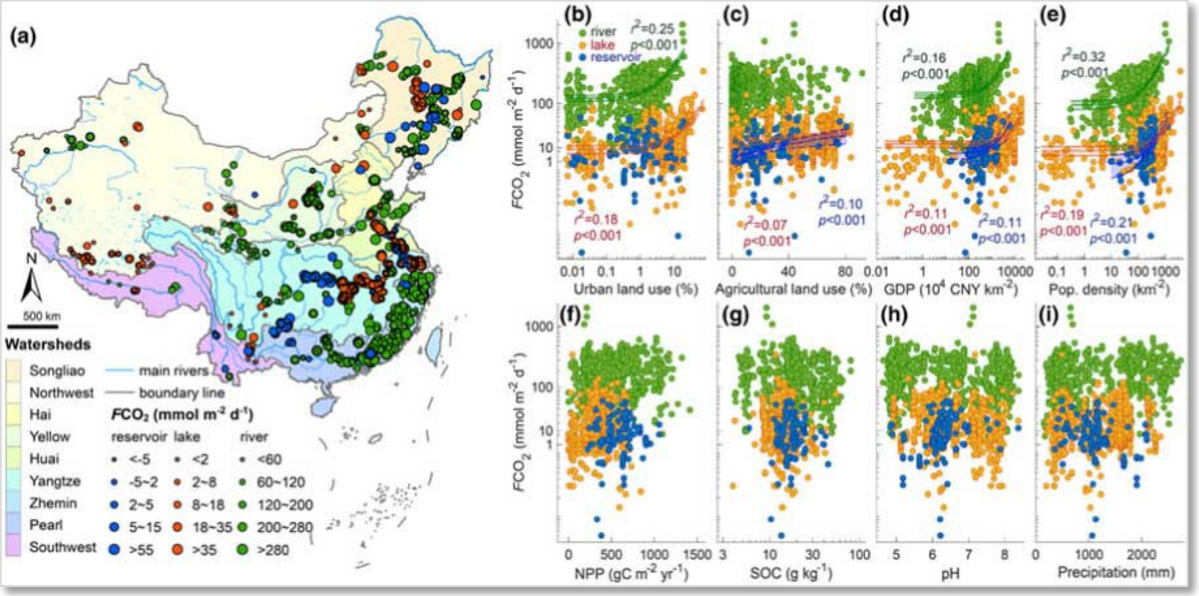
Accurately quantifying the carbon dioxide (CO_2) emissions from lakes remains challenging due to the large temporal and spatial variability (Hastie et al. 2018; Borges et al. 2022; Lauerwald et al. 2023)

Reasons for uncertainties

Human activities ➡ Land use alterations

Urban land use is the typical land use type

(Song et al. 2022)



(Wang et al. 2023)

Lakes in metropolitan areas are typically characterized by relatively small surface area, shallow waters, increased impervious surface cover, high population density, and eutrophication (Costadone and Sytsma, 2022; Song et al. 2022)

urban land use, GDP (gross domestic production), and population density were positively related to the emission of CO_2 from lakes.

1. Spatial-temporal characteristics of CO_2 emissions in urban lakes remain unclear

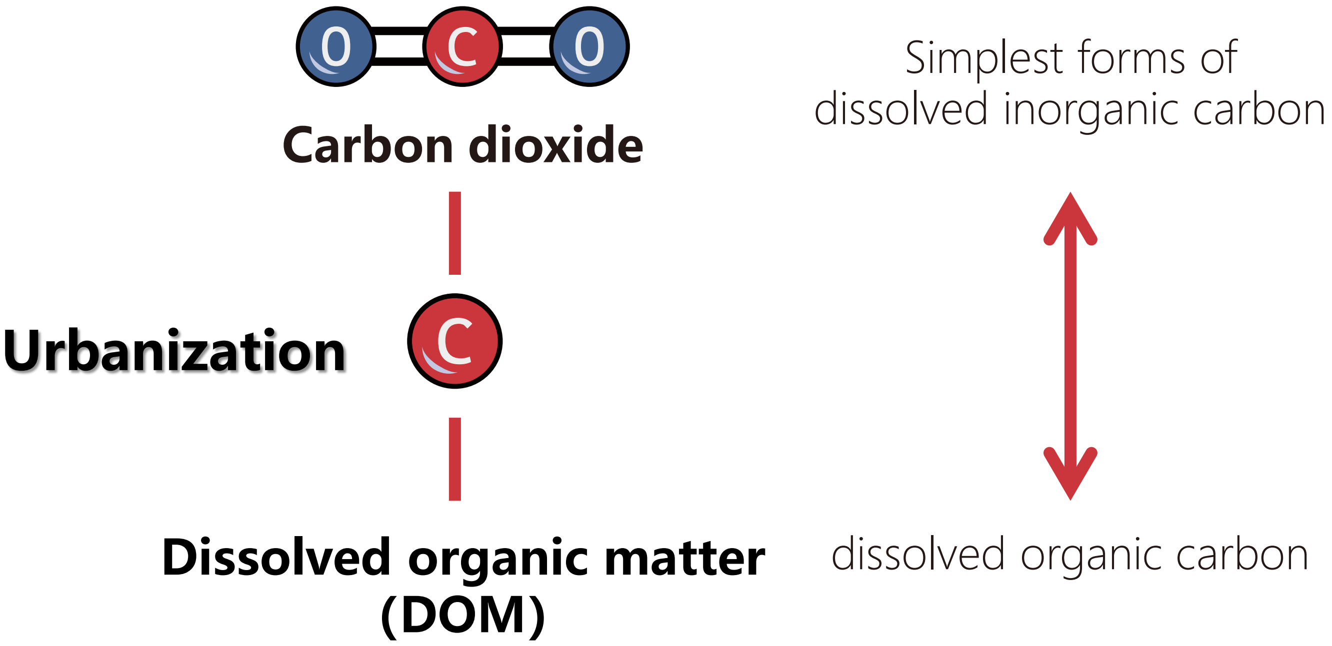
Table 4
Case studies on CO_2 fluxes ($mmol\ m^{-2}\ d^{-1}$) in urban lakes.

