

Table S1. Detailed physicochemical characteristics for seven field campaigns.

Tributary & altitude	Time	T ² (°C)	pH	Salinity (ppt)	Flow rate (m s ⁻¹)	Discharge ³ (c.m.s)	TSM ² (mg L ⁻¹)	POC (mg m ⁻³)	δ ¹³ C POC (‰)	DIC (mM)	δ ¹³ C DIC (‰)	DOC (μM)	Chl a (mg m ⁻³)	TIN ⁴ (μM)	NH ₄ ⁺ (μM)	PO ₄ ²⁻ (μM)	SO ₄ ²⁻ (mM)	Cl ⁻ (mM)	Na ⁺ (mM)	Mg ²⁺ (mM)	K ⁺ (mM)	Ca ²⁺ (mM)
MLL01 699 m	2020. Mar ¹	18.0	8.4	NA	0.3	NA	29.29	134	-27.6	2.25	-3.7	22.10	NA	3.8	0.9	0.09	2.98	0.01	0.17	0.67	0.04	3.37
	2020. May ¹	21.6	8.4	0.37	NA	NA	8.79	189	-27.5	1.58	-1.2	18.75	0.499	2.7	0.3	0.02	3.17	0.01	0.17	0.66	0.04	3.36
	2020. Jul	25.9	8.8	NA	NA	NA	76.95	1111	-24.5	1.94	0.6	48.53	0.097	8.6	2.2	0.03	3.59	0.01	0.17	0.63	0.05	3.44
	2020. Aug-1	23.5	8.3	0.37	1.2	NA	236.16	3753	-24.1	1.87	-1.2	25.65	0.002	13.5	2.1	0.11	NA	NA	0.15	0.65	0.06	3.46
	2020. Aug-2	24.6	8.4	0.35	1	NA	NA	NA	NA	NA	-4.5	18.10	NA	7.8	NA	0.01	3.26	0.01	0.15	0.60	0.05	3.09
	2020. Oct	19.5	8	0.36	1.3	NA	NA	NA	NA	1.96	-1.9	29.30	0.103	10.1	9.6	0.02	3.21	0.01	0.14	0.62	0.04	3.19
	2021. Jan ¹	12.3	7.4	NA	NA	NA	6.98	133	-27.1	1.91	-3.3	21.03	0.390	13.9	0.5	0.04	2.92	0.01	0.17	0.65	0.04	3.51
CWL01 375 m	2020. Mar ¹	19.5	8.3	0.33	1.3	NA	32.92	252	-26.1	2.59	-3.4	20.28	NA	4.7	2.5	0.06	1.65	0.06	0.77	0.46	0.04	2.16
	2020. May ¹	27.3	8.3	0.27	1.8	NA	0.92	355	-26.3	1.88	0.1	26.67	2.052	1.7	2.0	0.05	1.57	0.05	0.75	0.43	0.04	2.05
	2020. Jul	NA	NA	NA	NA	NA	NA	2454	-21.5	2.02	-4.3	55.11	0.841	5.0	3.3	0.03	1.57	0.04	0.47	0.32	0.03	1.81
	2020. Aug-1	27.4	7.9	0.26	0.9	NA	50.05	500	-25.3	1.26	-2.0	22.79	0.146	6.5	4.3	0.06	NA	NA	0.51	0.36	0.05	2.05
	2020. Aug-2	27.5	7.9	0.27	1.8	NA	4.17	213	-27.2	NA	-3.2	21.23	0.374	5.8	NA	0.12	1.51	0.04	0.49	0.33	0.04	1.89
	2020. Oct	23.3	7.8	0.26	2	NA	NA	NA	NA	2.14	-1.5	25.78	0.958	6.8	7.0	0.04	1.52	0.04	0.52	0.38	0.04	2.03
	2021. Jan ¹	13.8	8.9	NA	2.2	NA	3.18	99	-28.0	2.06	-2.9	24.93	0.616	9.3	3.1	0.01	1.61	0.04	0.46	0.34	0.03	2.09
DL 382 m	2020. Mar ¹	21.2	8.3	0.31	1.8	4.29	31.35	194	-26.3	2.80	-2.1	17.71	NA	19.5	1.1	0.12	1.10	0.66	2.04	0.23	0.15	1.69
	2020. May ¹	29.5	8.4	0.27	1.7	4.30	1.95	198	-26.1	1.99	-1.3	24.13	0.809	14.5	0.3	0.12	1.26	0.71	1.93	0.22	0.14	1.44
	2020. Jul	25.5	8.4	0.22	NA	3.22	2.17	273	-26.0	2.13	-2.6	65.30	1.743	12.1	3.0	0.16	1.12	0.46	1.23	0.18	0.10	1.42
	2020. Aug-1	27.6	8.1	0.23	1.4	5.68	6.70	308	-25.8	2.13	-1.3	26.60	0.700	21.7	3.6	0.11	NA	NA	1.05	0.20	0.09	1.51
	2020. Aug-2	29.1	8.2	0.25	2	5.46	NA	NA	NA	NA	-2.8	25.35	NA	14.0	2.8	0.15	1.09	0.46	1.19	0.19	0.09	1.41
	2020. Oct	24.1	7.1	0.52	2.1	4.87	NA	NA	NA	2.21	-1.1	24.32	0.967	16.1	16.1	0.12	1.04	0.52	1.33	0.20	0.10	1.40
	2021. Jan ¹	14.9	8.6	NA	1.8	NA	1.26	86	-26.9	2.50	-2.4	18.95	0.475	20.0	2.9	0.23	1.03	0.45	1.18	0.20	0.09	1.53
LY04 238 m	2020. Mar ¹	23.4	8.2	0.3	1	1.2	32.18	186	-28.0	1.97	-3.0	18.92	NA	5.9	1.6	0.07	1.35	0.06	0.67	0.82	0.08	2.14
	2020. May ¹	25.6	8.3	0.28	1.2	2.07	3.33	214	-27.4	2.24	-5.0	20.39	0.305	7.4	1.9	0.07	1.46	0.06	0.68	0.84	0.08	1.80
	2020. Jul	28.2	8.2	0.27	2.5	5.01	377.09	6280	-20.2	2.50	-4.0	17.66	0.001	3.1	4.8	0.07	1.96	0.05	0.48	0.94	0.08	1.74
	2020. Aug-1	29.6	8	0.33	2	5.03	619.95	12443	-20.6	1.86	-1.2	23.93	0.003	13.1	5.9	0.08	NA	NA	0.48	0.90	0.09	1.83
	2020. Aug-2	27.6	8.2	0.28	2.4	5.01	NA	NA	NA	NA	-4.0	27.37	NA	11.6	NA	0.12	1.62	0.05	0.47	0.83	0.08	1.71
	2020. Oct	24.1	7.9	0.26	1.4	3.33	NA	NA	NA	2.54	-2.4	22.93	0.150	10.6	10.8	0.05	1.51	0.05	0.47	0.80	0.06	1.73
	2021. Jan ¹	14.3	8.8	NA	2.2	5.45	8.32	121	-27.2	2.81	-3.6	12.95	0.432	11.4	3.1	0.06	1.44	0.05	0.50	0.80	0.06	1.85
BNE 7 m	2020. Mar ¹	25.3	8.2	0.32	NA	5.08	31.05	277	-26.1	2.35	-5.4	42.58	NA	40.9	1.9	0.31	1.39	0.28	0.74	0.66	0.08	2.19
	2020. May ¹	25.6	8.5	0.3	1	3.06	1.90	296	-27.0	1.87	-5.8	40.18	1.427	29.5	1.5	0.26	1.42	0.27	0.73	0.67	0.07	2.09
	2020. Jul	28.8	7.6	0.3	1	35.7	13.07	360	-26.0	2.79	-6.3	76.94	0.293	14.0	3.4	0.08	2.06	0.28	0.74	0.74	0.09	2.20
	2020. Aug-1	30.4	7.9	0.29	1.1	41.35	198.18	4204	-24.0	2.06	-1.3	44.39	0.095	48.3	4.1	0.29	NA	NA	0.77	0.66	0.09	2.03
	2020. Aug-2	28.6	7.8	0.59	1.4	75.75	NA	NA	NA	NA	-6.8	26.43	NA	33.2	5.3	0.18	1.77	0.24	0.73	0.69	0.09	2.11
	2020. Oct	24.3	7.9	0.3	1.2	67.51	NA	NA	NA	2.88	-5.1	32.75	1.965	28.5	16.5	0.19	1.67	0.24	0.72	0.69	0.08	2.10
	2021. Jan ¹	13.7	8.5	NA	1.1	13.41	2.80	161	-26.0	1.86	-5.7	24.09	2.039	19.9	1.7	0.17	1.57	0.22	0.72	0.65	0.07	2.20

