Sect. S1: Information about restoration activities and restored reaches

The restored reaches (R1 and R2) were compared to an upstream degraded "control-section". We selected the degraded reach (D) to be characteristic for the channelized state of the River Ruhr, and to reflect the conditions of the restored reaches prior to restoration (Fig. S1, S2). Accordingly, the hydromorphology of the degraded reach had been largely modified by channelization and bank fixation, resulting in lower physical stream quality (e.g. smaller wetted channel width, no islands and no accumulations of woody debris).
Restoration involved the widening of the riverbed and the reconnection of the river with its floodplain by creating a shallower river profile and by removing bank fixations. Furthermore, secondary channels and island were generated, instream structures - such as woody debris - were added and shallow habitats were created, potentially providing more space for autotrophs (Fig. S3, S4, S5, S6, S7, S8). The restored reaches differed in restoration effort (R1: moderate restoration effort and R2: high restoration effort). Briefly, R2 represented higher effort than R1 due to larger soil moving activities and higher costs for measures implemented (Table S1). Moreover, differences in restoration effort were obvious from measures implemented along the two reaches: In R1, removal of bank fixation and widening of the riverbed mainly focused on one (right) shoreline only, while the other (left) shoreline remained fixed due to railroad constrains (Fig. S7). On the contrary, R2 was substantially widened, bank fixation was removed at both shorelines and islands were created along the reach (Fig. S8). The differences between the restored reaches are further described by measurement results presented in our study (Table 2).

Table S1: Restoration costs and soil moving activities indicating differences in restoration effort between R1 and R2

Reach	**Costs (€)**	**Soil excavation (m^3)**	**Soil shifting (m^3)**
R1	1,400,000	44,000	15,000
R2	1,930,000	61,000	18,000

Fig. S1: Photo of the upstream degraded „control-section“ (D) (photo by A. Lorenz).

Fig. S2: Conditions of restored reaches prior to restoration (photo by A. Lorenz).

Fig. S3: Photo of the 1st restored reach (R1) (photo by B. Kupilas).

Fig. S4: Photo of the 1st restored reach (R1) (photo by B. Kupilas).

Fig. S5: Photo of the 2nd restored reach (R2) (photo by B. Kupilas).

Fig. S6: Photo of the 2nd restored reach (R2) (photo by B. Kupilas).