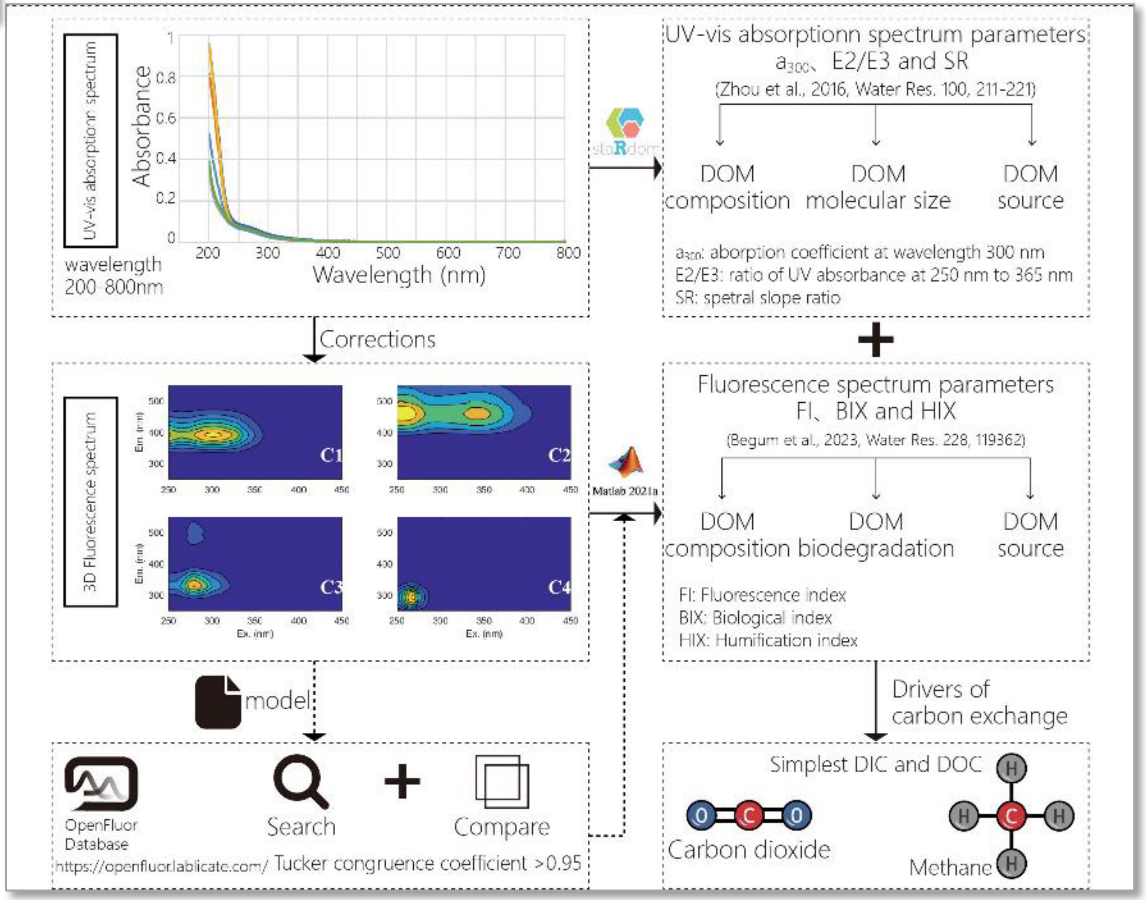
Daytime only

Studies	Cities (Country)	Lake number	Surface area (km^2)	CO_2 fluxes ($mmol\ m^{-2}\ d^{-1}$)	N_{obs}	Methods	Sampling period	Sampling time
Xing et al. (2005)	Wuhan (China)	1	33	7.55 ± 3.64 (−31.96– 86.95)	468	FCM	9:00–11:00	Apr. 2003 to Mar. 2004
Natchimuthu et al. (2014)	Linköping (Sweden)	1	0.0012	1.1 ± 6.7 (−9.8– 16)	27	FCM	12:00–15:00	Jun. to Oct. 2010
Zhao et al. (2017)	Nanjing (China)	1	3.7	60.05 (−5.78– 77.53)	200	FCM	daytime only	Jun. and Oct. 2014
Bergen et al. (2019)	Gelderland (Netherlands)	9	0.004635	79.17 ± 33.33	/	FCM	24-h period	Jul. 2013 to May. 2014
Gorsky et al. (2019)	Williamsburg (USA)	15	0.0271	34.09 (32.89– 160.37)	45	FCM	8:00–11:00	Jun. to Aug. 2018
Peacock et al. (2019)	Uppsala (Sweden)	40	0.00159	17.08 (−4.25– 78.42)	40	HEM, BLM	10:00–16:00	30 May. and 1 Jun. 2018
Audet et al. (2020)	Silkeborg (Denmark)	37	0.002069	4.36 ± 5.52	146	HEM, BLM	08:00–16:00	Aug. and Nov. 2018, Mar. and Jun. 2019
Xiao et al. (2020)	Wuxi (China)	1	8.6	25 ± 13.63	48	WCE, BLM	10:00–15:00	2004–2015
Peacock et al. (2021)	Uppsala (Sweden)	9	0.001128	82.8	89	FCM	9:00–15:00	Apr. to Dec. 2018
Goeckner et al. (2022)	Manatee (USA)	5	0.01097	135 (−308– 779.5)	65	FCM	10:00–14:00	Jun. 2019 and May. 2020
Yang et al. (2022)	Chengdu (China)	1	0.82	−655.2 ± 256.8	11	WCE, BLM	7:00–17:00	Jan. to Sep. 2020
Zhang et al. (2023)	Wuhan (China)	4	3.1–47.6	5.26 ± 18.55 2.03 ± 11.29		HEM, BLM	8:00–18:00	Oct. 2021 to Jun. 2022
This study	Wuhan (China)	1	47	8.76 ± 9.78 (−12.29– 32.69)	129,543	NDIR sensor, BLM	24-h period	Nov. and Dec. 2022, Mar. 2023

N_{obs}: Number of observations; FCM: Floating chamber method; HEM: Headspace equilibrium method; BLM: Boundary layer method; WCE: Water chemistry equilibrium.

2. The connection between CO_2 emissions and optical properties of DOM has rarely been reported





Organic carbon shares common pathways with CO_2, and DOM degradation governs spatial and temporal variations in CO_2 production

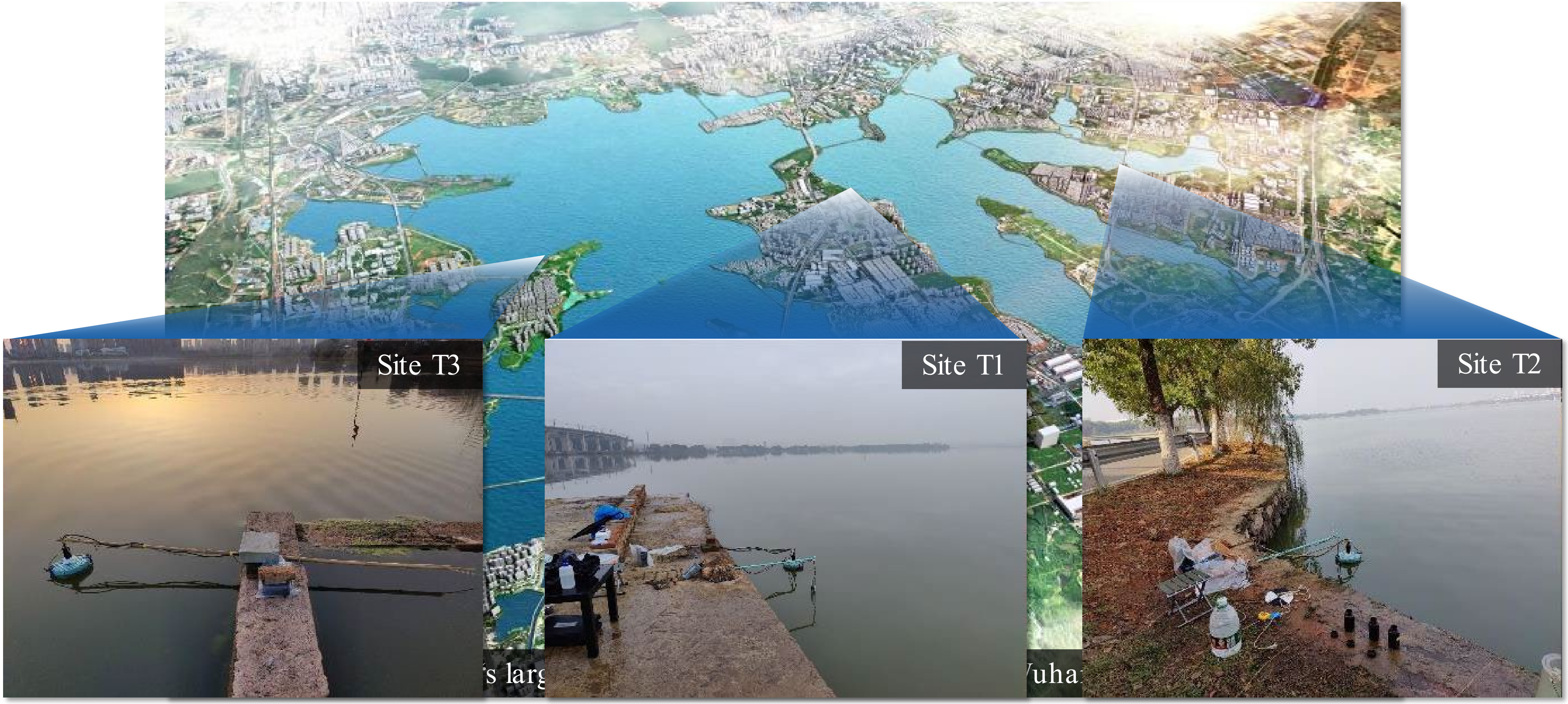
(Begum et al. 2023; Ni et al. 2024)