* Parameters shown in bold are significantly different between the wet and dry seasons (linear mixed-effects model with site as random effect, $p < 0.05$)

¹ Dry seasons.

² T: water temperature; TSM: total suspended matter.

³ Data retrieved from Water Resource Agency, Taiwan, Hydrological Yearbook, stations 2200H011 (Taitung Bridge), 2200H021 (Dalun), and 2200H029 (Luming Bridge). No WRA gauging station is deployed in the immediate sub-basin for site MLL01 and CWL01.

⁴ TIN includes nitrate and nitrite (nitrite was below detection limit).

Table S2. Linear mixed-effects model results for seasonal differences (wet vs. dry) in environmental parameters.

Parameter	Transformation	N	Wet-Dry*	SE	<i>t</i>	<i>df</i>	<i>p</i>
T (°C)	none	34	5.89	1.45	4.06	28	<0.001
pH	none	34	-0.35	0.12	-2.97	28	0.003
TSM (mg L ⁻¹)	log ₁₀	25	1.05	0.33	3.16	19	0.002
POC (mg m ⁻³)	log ₁₀	26	0.85	0.16	5.25	20	<0.001
δ ¹³ C-POC (‰)	none	26	2.8	0.64	4.36	20	<0.001
DOC (µM)	none	35	9.45	4.21	2.24	29	0.025
Chl-a (mg m ⁻³)	log ₁₀	26	-0.73	0.27	-2.72	20	0.007
NH ₄ ⁺ (µM)	log ₁₀	32	0.57	0.1	5.75	26	<0.001
Sulphate (mM)	none	30	0.17	0.06	2.85	24	0.004
Sodium (mM)	none	35	-0.17	0.06	-2.81	29	0.005
Calcium (mM)	none	35	-0.12	0.036	-3.48	29	<0.001
Non-significant (<i>p</i> ≥ 0.05)							
DIC (mM)	none	30	-0.02	0.13	-0.19	24	0.852
δ ¹³ C-DIC (‰)	none	35	0.4	0.5	0.81	29	0.421
NO ₃ ⁻ +NO ₂ ⁻ (µM)	none	35	0.85	2.12	0.4	29	0.69
PO ₄ ²⁻ (µM)	none	35	-0.01	0.02	-0.67	29	0.504
Chloride (mM)	none	30	-0.03	0.02	-1.58	24	0.113
Magnesium (mM)	none	35	-0.008	0.013	-0.59	29	0.557
Potassium (mM)	none	35	<0.001	0.005	0	29	1

*Wet-Dry: estimates represent the wet-minus-dry difference; positive values indicate higher concentrations in the wet season; for log transformed variables (indicated), the estimate is on the log₁₀ scale.