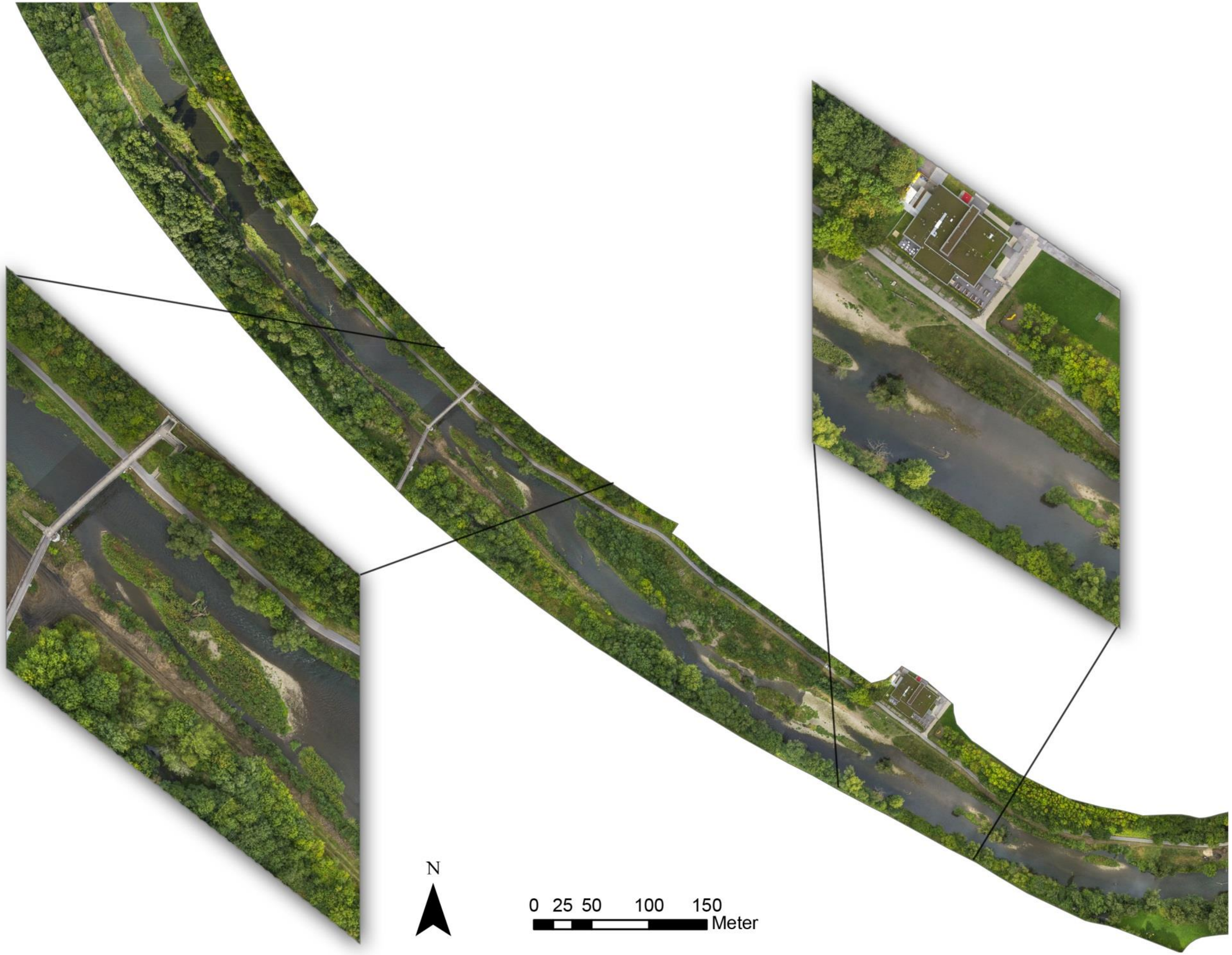
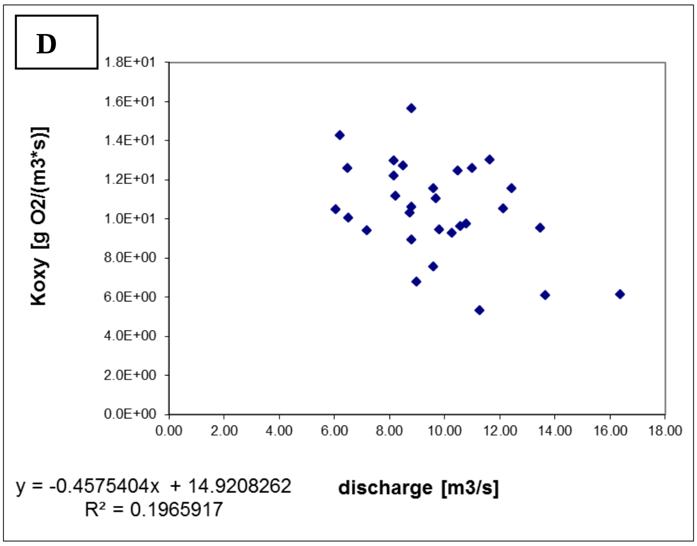


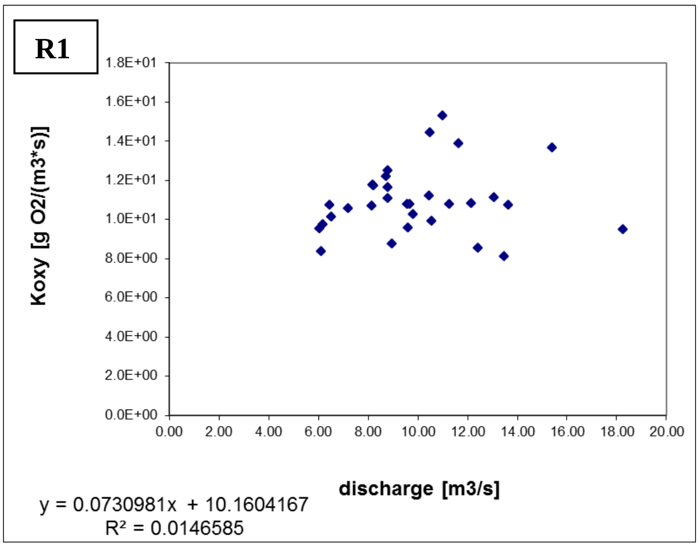
Fig. S7: 1st restored reach (R1) (photo by NZO GmbH, Germany).