Optical properties of DOM (molecular weight, aromaticity and fluorescent components) can indicate the sources of carbon, revealing the key drivers of CO_2 production and emissions

(Zhou et al. 2018; Begum et al. 2023)

02

Sampling sites



02

Sampling campaigns

Sampling time

2022.11-2023.5□ Three diurnal samplings in each dry and wet seasons□

Sampling procedures

Water samples were taken every hour (n=24*6)

In situ measurements of CO_2 concentrations over every 24 h period

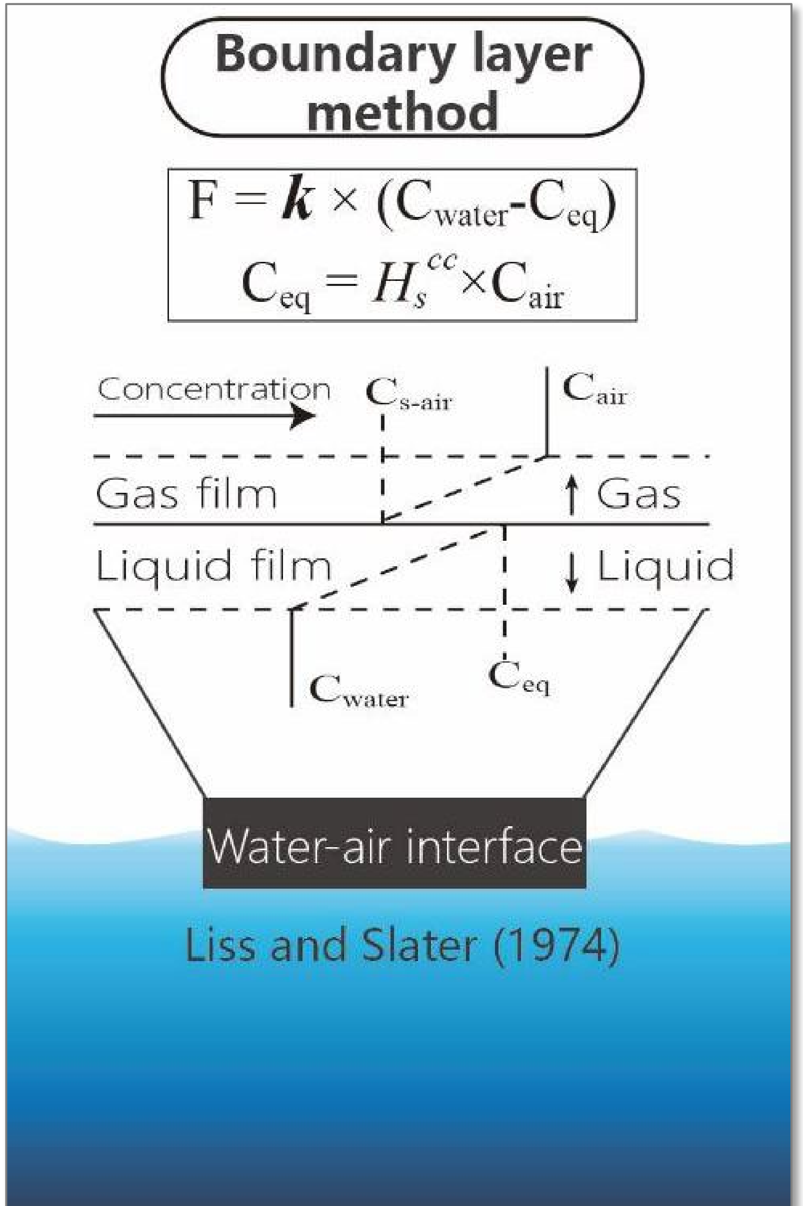
Sampling equipment

Non-dispersive infrared (NDIR) CO_2 sensor

Continuous measurements of cCO_2 which recorded every 2 seconds

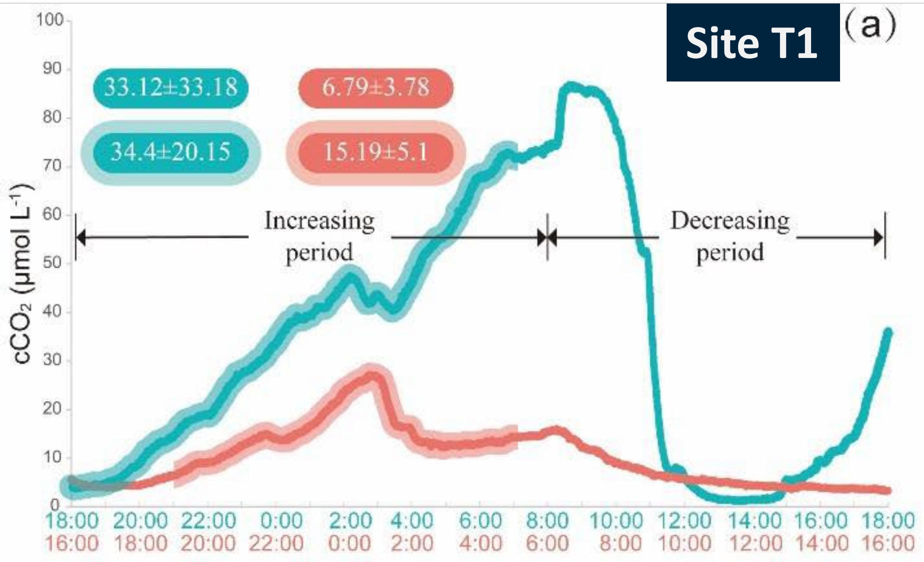
Water-air interface

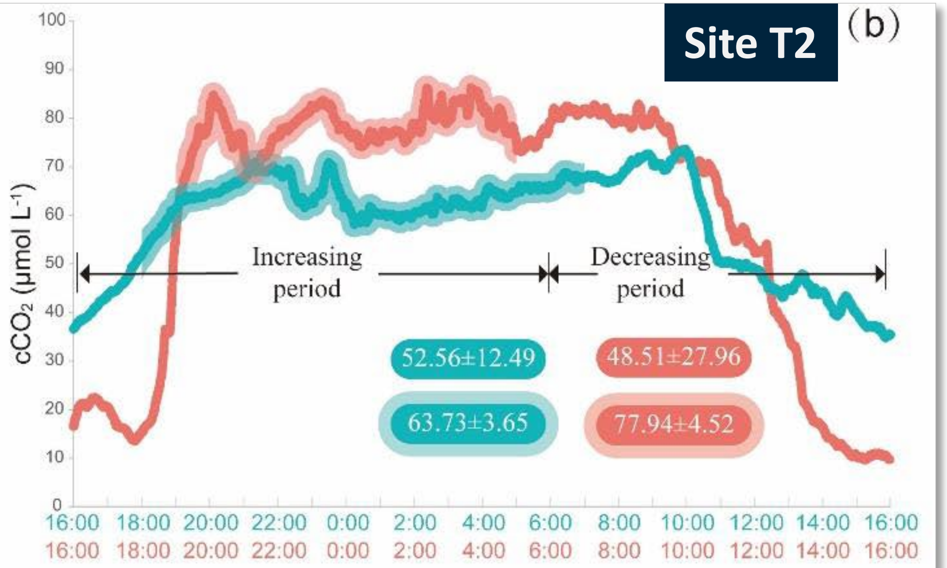
Relied on the gas transfer velocity k

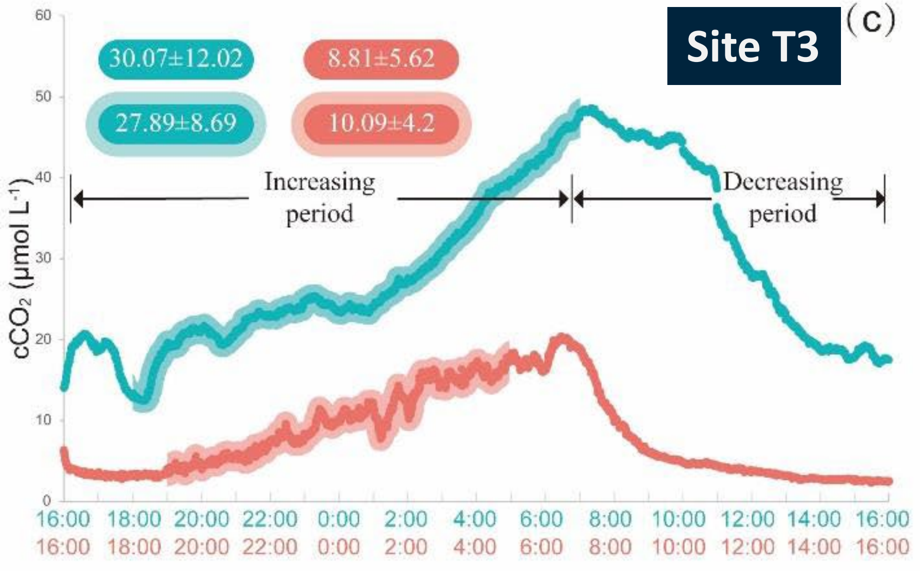


Diurnal variations of CO_2 fluxes