Table S3. Metabolic rates of autotrophy and heterotrophy measured in this study.

Site	Time	Autotrophy		Substrate	Heterotrophy		Ratio
		Light condition	Uptake Rate (mg-C m ⁻³ h ⁻¹)		Uptake Rate (mg-C m ⁻³ h ⁻¹)	Catabolic rate (mg-C m ⁻³ h ⁻¹)	
MLL01	Mar 2020	Light	0.12 ± 0.03				
		Dark	bdl				
	May 2020	Light	0.076 ± 0.01				
		Dark	0.001				
	Aug 2020	Light	0.60 ± 0.02	Gly	0.061 ± 0.01	6.50 ± 0.62	105.54
		Dark	0.69	Leu	0.004 ± 0.00	5.58 ± 1.66	1295.70
	Jan 2021	Light	0.03 ± 0.017	Gly	bdl	27.17 ± 9.10	inf
		Dark	bdl	Leu	bdl	22.75 ± 0.75	inf
CWL01	Mar 2020	Light	0.47 ± 0.04				
		Dark	0.05				
	May 2020	Light	0.18 ± 0.02				
		Dark	0.01				
	Aug 2020	Light	0.38 ± 0.08	Gly	0.02 ± 0.001	154.48 ± 25.38	7701.82
		Dark	0.02	Leu	0.005 ± 0.0006	62.00 ± 20.33	12431.40
	Jan 2021	Light	0.05 ± 0.01	Gly	0.001 ± 0.0006	25.79 ± 3.27	24883.41
		Dark	bdl	Leu	0.01 ± 0.004	20.49 ± 5.44	1688.73
DL	Mar 2020	Light	0.46 ± 0.09				
		Dark	bdl				
	May 2020	Light	0.29 ± 0.02				
		Dark	0.02				
	Aug 2020	Light	0.25 ± 0.01	Gly	0.048 ± 0.003	63.86 ± 30.78	1328.83
		Dark	bdl	Leu	0.009 ± 0.003	11.98 ± 1.01	1350.84
	Jan 2021	Light	bdl	Gly	bdl	4.57 ± 4.36	inf
		Dark	bdl	Leu	bdl	11.13 ± 10.44	inf
LY04	Mar 2020	Light	0.11 ± 0.01				
		Dark	bdl				
	May 2020	Light	0.13 ± 0.02				
		Dark	0.01				
	Aug 2020	Light	1.10 ± 0.05	Gly	0.08 ± 0.03	63.61 ± 43.70	737.09
		Dark	1.60	Leu	0.12 ± 0.10	16.43 ± 3.79	134.06
	Jan 2021	Light	0.09 ± 0.01	Gly	0.001 ± 0.001	7.39 ± 2.77	5136.36
		Dark	0.00	Leu	0.001 ± 0.001	12.84 ± 3.77	9137.88
BNE	Mar 2020	Light	1.04 ± 0.03				
		Dark	0.03				
	May 2020	Light	0.89 ± 0.19				
		Dark	bdl				
	Aug 2020	Light	1.98 ± 0.28	Gly	0.49 ± 0.079	67.31 ± 18.12	137.06
		Dark	0.19	Leu	0.07 ± 0.01	57.97 ± 27.61	777.27
	Jan 2021	Light	0.58 ± 0.03	Gly	0.01 ± 0.002	62.97 ± 25.66	4506.05
		Dark	0.003	Leu	0.004 ± 0.002	37.62 ± 10.13	9362.04

Table S4. Read numbers and alpha diversities for environmental samples.

Sample	Reads	Observed ASVs	Chao1	SE of Chao1 ¹	Shannon index
BNE_Mar_2020	12236	209	226.27	10.23	4.43
BNE_May_2020	13956	291	340.04	18.18	4.43
BNE_Jul_2020	29426	708	801.15	19.24	5.25
BNE_Aug_2020	14994	338	345.50	4.27	4.88
BNE_Jan_2021	47690	1072	1370.43	41.73	5.99
CWL01_Mar_2020	49887	1441	2037.99	62.61	6.10
CWL01_May_2020	37811	1299	1583.22	37.02	6.63
CWL01_Aug_2020	40062	1690	2309.96	61.81	6.96
CWL01_Jan_2021	18358	668	716.01	12.89	5.93
DL_Mar_2020	17139	716	783.08	15.57	5.77
DL_May_2020	22752	816	936.63	22.81	5.94
DL_Jul_2020	19271	719	774.03	14.03	5.99
DL_Aug_2020	18152	796	860.01	14.90	6.02
DL_Jan_2021	30383	747	859.99	22.13	5.15
LY04_Mar_2020	19578	948	1057.56	21.26	6.43
LY04_May_2020	28621	1265	1519.01	34.13	6.55
LY04_Jul_2020	5220	306	306.00	0.00	4.87
LY04_Aug_2020	7169	419	421.63	2.18	5.54
LY04_Jan_2021	40904	880	990.19	20.61	5.91
MLL01_Mar_2020	10512	715	742.60	8.65	6.20
MLL01_May_2020	14418	922	983.94	13.68	6.38
MLL01_Jul_2020	9353	369	380.94	6.03	5.23
MLL01_Aug_2020	13001	728	777.63	12.61	5.87
MLL01_Jan_2021	11894	476	483.93	4.41	5.70

* Reads of CWL01_Jul_2020 was excluded from the analysis due to limited number.