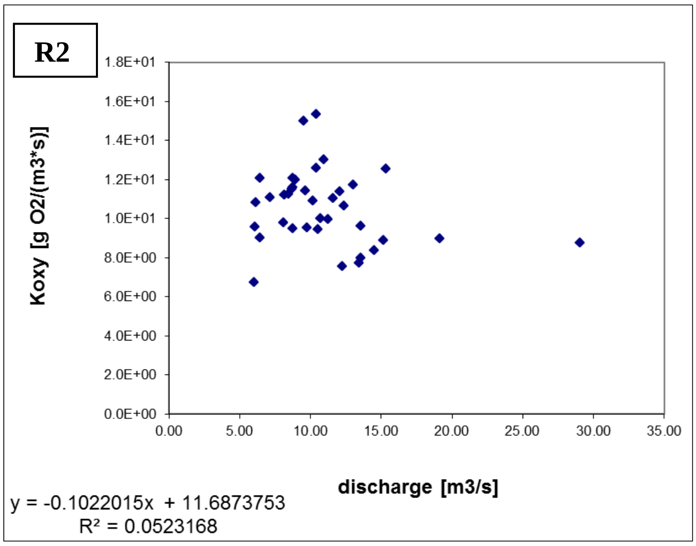
Fig. S8: 2nd restored reach (R2) (photo by NZO GmbH, Germany).

Sect. S2: K_{oxy}^{20} - discharge relationships for stations in D, R1 and R2.