03 Results & discussion







Dry season (n = 129543)

Wet season (n = 129492)

Figure 1. Continuous measurements of dissolved CO_2 concentrations (μmol L^{-1}) over a 24 h period in Tangxun Lake during the dry and wet seasons

It began increasing around 18:00, continued to rise throughout the night, and started to decline around 6:00. The declining trend persisted during the daytime, with a steep decline typically starting around 10:00

Dry season

Day： 38.58 ± 23.8 μmol L^{-1}

Night： 42.01 ± 20.2 μmol L^{-1}

Wet season

Day： 20.70 ± 25.73 μmol L^{-1}

Night： 34.38 ± 31.19 μmol L^{-1}

Results & discussion

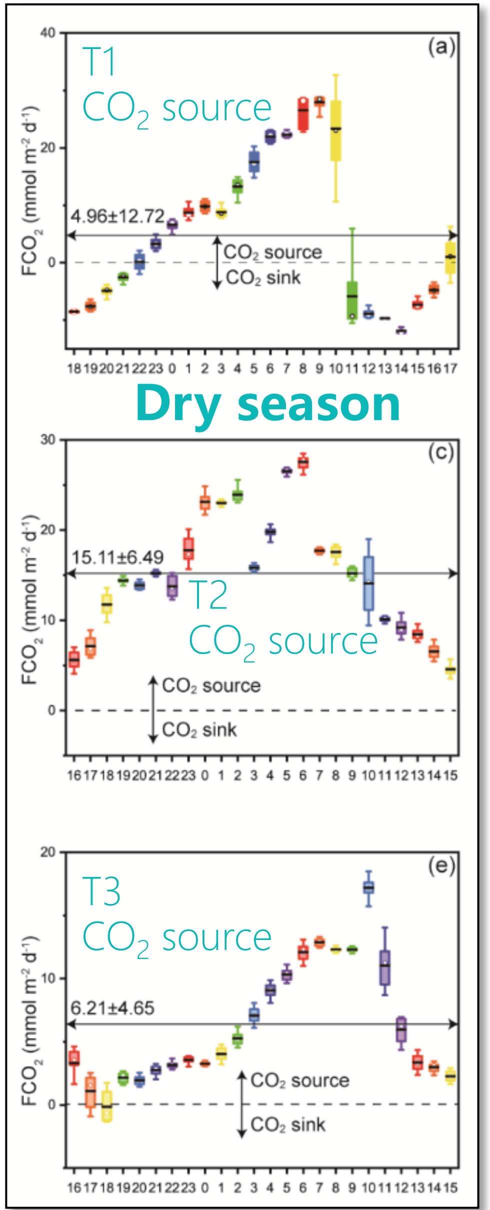


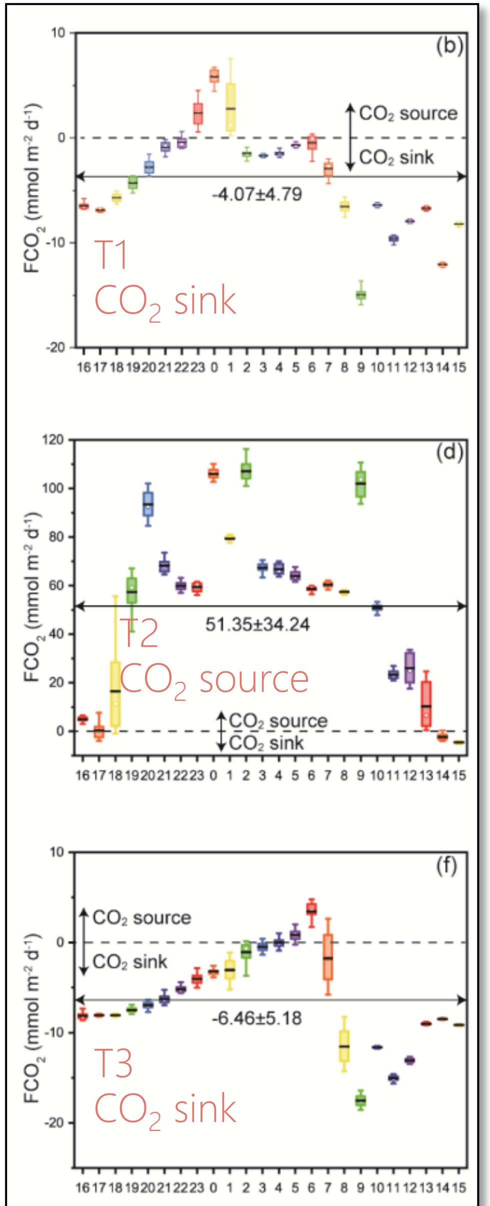
Figure 2. Hourly variations in FCO_2 (mmol m^{-2} d^{-1}) at Site T1 (a & b), T2 (c & d) and T3 (e & f) during the dry (a, c, and e) and wet (b, d and f) seasons.