¹ Standard error of Chao1 index.

Table S5. Pearson correlation for the physicochemical characteristics.

	T	pH	TSM	POC	$\delta^{13}\text{C}$ -POC	DOC	NH_4^+	Chl a	DIC	$\delta^{13}\text{C}$ -DIC	TIN ¹	PO_4^{2-}	SO_4^{2-}	Cl^-	Na^+	Mg^{2+}	K^+	Ca^{2+}
T	1																	
pH	-0.29	1																
TSM	0.37	-0.19	1															
POC	0.39	-0.21	0.99**	1														
$\delta^{13}\text{C}$ -POC	0.49*	-0.20	0.89**	0.83**	1													
DOC	0.34*	-0.09	-0.08	-0.02	0.20	1												
NH_4^+	0.13	-0.56**	0.66**	0.67**	0.67**	0.00	1											
Chl a	-0.12	0.10	-0.46	-0.41	-0.31	0.16	0.11	1										
DIC	-0.12	0.00	-0.09	-0.11	-0.06	0.06	0.29	0.05	1									
$\delta^{13}\text{C}$ -DIC	0.09	0.06	0.22	0.21	0.15	-0.18	0.02	-0.24	-0.39*	1								
$\text{NO}_3^- + \text{NO}_2^-$	0.18	-0.15	0.03	0.05	0.02	0.26	0.14	0.14	0.18	-0.28	1							
PO_4^{2-}	0.22	-0.02	-0.03	-0.02	-0.04	0.23	0.01	0.31	0.17	-0.31	0.86**	1						
SO_4^{2-}	-0.15	0.05	0.15	0.10	0.05	0.01	-0.12	-0.42	-0.36	0.14	-0.31	-0.51**	1					
Cl^-	0.22	-0.07	-0.18	-0.20	-0.05	0.15	0.04	0.33	0.24	0.04	0.49**	0.57**	-0.57**	1				
Na^+	0.20	-0.03	-0.22	-0.20	-0.12	0.04	-0.01	0.39*	0.32	0.08	0.30	0.41*	-0.71**	0.94**	1			
Mg^{2+}	0.03	0.00	0.48*	0.43*	0.22	-0.07	0.02	-0.32	0.09	-0.36*	0.03	-0.07	0.39*	-0.60**	-0.59**	1		
K^+	0.37*	-0.09	0.13	0.11	0.09	0.08	0.03	0.09	0.33	-0.03	0.45**	0.49**	-0.52**	0.88*	0.84**	-0.18	1	
Ca^{2+}	-0.33	0.09	-0.02	-0.07	-0.14	-0.04	-0.22	-0.27	-0.33	0.08	-0.18	-0.33*	0.94**	-0.58**	-0.71**	0.36*	-0.55**	1

* Results with significant difference are indicated by asterisks (*: $p < 0.05$, **: $p < 0.01$).

¹ TIN includes nitrate and nitrite (nitrite is below detection limit).

Table S6. Estimates of catchment scaled CO₂ emission based on the extrapolation of site incubation data.

Site & AVE depth (m)	Time	Flux derived from incubation					CO ₂ consumption flux ² (mol m ⁻² yr ⁻¹)	Estimated flux and yield		River surface area ³ (m ²)	Net emission ⁴ (mol yr ⁻¹)	Total yield (mol yr ⁻¹)	
		Uptake rate ¹ (mol m ⁻² day ⁻¹)	CO ₂ production ¹ (mol m ⁻² day ⁻¹)			CO ₂ production flux ² (mol m ⁻² yr ⁻¹)							
	Substrate	DIC	Gly	Leu	Gly	Leu		DIC	Gly	Leu			
MLL01 0.5 m	Mar 2020	6.2E-05						0.13	6.14	5.16	1.22E+05	6.15E+05	7.89E+07 (4.56E+07 - 1.14E+08)
	May 2020	3.9E-05											
	Aug 2020	6.5E-04	6.2E-05	4.3E-06	6.50E-03	5.59E-03							
	Jan 2021	1.8E-05	bdl	bdl	2.72E-02	2.28E-02							
CWL01 0.7 m	Mar 2020	3.7E-04						0.09	46.15	21.11	2.82E+06	5.92E+07	
	May 2020	1.3E-04											
	Aug 2020	2.8E-04	2.0E-05	5.0E-06	2.16E-01	8.68E-02							
	Jan 2021	4.0E-05	1.0E-06	1.2E-05	3.61E-02	2.87E-02							
DL 0.5 m	Mar 2020	2.3E-04						0.05	12.52	4.22	1.41E+06	5.88E+06	
	May 2020	1.6E-04											
	Aug 2020	1.3E-04	4.8E-05	8.9E-06	6.39E-02	1.20E-02							
	Jan 2021	0.0E+00	bdl	bdl	4.58E-03	1.11E-02							
LY04 0.5 m	Mar 2020	6.0E-05						0.26	12.99	5.35	2.36E+06	1.20E+07	
	May 2020	7.2E-05											
	Aug 2020	1.4E-03	8.6E-05	1.2E-04	6.36E-02	1.64E-02							
	Jan 2021	5.0E-05	1.4E-06	1.4E-06	7.40E-03	1.28E-02							
BNE 0.7 m	Mar 2020	7.5E-04						0.39	33.29	24.44	5.17E+04	1.24E+06	
	May 2020	6.3E-04											
	Aug 2020	1.5E-03	4.9E-04	7.5E-05	9.42E-02	8.12E-02							
	Jan 2021	4.1E-04	1.4E-05	4.0E-06	8.82E-02	5.27E-02							

¹ CO₂ uptake rate per day = sum of DIC rate (light and dark) per hour (Table S2) x 12 hours x depth (m), or amino acid uptake rate per hour (Table S2) x 24 hours x depth. CO₂ production per day = amino acid catabolic rate per hour (Table S2) x 24 hours x depth.