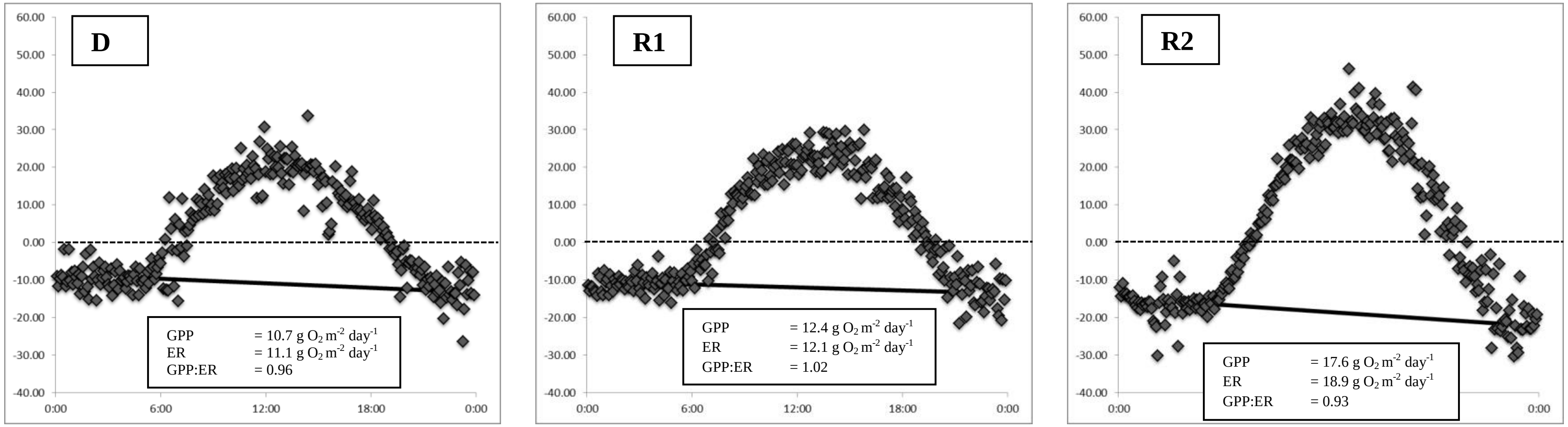
All regressions with P>0.05



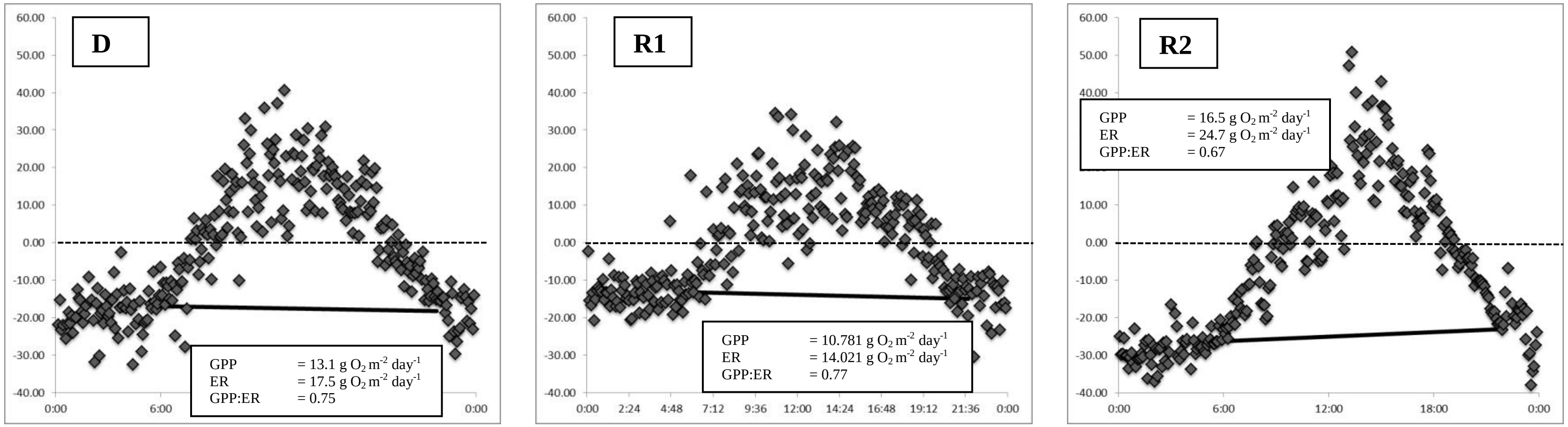




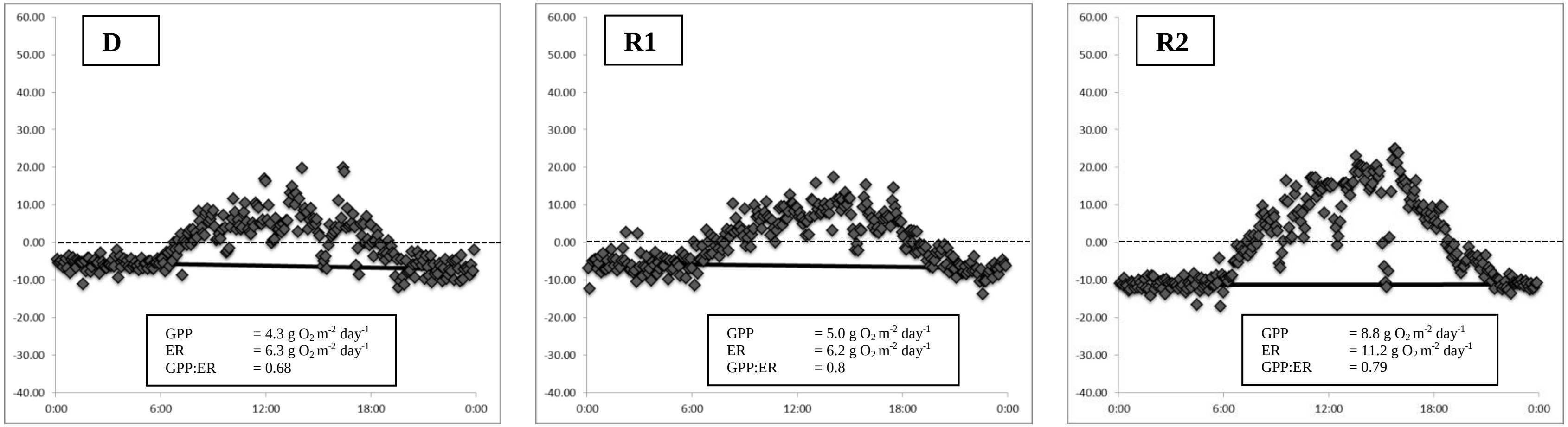
Sect. S3: Diurnal patterns of ecosystem metabolism in the sampling stations at D, R1 and R2 for days on which GPP and ER were among the highest respectively lowest rates measured