Time	Hourly fluxes	Average flux	Absolute value
0:00	23.6	11.18	12.42
1:00	19.15	11.18	7.97
2:00	23.93	11.18	12.75
3:00	16.15	11.18	4.97
4:00	17.9	11.18	6.72
5:00	19.74	11.18	8.56
6:00	20.54	11.18	9.36
7:00	18.1	11.18	6.92
8:00	15.96	11.18	4.79
9:00	20.82	11.18	9.64
10:00	14.55	11.18	3.38
11:00	2.31	11.18	8.86
12:00	1.88	11.18	9.3
13:00	-0.57	11.18	11.75
14:00	-4.19	11.18	15.37
15:00	-3.73	11.18	14.91
16:00	-0.93	11.18	12.11
17:00	-0.9	11.18	12.08
18:00	0.96	11.18	10.22
19:00	9.1	11.18	2.08
20:00	15.77	11.18	4.59
21:00	12.76	11.18	1.58
22:00	11.87	11.18	0.69
23:00	13.72	11.18	2.55

The optimal sampling time for estimating whole-day CO_2 emission is around 10:00 in the morning

Supported by Potter and Xu (2023)

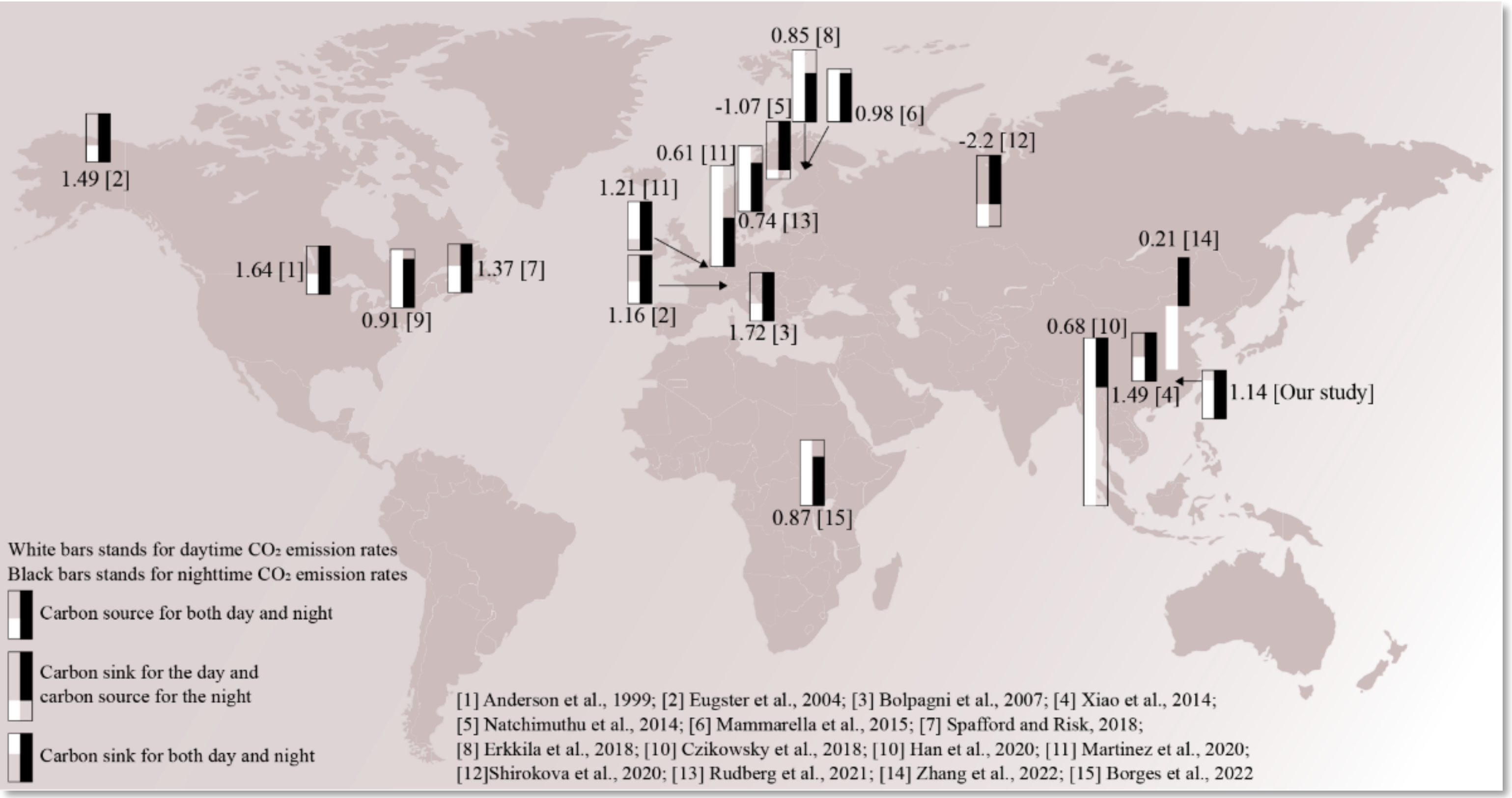
Wet season



03

Results & discussion

Figure 4. Diel factors of CO_2 from the global lakes



F= **Diel factor** *Day = (Day+Night)/2

R_{dn}=Day/Night

Diel factor =F/Day=(Day+Night)/2=(1+1/R_{dn})/2

Global lakes	**Tangxun lake**
R_{dn}: 0.79	R_{dn}: 0.42
the diel factor: 1.1	the diel factor: **1.7**
10% underestimation	**70%** underestimation

Accounting for night-time CO_2 emissions can increase regional estimates by 70%

03

Results & discussion

Table 1. Case studies on diel variability of CO_2 fluxes (mmol m^{-2} d^{-1}) from global lakes.

System name	Reference	Climate zone	Area (km^2)	Sampling date	Methods	Daytime	Nighttime	Ratio
Williams Lake	Anderson et al., 1999	Temperate	0.37	Apr. 1992, 1994	ECM	41.64	99.4	0.42
Toolik Lake	Eugster et al., 2003	Subarctic	1.5	27–31 Jul. 1995	ECM	4.25	12.5	0.34
Soppensee Lake	Eugster et al., 2003	Temperate	0.25	21 to 23 Sep. 1998	ECM	20	26.58	0.75
[illegible] Lake	Bolpagni et al., 2007	Temperate	0.05	29–[illegible] Jul. 2005	FCM	79.8	218	0.37
Unnamed pond	Xiao et al., 2014	Subtropical	0.0025	Jul. and Oct. 2013	FCM	22.56	44.88	0.5
Unnamed pond	Natchimuthu et al., 2014	Boreal	0.0012	17–18 Aug. 2010	FCM	−6.1	31.8	−0.19
[illegible]	Mammarella et al., 2015	Boreal	0.62	Jun. to Oct. 2010; 2[illegible]	[illegible]	[illegible]	[illegible]	1.08
Kuivajärvi Lake	Erkkila et al., 2018	Boreal	0.62	11–26 Sep. 2014	FCM	53.57	25.06	2.14
Kuivajärvi Lake	Erkkila et al., 2018	Boreal	0.62	11–26 Sep. 2014	BLM	96.21	65.32	1.47
Lochaber Lake	Spafford and Risk, 2018	Temperate	13.5	21 Apr. and 8 Nov. 2016	FCM	10.87	19.56	0.56
Pleasant Lake	Czikowsky et al., 2018	Temperate	6	16 Sep. and 11 Oct. 2010	ECM	30	27	1.11
Pleasant Lake	Czikowsky et al., 2018	Temperate	6	16 Sep. and 11 Oct. 2010	BLM	25.5	20	1.28
Ngoring Lake	Han et al., 2020	Subtropical	610.7	Jul.[illegible] 2011–2013	[illegible]	[illegible]	[illegible]	3.42
Lake Dagow	Martinez-Cruz et al., 2020	Temperate	0.24	12–13 Jul. 2015	FCM	9.68	4.67	2.07
Lake Stechlin	Martinez-Cruz et al., 2020	Temperate	4.25	10–11 Jul. 2015	FCM	−4.56	−5.86	0.78
Lake [illegible]	Shirokova et al., 2020	Boreal	0.016	26 [illegible]	[illegible]	[illegible]1.67	10	−0.17
Lake Venasjön	Rudberg et al., 2021	Temperate	0.69	14 Jun.–25 Sep. 2018	FCM	94.08	56.4	1.67
Lake Parsen	Rudberg et al., 2021	Temperate	0.13	28 Sep.- 25 Oct. 2018	FCM	30.24	19.44	1.56
Lake Ljusvattentjärn	Rudberg et al., 2021	Temperate	0.017	11 Jul. - 22 Aug. 2017	FCM	10.56	7.68	1.38
Ulansuhai Lake	Zhang et al., 2022	Temperate	293	Apr.- Oct. 2019	FCM	−3.87	2.99	−1.29
Lake Kivu	Borges et al., 2022	Tropical	2700	23–24 Mar. 2007	BLM	9.1	6.76	1.35
Tangxun Lake	This study	Subtropical	47	Nov., Dec. 2022, Mar. 2023	BLM	7.68	9.68	0.79

FCM: Floating chamber method; HEM: Headspace equilibrium method; BLM: Boundary layer method; Ratio: Day/night fluxes.