² CO₂ consumption flux per year = {[average of DIC rate for dry season (Mar 2020 + May 2020 + Jan 2021) x 182 days + [DIC rate for wet season (Aug 2020)] x 183 days}.

CO₂ production flux per year = CO₂ production rate per day of Jan 2021 x 182 days + CO₂ production rate per day of Aug 2020 x 183 days.

³ River surface area was assumed to be 0.47% of the catchment area (following Raymond et al., 2013).

⁴ Net emission = [CO₂ production flux per year (Leu) - CO₂ consumption flux per year] x river surface area.

⁵ Total yield was sum of net emission from individual tributary. The range for total yield reflects propagated uncertainty from two sources: replicate-based variability in the leucine catabolic rate (Table S3) and a ± 50% uncertainty assigned to river surface area (Section 2.5), combined via root-sum-square propagation at each site ($\sqrt{[(\text{STDEV}/\text{mean})^2 + 0.5^2]}$) and then across sites ($\sqrt{[\sum(\text{uncertainty}_i \times \text{Net emission}_i)^2]} / \text{Total yield}$).

Table S7. River hydraulic parameters and estimates of CO₂ exchange fluxes at the air-river interface.

Site	Time	Velocity (m s ⁻¹)	Slope (m m ⁻¹)	ε_D^1 (m ² s ⁻³)	k_{600} (m d ⁻¹)	T (°C)	ScCO ₂ ²	kCO ₂ (m d ⁻¹)	Measured pCO ₂ in river (atm)	Δ CO ₂ ³ (atm)	Flux (mol m ⁻² d ⁻¹)	Tributary rate ⁴ (mole yr ⁻¹)	Average rate ⁵ (mole yr ⁻¹)	Total flux ⁶ (mole yr ⁻¹)
CWL01	Jan 2020	1.60	0.013	0.013	4.8	20.8	576.35	4.94	1.09E-02	3.57E-04	1.76	1.81E+09	8.60E+08	2.08E+09 (9.57E+08 – 3.20E+09)
MLL01		1.30	0.097	0.076	29.8	12.8	878.33	24.61	1.08E-02	3.52E-04	8.67	3.87E+08	3.34E+08	
DL		1.10	0.0066	0.004	3.3	27.1	423.64	3.90	4.30E-03	1.32E-04	0.52	2.66E+08	2.22E+08	
LY04		2.20	0.010	0.014	5.0	21.1	568.00	5.10	5.00E-03	1.56E-04	0.80	6.87E+08	6.55E+08	
BNE		0.40	0.0029	0.0004	1.4	18.2	656.07	1.38	5.16E-03	1.62E-04	0.22	4.21E+06	8.00E+06	
CWL01	May 2020	1.80	0.013	0.015	5.1	27.3	419.25	6.07	1.95E-03	5.23E-05	0.32	3.26E+08		
MLL01		0.70	0.097	0.035	11.7	21.6	554.41	12.16	2.24E-03	6.21E-05	0.76	3.37E+07		
DL		1.30	0.0066	0.005	3.5	29.5	370.78	4.47	2.16E-03	5.96E-05	0.27	1.37E+08		
LY04		1.20	0.010	0.007	3.9	25.6	457.01	4.46	3.00E-03	8.79E-05	0.39	3.38E+08		
BNE		0.90	0.0029	0.001	2.3	25.6	457.01	2.58	2.69E-03	7.75E-05	0.20	3.77E+06		
CWL01	Jul 2020	1.90	0.013	0.016	5.2	26.7	432.47	6.10	8.37E-03	2.71E-04	1.65	1.70E+09		
MLL01		1.90	0.097	0.118	49.9	25.9	450.26	57.54	9.25E-03	3.01E-04	17.30	7.72E+08		
DL		1.90	0.0066	0.008	4.1	25.5	459.27	4.68	4.97E-03	1.55E-04	0.73	3.74E+08		
LY04		2.50	0.010	0.016	5.2	28.2	399.49	6.39	7.59E-03	2.44E-04	1.56	1.35E+09		
BNE		1.10	0.0029	0.002	2.5	28.8	386.29	3.06	9.02E-03	2.93E-04	0.90	1.69E+07		
CWL01	Oct 2020	2.00	0.013	0.017	5.3	23.3	510.90	5.73	1.69E-03	4.37E-05	0.25	2.57E+08		
MLL01		1.30	0.097	0.076	29.8	19.5	614.46	29.43	7.15E-03	2.29E-04	6.75	3.01E+08		
DL		2.20	0.0066	0.009	4.3	24.1	491.63	4.79	2.28E-03	6.36E-05	0.30	1.57E+08		
LY04		1.30	0.010	0.008	4.0	24.1	491.63	4.45	4.66E-03	1.44E-04	0.64	5.54E+08		
BNE		1.20	0.0029	0.002	2.6	24.3	486.91	2.83	4.19E-03	1.29E-04	0.36	6.87E+06		
CWL01	Jan 2021	1.90	0.013	0.016	5.2	18.5	646.13	4.99	1.60E-03	4.04E-05	0.20	2.07E+08		
MLL01		1.80	0.097	0.111	46.4	14.5	798.47	40.22	3.31E-03	9.87E-05	3.97	1.77E+08		
DL		1.40	0.0066	0.006	3.6	22.3	536.02	3.84	3.06E-03	9.02E-05	0.35	1.78E+08		
LY04		2.10	0.010	0.013	4.9	18.3	652.73	4.67	2.96E-03	8.67E-05	0.41	3.50E+08		
BNE		1.50	0.0029	0.003	2.8	21.4	559.79	2.90	4.83E-03	1.50E-04	0.44	8.21E+06		

¹ ε_D , energy dissipation rate. $\varepsilon_D = gSv \text{ m}^2 \text{ s}^{-3}$, g, acceleration due to gravity; S, slope; v, velocity.