Day 17

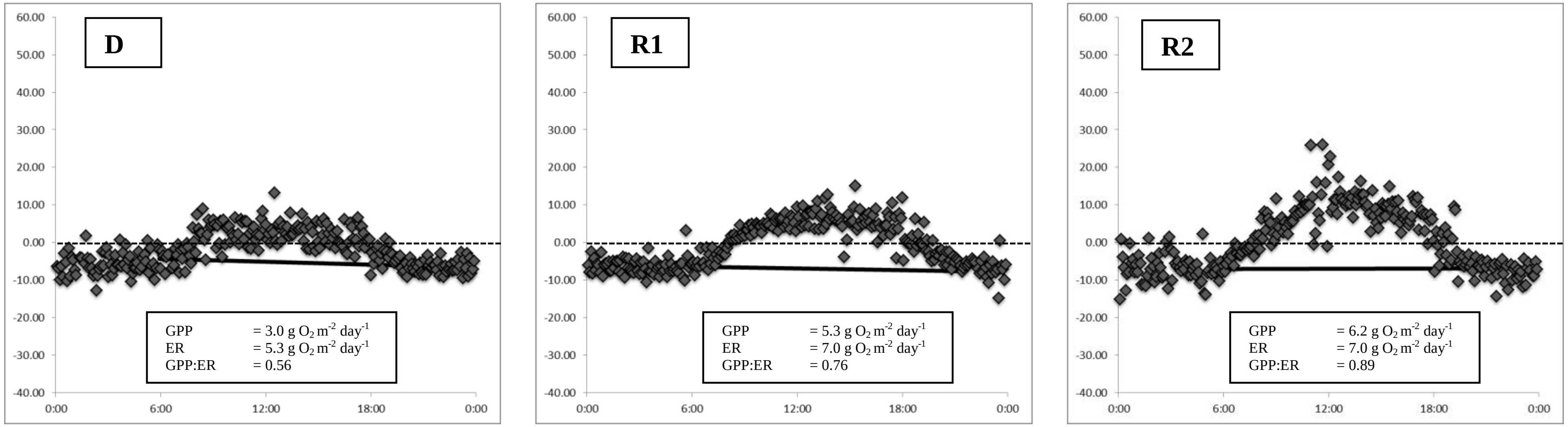


Day 1



D
GPP = 4.3 g O2 m-2 day-1
ER = 6.3 g O2 m-2 day-1
GPP:ER = 0.68
R1
GPP = 5.0 g O2 m-2 day-1
ER = 6.2 g O2 m-2 day-1
GPP:ER = 0.8
R2
GPP = 8.8 g O2 m-2 day-1
ER = 11.2 g O2 m-2 day-1
GPP:ER = 0.79
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
0:00
6:00
12:00
18:00
0:00

Day 40



D
GPP = 3.0 g O2 m-2 day-1
ER = 5.3 g O2 m-2 day-1
GPP:ER = 0.56
R1
GPP = 5.3 g O2 m-2 day-1
ER = 7.0 g O2 m-2 day-1
GPP:ER = 0.76
R2
GPP = 6.2 g O2 m-2 day-1
ER = 7.0 g O2 m-2 day-1
GPP:ER = 0.89
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
0:00
6:00
12:00
18:00
0:00

Sect. S4: Comparison of metabolic rates estimated in our study with literature data

GPP and ER estimated in this study were among the highest values reported for similar sized rivers (discharge between 5 - 50 $m^3 s^{-1}$, Appendix S5); especially those of the sampling station R2. In comparison to other streams, higher GPP and ER were reported for formerly polluted streams with a channelized river course and degraded floodplain in the Basque country (Izagirre et al. 2008); accordingly, a direct comparison to the Ruhr seems inappropriate. Besides size, none of the rivers in our literature review was comparable to the Ruhr regarding the river characteristics: sediment structure, hydromorphology/river state, macrophytes, and geographic region (Appendix S5). Consequently, metabolism reference values from rivers similar to the Ruhr are not available. However, higher GPP and ER after restoration of flow patterns have been reported by Colangelo (2007), supporting our findings of higher metabolic rates following restoration. Of all the rivers for which metabolism has been reported, the channelized river Thur (Uehlinger 2006) is closest to the Ruhr regarding size, sediment, and region. Average GPP and ER reported for the Thur were similar to those of the channelized sampling station D. Thus, relatively low GPP and ER in hydromorphologically altered rivers may be common.

References:

Colangelo, D.J. (2007) Response of river metabolism to restoration of flow in the Kissimmee River, Florida, U.S.A. Freshwater Biology, 52, 459–470. doi:10.1111/j.1365-2427.2006.01707.x.