R_{dn}

Boreal lakes:1.25

Temperate lakes: 0.71

Subtropical lakes: 0.5

photochemical mineralization in boreal lakes

vs

photosynthesis in lower-latitude lakes

(Weyhenmeyer et al.,2015; Zhang et al., 2023)

R_{dn}

ECM & FCM: 0.67

BLM: >1

The boundary layer method may fail to predict this short-lived but significantly increased gas transfer efficiency at night due to heat loss

(Prodgrajsek et al.,2015; Holgerson and Raymond et al., 2016)

03 Results & discussion

Table 2. Description of the four components identified by PARAFAC analysis in Tangxun Lake

Components	Excitation max (nm)	Emission max (nm)	Openfluor comparison	Descriptions and sources of DOM	References
C1	300	393	57	Humic-like. Anthropogenic from wastewater and agriculture	(Coble, 2007; Chen et al., 2021)
C2	255	458	65	Humic-like. Terrestrial	(Coble, 2007; Chen et al., 2021)
C3	280	328	4	Protein-like, tryptophan-like. Autochthonous	(Coble, 2007; Lee et al., 2020)
C4	270	294	2	Protein-like, tyrosine-like. Autochthonous	(Coble, 2007; Chen et al., 2018)

More bioliable substrates (protein-like, usually from algae)

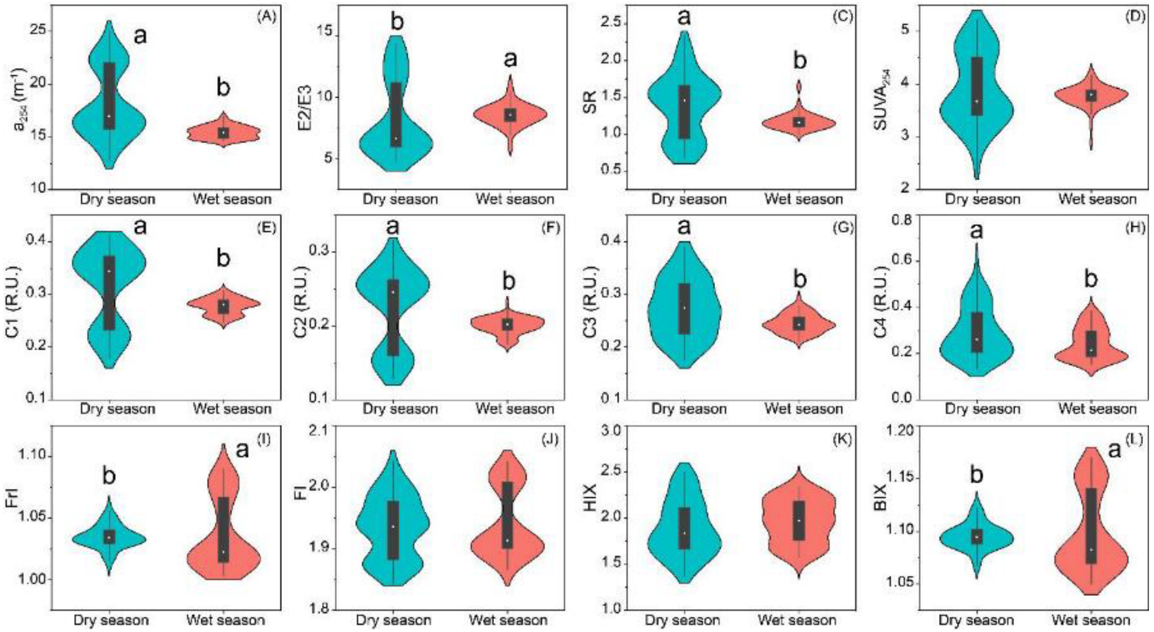


Figure 6. Distribution of CDOM concentration (A-D) in Tangxun Lake waters, its fluorescent components (E-H) and EEMs indices (I-L) during the dry and wet seasons

the relatively high optical indices in our study, i.e., FI > 1.9, SR > 1 and BIX > 1 suggest that biological metabolism dominates the DOM pool after receiving anthropogenic sources, making the lake protein-like dominant rather than humic-like.