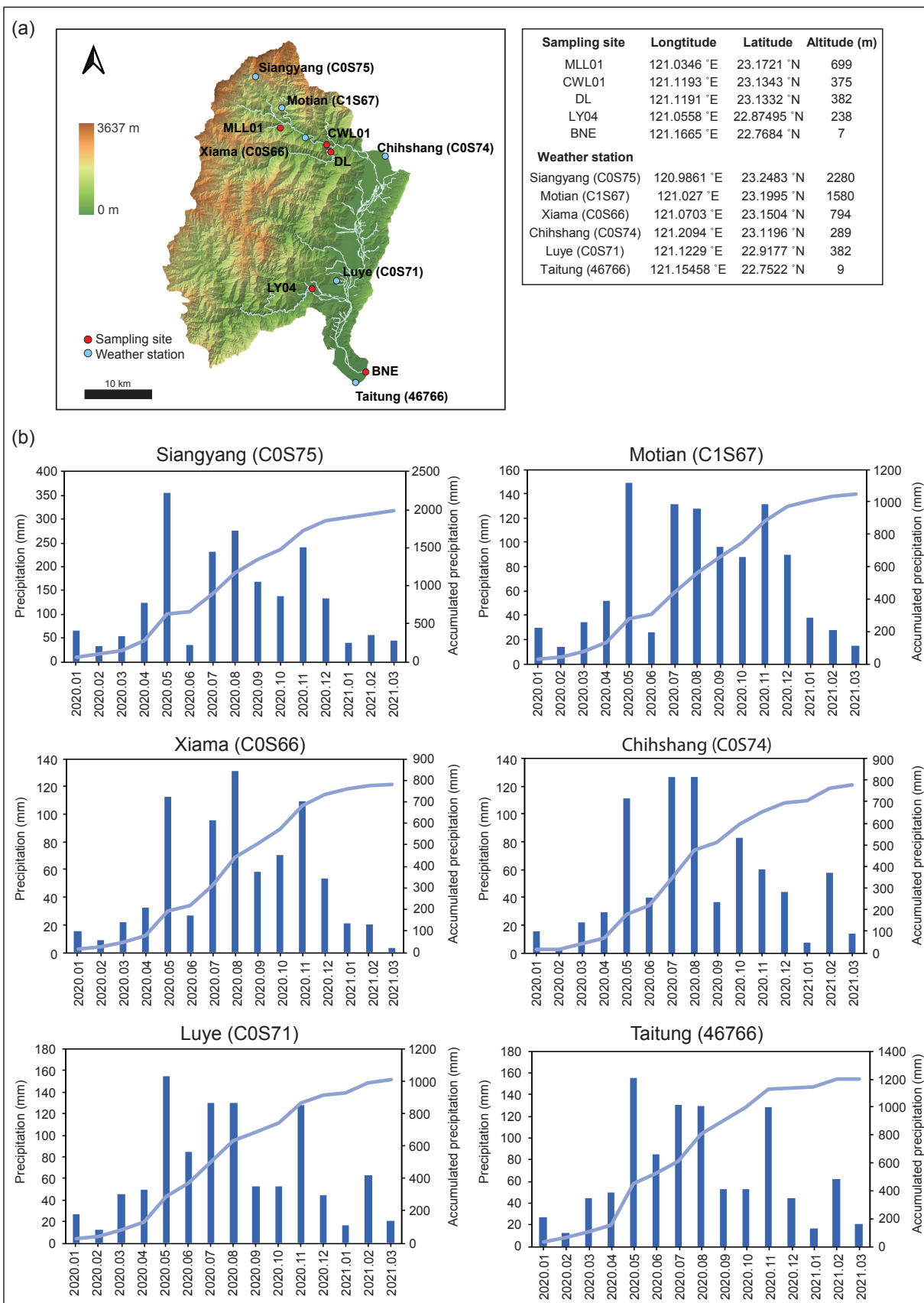
²ScCO₂: Schmidt number for CO₂ (Wanninkhof 2014).

³ Δ CO₂ = measured pCO₂ – CO₂ (air) (4.1E-04 atm).

⁴Tributary rate = flux × 365 days × river surface area (1.22E+05 m² for MLL01, 2.82E+06 m² for CWL01, 1.41E+06 m² for DL, 2.36E+6 m² for LY04, 5.17E+4 m² for BNE).

⁵Average rate = mean tributary rate for each site (average across the five sampling campaigns).

⁶Total flux was the sum of Average rate from individual tributaries. The range for Total flux reflects propagated uncertainty from two sources: the variability in measured flux across the five sampling campaigns at each site and a ± 50% uncertainty assigned to river surface area (Section 2.5), combined via root-sum-square propagation at each site ($\sqrt{[(\text{STDEV}/\text{mean})^2 + 0.5^2]}$) and then across sites ($\sqrt{[\sum (\text{uncertainty}_i \times \text{Average rate}_i)^2]}$ / Average rate).