Izagirre, O., U. Agirre, M. Bermejo, J. Pozo & A. Elosegi (2008) Environmental controls of whole-stream metabolism identified from continuous monitoring of Basque streams. Journal of the North American Benthological Society, 27, 252–268. doi: 10.1899/07–022.1.

Uehlinger, U. (2006) Annual cycle and inter-annual variability of gross primary production and ecosystem respiration in a floodprone river during a 15-year period. Freshwater Biology, 51, 938–950. doi: 10.1111/j.1365-2427.2006.01551.x.

Sect. S5: Comparison with literature data, (a) river charatersitics

Sampled river	**River characteristics**					
Name, geographic region	**Sediment structure**	**Hydromorphology/river state**	**Macrophytes**	**Additional information**	**Width (m)**	**Q ($m^3 s^{-1}$)**
Kissimmee River, Florida, USA	Sand	Channelised, restored habitat structure in river channel with continuous flow	Reduced cover of floating and mat forming vegetation	Sub-tropical, low-gradient, blackwater	15 – 30	36.60
Kansas River, Kansas, USA	Sand	Slightly braided, moderatley degraded (oxbow wetlands gone, bordered by cropland, no heavy industry or large urban area, some reservoirs)	No macrophytes, diatoms main primary producers	Prairie river, shallow	75	14.36
Omo River, Fuji River Basin, Japan	Cobbles, boulders	Relativly good, degraded water quality due to agricultural land use	Less than 5% cover	Open-canopy lowland stream draining urban and agricultural land	N.a.	5.12
Aizarnazabal, Basque Country, Spain	Bedrock, cobble	Narrow and steep valleys with short and steep streams, biotic index: excellent	Occasionally, periphyton main primary producer	Humid-oceanic climate, formerly polluted	22.7	6.27
Alegia, Basque Country, Spain	Bedrock, cobble	Narrow and steep valleys with short and steep streams, biotic index: good	Occasionally, periphyton main primary producer	Humid-oceanic climate, formerly polluted	36.2	6.96
Altzola, Basque Country, Spain	Bedrock, cobble	Narrow and steep valleys with short and steep streams, biotic index: poor	Occasionally, periphyton main primary producer	Humid-oceanic climate, formerly polluted	31.1	9.47
Amorebieta, Basque Country, Spain	Bedrock, cobble	Narrow and steep valleys with short and steep streams, biotic index: very poor	Occasionally, periphyton main primary producer	Humid-oceanic climate, formerly polluted	23.3	5.55
Lasarte, Basque Country, Spain	Bedrock, cobble	Narrow and steep valleys with short and steep streams, biotic index: fair	Occasionally, periphyton main primary producer	Humid-oceanic climate, formerly polluted	46.4	22.74
Little Tennessee River, North Carolina, USA	Sand becoming a mix of bedrock, large boulders, and sand	Broad alluvial valley becoming constrained valley	N.a.	N.a.	N.a.	12.90
Thur River, Switzerland	Gravel	Channelised with stabilised banks, with reach partly being opened (i.e. removal of bank fixation)	N.a.	Alpine river	35	48.70
Murrumbidgee River, Darlington Point, Australia	Clay, silt with sandy bars	Degraded, but not channelized	Very little macrophytes	In an agricultural area	N.a.	22.00
Daly, Australia	Sand, gravel	Natural, about 5% of the land cleared of natural vegetation, no dams, essentially natural flow, intermittent river	Very little macrophytes	5th - 7th order, tropical, shallow, clear water, low nutrient concentration, open canopy	N.a.	24.00
Mitchell River (MCC, upper site), Australia	Sand, bedrock	Continuous run-pool channel morphology	No macrophytes	Dry season sampled, riparian vegetation present	32	27.20
Buffalo Fork, Wyoming, USA	Cobble, gravel/pebble	Natural	No macrophytes	N.a.	35.2	19.10
Green River, Wyoming, USA	Cobble, boulder	Natural	N.a.	Below a dam	62.5	25.50
Salmon River, USA	Cobble, gravel	Natural	No macrophytes	N.a.	50.5	25.90
Tippecanoe River, Indiana, USA	Gravel, pebble with sand and fine sediment	Natural	No macrophytes	N.a.	50.6	19.00
Muskgeon River, Michigan, USA	Sand, silt, clay with gravel and cobbles	Natural	9% cover	N.a.	67	33.00
Manistee River, Michigan, USA	Sand, silt, clay with gravel and pebble	Natural	13% cover	N.a.	52.5	36.50
Bear River, Utah, USA	Sand, silt, clay	Natural morphology but hydrologically altered	No macrophytes	N.a.	37.3	16.00