Results & discussion

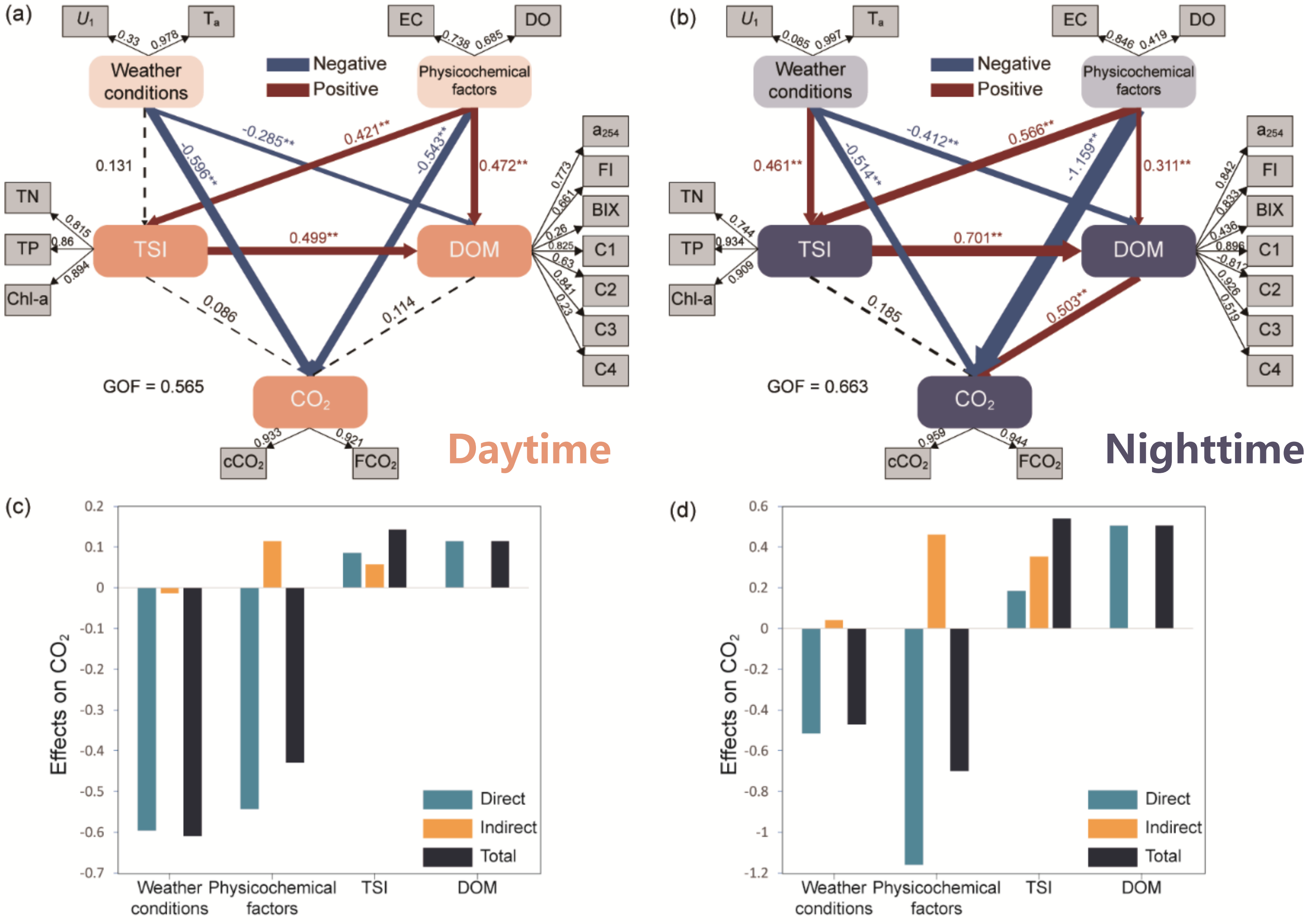
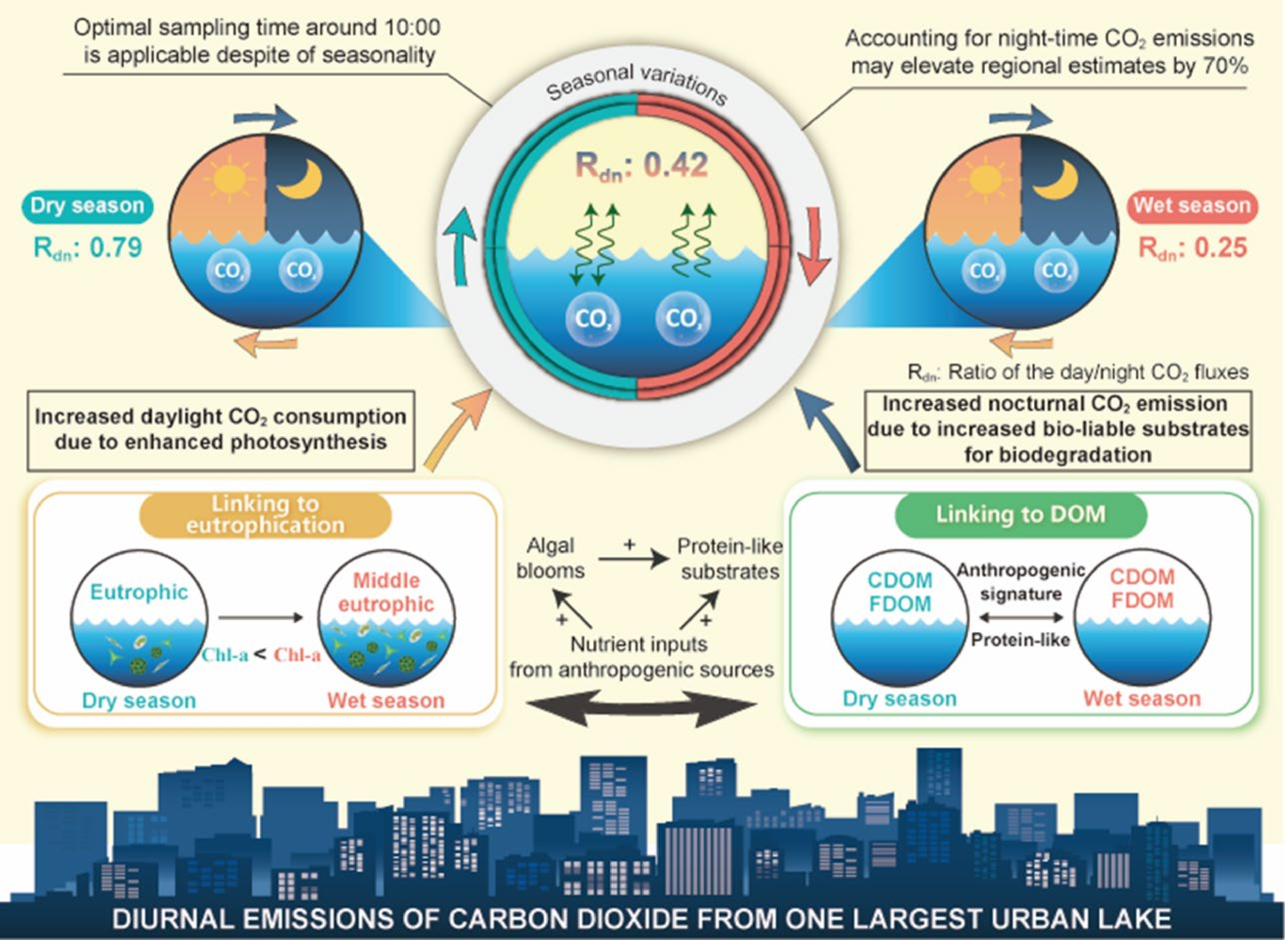


Figure 7. Partial least squares path modelling (PLS-PM) linking changes with weather conditions (U_1 and T_a), physiochemical factors (EC and DO), TSI (TN, TP, and Chl-a) and DOM (a_{254}, FI, BIX, C1, C2, C3, and C4) to changes in CO_2 (cCO_2 and FCO_2) in the (a) daytime and (b) nighttime.

During the daytime, effects of TSI and DOM on CO_2 were insignificant, but at night, DOM had a major influence on CO_2, with TSI indirectly affecting CO_2 by regulating DOM dynamics



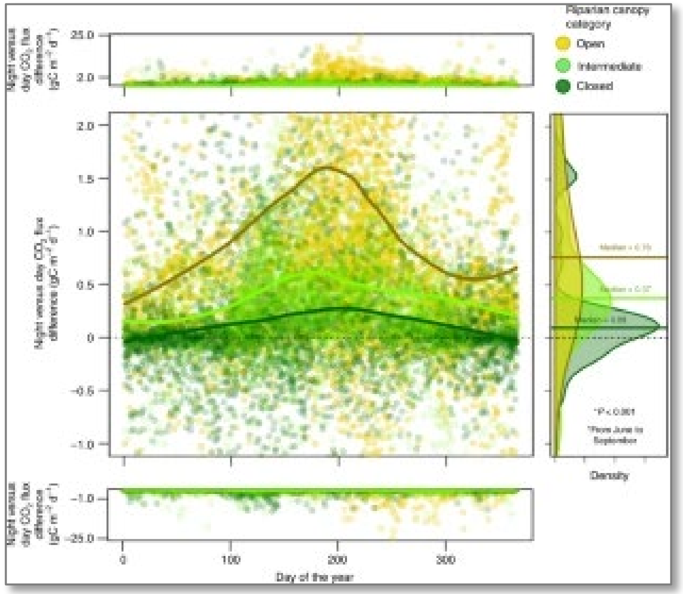
Graphic abstract

Diel patterns of CO_2 fluxes

Diel patterns of CO_2 fluxes driven by eutrophication and DOM

Results & discussion

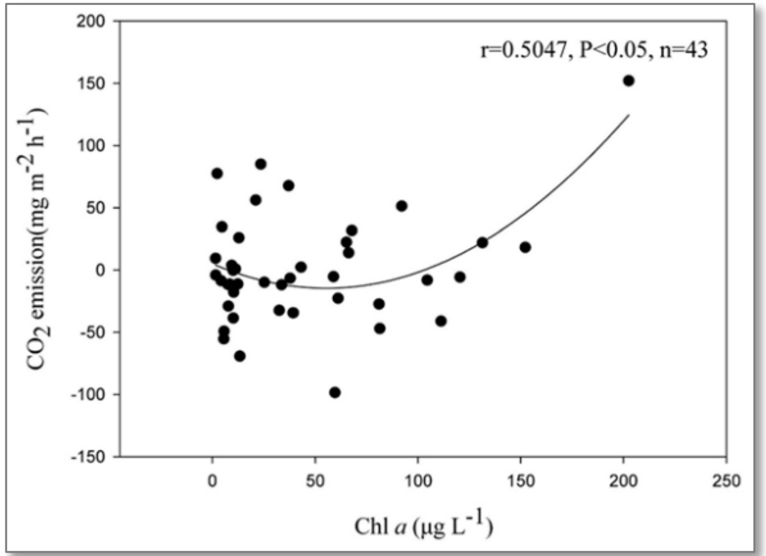
Evidence from other studies



Seasonal pattern of diel changes in CO_2 emission fluxes from streams

where diel CO_2 emissions are governed by the riparian canopy cover in headwaters (affecting light penetration and primary production) and DOC (affecting the water color)

Gómez-Gener et al. 2021. Global carbon dioxide efflux from rivers enhanced by high nocturnal emissions. Nature Geoscience 14(5), 289-294.