(a)



(b)



(c)



(d)



(e)



Figure S2. Field photographs of the five sampling sites along the Beinan River catchment. (a) MLL01, headwater tributary with a steep boulder- and cobble-dominated channel within a forested valley. (b) CWL01, upper main stem with a coarse-grained braided reach and exposed gravel bars during low flow. (c) DL, mid-catchment tributary near a road bridge with a coarse-grained bed. (d) LY04, lower tributary in a forested valley with a broader braided cobble-bed reach. (e) BNE, Beinan River mouth with engineered wave-dissipating tetrapods immediately inshore. The photographs illustrate the channel morphology and substrate at each site (See Section 2.1).

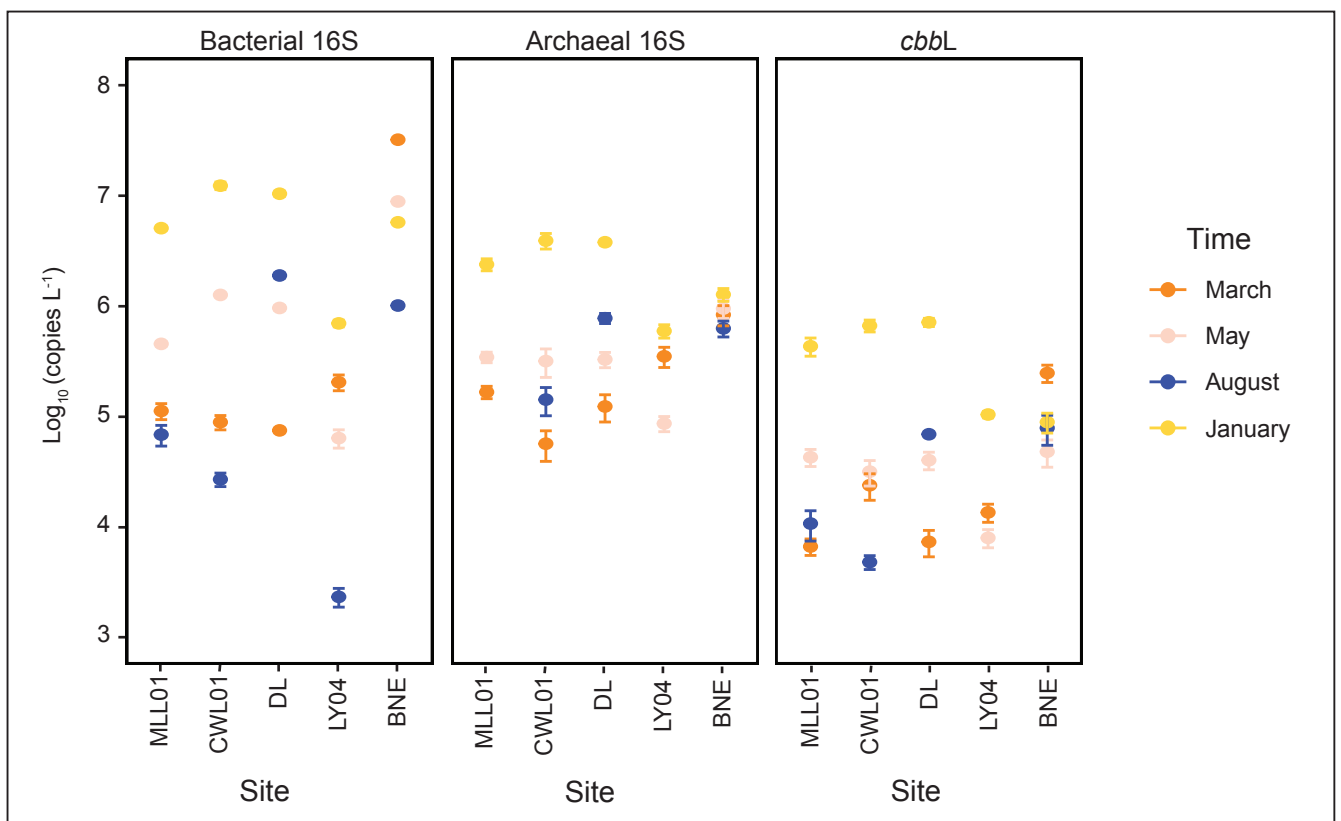


Figure S3. Gene copy numbers of 16S rRNA gene for bacteria and archaea, and functional gene *cbbL* for river samples. Sampling times are presented by colors. Values below the detection limit are not shown (archaeal 16S genes for August samples from MLL01 and LY04; *cbbL* genes for August sample at LY04).