Green River at Ouray, Utah, USA	Sand, silt, clay	Natural	1% cover	N.a.	111.8	37.90
Green River at Gray Canyon, Utah, USA	Fine sediments with gravel and cobbles	Natural	< 1% cover	N.a.	79.1	41.00
Chena1, Alaska, USA	N.a.	Natural flow regime, undeveloped	N.a.	Sub-arctic, clear-water river, upper catchment ~undeveloped, lower catchment with urban development	N.a.	42.00
Chena2, Alaska, USA	N.a.	Natural flow regime, undeveloped	N.a.	Sub-arctic, clear-water river, upper catchment ~undeveloped, lower catchment with urban development	N.a.	44.50
Chena3, Alaska, USA	N.a.	Natural flow regime, undeveloped	N.a.	Sub-arctic, clear-water river, upper catchment ~undeveloped, lower catchment with urban development	N.a.	47.00
Chena4, Alaska, USA	N.a.	Natural flow regime, undeveloped	N.a.	Sub-arctic, clear-water river, upper catchment ~undeveloped, lower catchment with urban development	N.a.	47.50
Ichetucknee, Florida, USA	N.a.	N.a.	N.a.	N.a.	N.a.	8.90
East Fork, Indiana, USA	N.a.	Natural	N.a.	N.a.	47.9	14.00

N.a. = not available

Sect. S5: comparison with literature data, (b) metabolic rates

Sampled river	Metabolism				
Name, geographic region	**GPP (g O_2 m^{-2} d^{-1})**	**ER (g O_2 m^{-2} d^{-1})**	**GPP:ER**	**NEP (g O_2 m^{-2} d^{-1})**	**Reference**
Kissimmee River, Florida, USA	3.95	-9.44	0.42	-5.49	Colangelo, D.J. (2007) Response of river metabolism to restoration of flow in the Kissimmee River, Florida, U.S.A. Freshwater Biology, 52, 459–470.
Kansas River, Kansas, USA	8.40	-12.12	0.69	-3.72	Dodds, W.K., J.J. Beaulieu, J.J. Eichmiller, J.R. Fischer, N.R. Franssen, D.A. Gudder, A.S. Makinster, M.J. McCarthy, J.N. Murdock, J.M. O'Brien, J.L. Tank & R.W. Sheibley (2008) Nitrogen cycling and metabolism in the thalweg of a prairie river. Journal of Geophysical Research, 113, G04029.
Omo River, Fuji River Basin, Japan	3.83	-9.13	0.42	-5.30	Iwata, T., T. Takahashi, F. Kazama et al. (2007) Metabolic balance of streams draining urban and agricultural watersheds in central Japan. Limnology, 8, 243-250.
Aizarnazabal, Basque Country, Spain	11.00	-17.20	0.64	-6.20	Izagirre, O., U. Agirre, M. Bermejo, J. Pozo & A. Elosegi (2008) Environmental controls of whole-stream metabolism identified from continuous monitoring of Basque streams. Journal of the North American Benthological Society, 27, 252–268.
Alegia, Basque Country, Spain	4.40	-12.50	0.35	-8.10	Izagirre, O., U. Agirre, M. Bermejo, J. Pozo & A. Elosegi (2008) Environmental controls of whole-stream metabolism identified from continuous monitoring of Basque streams. Journal of the North American Benthological Society, 27, 252–268.
Altzola, Basque Country, Spain	6.40	-42.60	0.15	-36.20	Izagirre, O., U. Agirre, M. Bermejo, J. Pozo & A. Elosegi (2008) Environmental controls of whole-stream metabolism identified from continuous monitoring of Basque streams. Journal of the North American Benthological Society, 27, 252–268.
Amorebieta, Basque Country, Spain	2.80	-9.80	0.29	-7.00	Izagirre, O., U. Agirre, M. Bermejo, J. Pozo & A. Elosegi (2008) Environmental controls of whole-stream metabolism identified from continuous monitoring of Basque streams. Journal of the North American Benthological Society, 27, 252–268.
Lasarte, Basque Country, Spain	6.30	-13.50	0.47	-7.20	Izagirre, O., U. Agirre, M. Bermejo, J. Pozo & A. Elosegi (2008) Environmental controls of whole-stream metabolism identified from continuous monitoring of Basque streams. Journal of the North American Benthological Society, 27, 252–268.
Little Tennessee River, North Carolina, USA	3.18	-4.07	0.78	-0.89	McTammany, M.E., J.R. Webster, E.F. Benfield & M.A. Neatrour (2003) Longitudinal patterns of metabolism in a southern Appalachian river. Journal of the North American Benthological Society, 22, 359–370.
Thur River, Switzerland	5.00	-6.20	0.81	-1.20	Uehlinger, U. 2006. Annual cycle and inter-annual variability of gross primary production and ecosystem respiration in a floodprone river during a 15-year period. Freshwater Biology, 51, 938–950.
Murrumbidgee River, Darlington Point, Australia	1.71	-1.90	0.90	-0.19	Vink, S., M. Bormans, P.W. Ford & N.J. Grigg (2005) Quantifying ecosystem metabolism in the middle reaches of Murrumbidgee River during irrigation flow releases. Marine and Freshwater Research, 56, 227–241.
Daly, Australia	2.90	-5.34	0.54	-2.44	Townsend, S.A. & A.V. Padovan (2005) The seasonal accrual and loss of benthic algae (Spirogyra) in the Daly River, an oligotrophic river in tropical Australia. Marine and Freshwater Research, 56, 317–327.
Mitchell River (MCC, upper site), Australia	2.12	-4.47	0.47	-2.35	Hunt, R.J., T.D. Jardine, S.K. Hamilton & S.E. Bunn (2012) Temporal and spatial variation in ecosystem metabolism and food web carbon transfer in a wet-dry tropical river. Freshwater Biology, 57, 435-450.
Buffalo Fork, Wyoming, USA	0.80	-3.40	0.24	-2.60	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Green River, Wyoming, USA	19.90	-17.50	1.14	2.40	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Salmon River, USA	4.00	-5.10	0.78	-1.10	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Tippecanoe River, Indiana, USA	2.60	-5.30	0.49	-2.70	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Muskgeon River, Michigan, USA	3.00	-4.80	0.63	-1.80	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Manistee River, Michigan, USA	3.90	-4.40	0.89	-0.50	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Bear River, Utah, USA	1.10	-1.10	1.00	0.00	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.