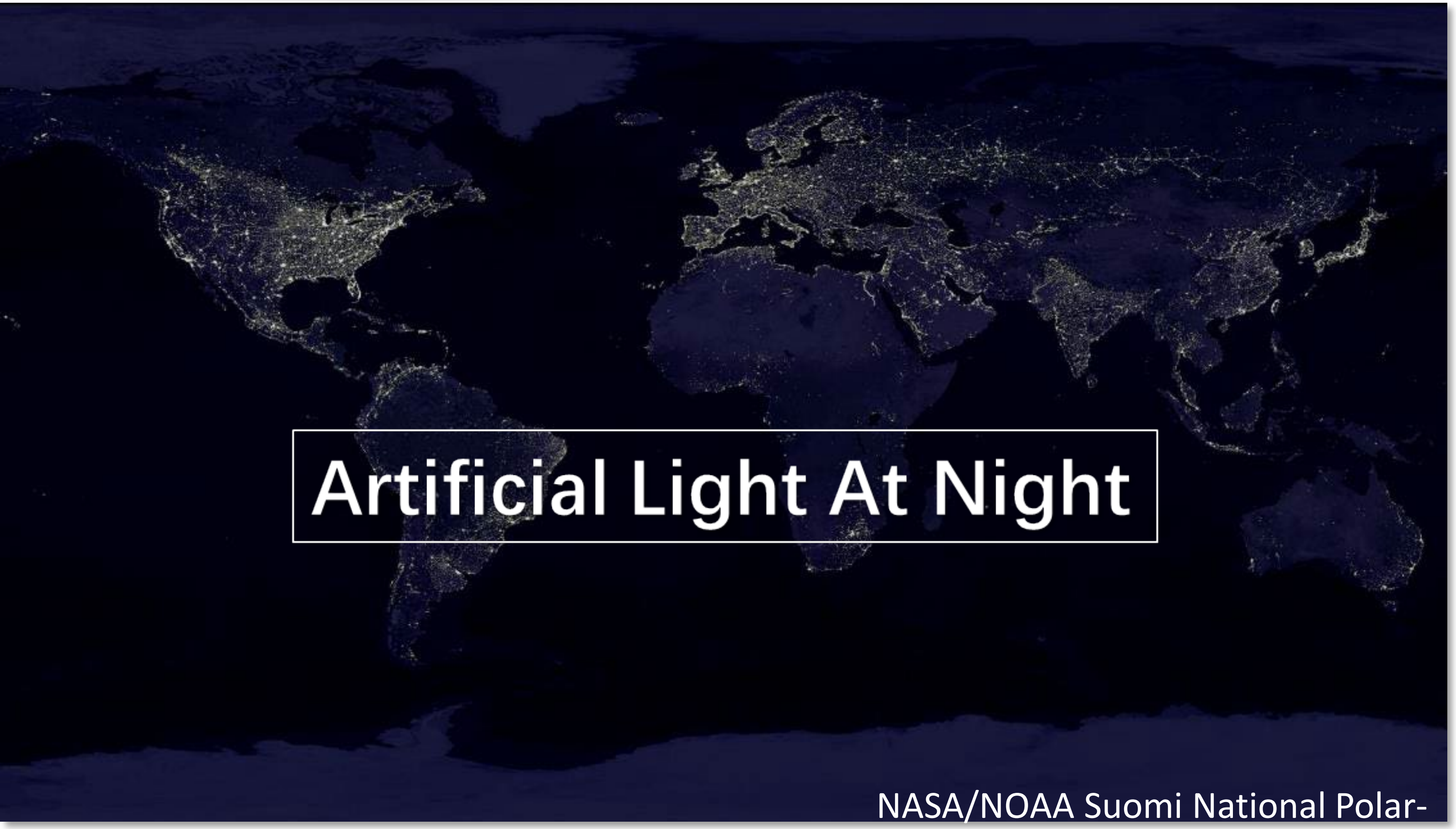
The v-shaped relationship between lake CO_2 emissions and Chl-a

when Chl-a was higher than 60 μg L^{-1}, CO_2 emissions increased with the increasing Chl-a

Zhang et al. 2024. Relationship between eutrophication and greenhouse gases emission in shallow freshwater lakes. Science of The Total Environment 925, 171610.

04

Prospects



Unique features in urban areas need special attention

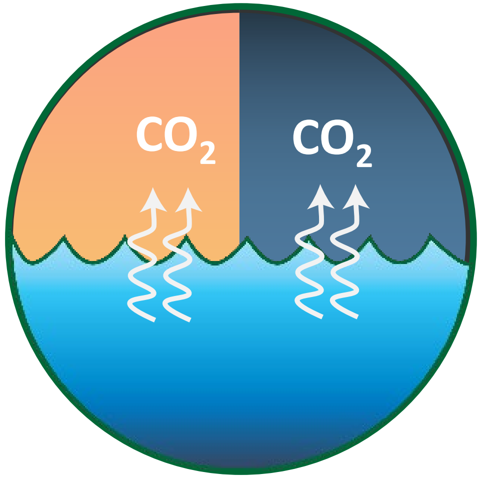
artificial lighting can greatly stimulate nocturnal photosynthesis, disrupt natural photosynthesis, or hamper the microbial diversity and their community respiration in aquatic systems, ultimately affect the diel variability of CO_2 fluxes in urban lakes

Fonvielle, J. *et al. Skyglow increases cyanobacteria abundance and organic matter cycling in lakes. Water Research* ***278, 123315 (2025).***

Grubisic, M. Waters under Artificial Lights: Does Light Pollution Matter for Aquatic Primary Producers? *Limnology and Oceanography Bulletin* ***27, 76-81 (2018).***

Hölker, F. *et al. Microbial diversity and community respiration in freshwater sediments influenced by artificial light at night. Philosophical Transactions of the Royal Society B: Biological Sciences* ***370, 20140130 (2015).***

Take-home messages



- The Tangxun Lake acts as the net CO_2 source
- 10:00 is suitable for sampling to represent diel CO_2 fluxes
- the underestimation by 70% without nighttime data
- Eutrophication enhances daytime CO_2 uptake
- DOM (higher protein-like DOM fraction) degradation dominates nighttime CO_2 emissions

Publications

1. Wang, Y., Ma, B., Shen, S., Zhang, Y., Ye, C., Jiang, H. and Li, S. 2023. Diel variability of carbon dioxide concentrations and emissions in a largest urban lake, Central China: Insights from continuous measurements. Science of The Total Environment 912, 168987.

2. Wang, Y., Ma, B., Xu, Y.J., Shen, S., Huang, X., Wang, Y., Ye, S., Tian, X., Zhang, Y., Wang, T. and Li, S. 2024. Eutrophication and dissolved organic matter exacerbate the diel discrepancy of CO_2 emissions in China's largest urban lake. Environmental Science & Technology 58(47), 20968-20978. (Cover article)

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