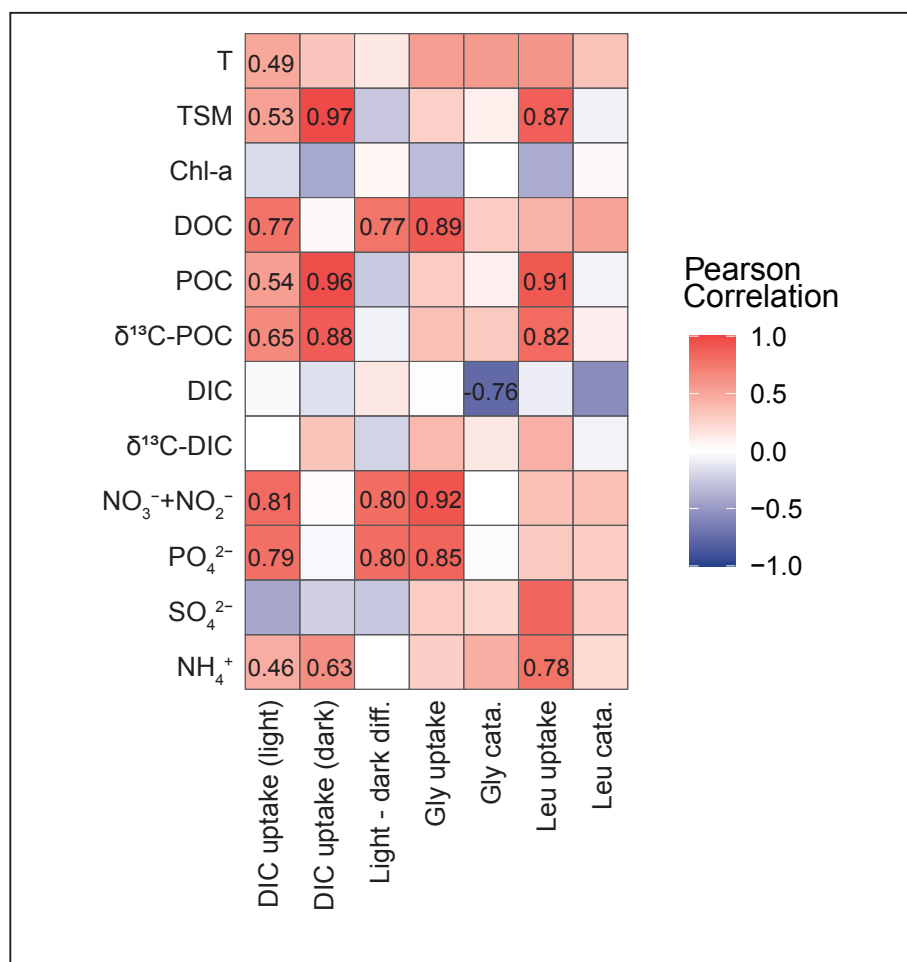


Figure S4. Heatmap showing Pearson correlations between metabolic rates and environmental factors. Environmental variables include nutrients (NH_4^+ , SO_4^{2-} , PO_4^{2-} , $\text{NO}_3^- + \text{NO}_2^-$), carbon related entities (DIC, POC, DOC and their $\delta^{13}\text{C}$ values), chlorophyll-a, total suspended matter, and temperature. Only significant correlation values are displayed ($p < 0.01$).

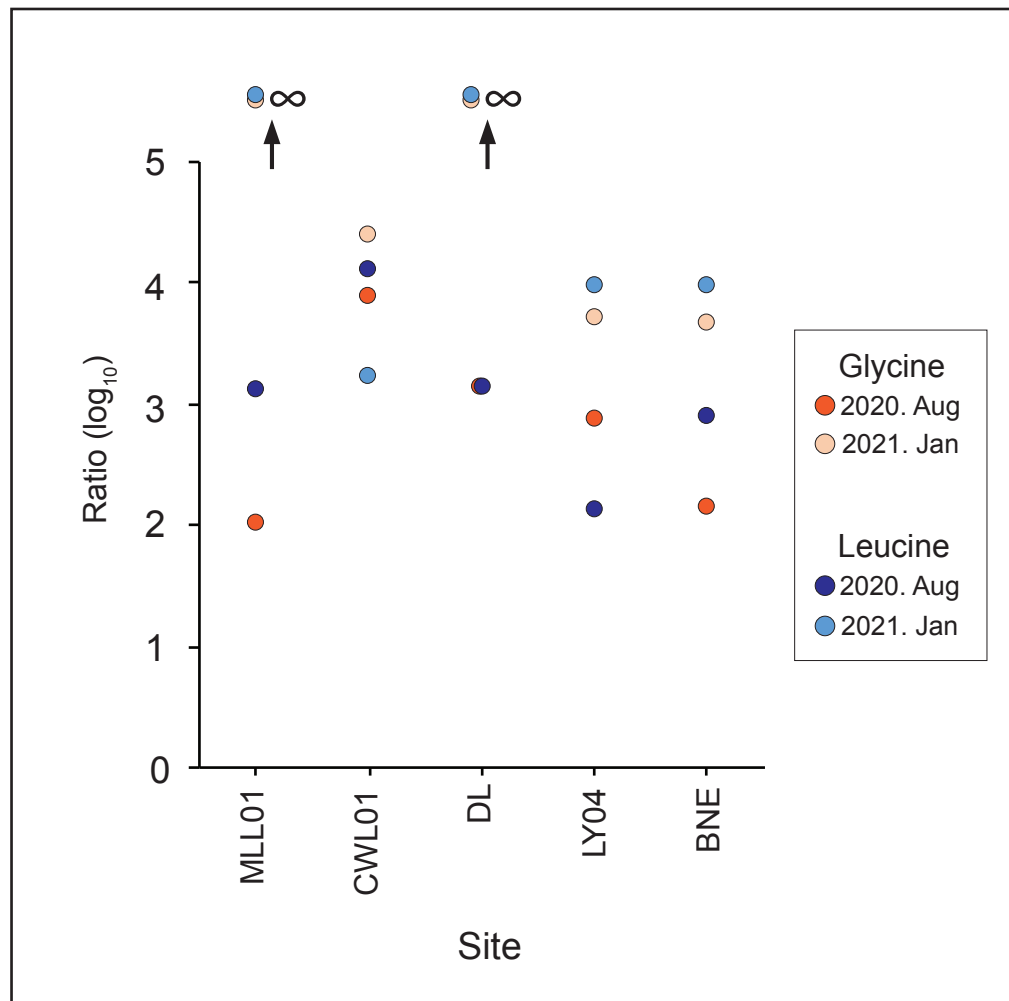


Figure S5. Ratios of catabolism-to-assimilation rates for incubations with amino acids in log₁₀ scale. Infinite ratios (∞) for sites MLL01 and DL were obtained given that the assimilation rate was below the detection limit.