Green River at Ouray, Utah, USA	1.10	-1.20	0.92	-0.10	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Green River at Gray Canyon, Utah, USA	0.30	-3.00	0.10	-2.70	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.
Chena1, Alaska, USA	3.25	-8.95	0.36	-5.70	Benson, E.R., M.S. Wipfli, J.E. Clapcott & N.F. Hughes (2013) Relationships between ecosystem metabolism, benthic macroinvertebrate densities, and environmental variables in a sub-arctic Alaskan river. Hydrobiologia, 701, 189–207.
Chena2, Alaska, USA	2.25	-5.80	0.39	-3.55	Benson, E.R., M.S. Wipfli, J.E. Clapcott & N.F. Hughes (2013) Relationships between ecosystem metabolism, benthic macroinvertebrate densities, and environmental variables in a sub-arctic Alaskan river. Hydrobiologia, 701, 189–207.
Chena3, Alaska, USA	1.85	-6.10	0.30	-4.25	Benson, E.R., M.S. Wipfli, J.E. Clapcott & N.F. Hughes (2013) Relationships between ecosystem metabolism, benthic macroinvertebrate densities, and environmental variables in a sub-arctic Alaskan river. Hydrobiologia, 701, 189–207.
Chena4, Alaska, USA	1.95	-5.90	0.33	-3.95	Benson, E.R., M.S. Wipfli, J.E. Clapcott & N.F. Hughes (2013) Relationships between ecosystem metabolism, benthic macroinvertebrate densities, and environmental variables in a sub-arctic Alaskan river. Hydrobiologia, 701, 189–207.
Ichetucknee, Florida, USA	10.00	-8.50	1.18	1.50	Heffernan, J.B. & M.J. Cohen (2010) Direct and indirect coupling of primary production and diel nitrate dynamics in a subtropical spring-fed river. Limnol. Oceanogr., 55, 677–688.
East Fork, Indiana, USA	4.70	-5.60	0.84	-0.90	Hall, R.O., J.L. Tank, M.A. Baker, E.J. Rosi-Marshall & E.R. Hotchkiss (2016) Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems, 19, 73-86.