

Response to the reviewers' comments

Summary

We would like to thank the three anonymous reviewers and Robert Pennington for their helpful comments during the interactive discussion stage. Following the reviewers' suggestions carefully, we have performed major re-analyses of our data and changes to the text and figures. We believe that our manuscript has been substantially improved by this major revision, and address these changes below in a detailed point-by-point response to the comments of the reviewers and Robert Pennington. Most relevant changes involved the additional calculation of metabolic rates for the combined restored reach (R1+R2) using the two-station method. Further, we changed our statistical approach and now use an autoregressive approach to address the autocorrelation issue of time-series data (using the ARIMA function in [R]). While the results of this new, statistically sophisticated approach closely resemble those of previously used simple rmANOVA, the use of the 2-station approach quantitatively supported our previous qualitative findings obtained from the one-station method. We believe that the use of the 2-station method was the most substantial criticism and that the revised manuscript addresses this issue well by exactly providing the data the reviewers asked for.

We would also like to emphasize the good agreement of results of the one-station and the two-station method in our restored reaches, i.e. that both clearly suggested metabolism increases due to restoration. This is an important finding from a practical point of view, e.g. for agency efforts to monitor restoration outcome, because the 1-station method is often more practical for routine measurements, while the 2-station technique is often considered a research method that is too complex for such purposes. Therefore, we believe that it is important to show and compare results from both techniques side by side in our study. At the end of this document, we also added our revised manuscript with changes marked as supplement to these responses.

Detailed response to reviewer 1

COMMENT:

The aim of this manuscript was to use ecosystem metabolism as a measure of ecosystem function in response to river restoration. The authors estimated ecosystem metabolism over 50 days within a mid-sized river reach that contained moderate (R1) and substantial (R2) restored reaches and a degraded (unrestored) (D) reach. The idea of using ecosystem function, especially ecosystem metabolism, as a response to river restoration is compelling, and in the direction where restoration work/research is needed and likely headed.

Using open channel diel changes in dissolved oxygen, the authors used a 1-station approach to estimate ecosystem metabolism. As both restored (R1 and R2) and unrestored reaches are in succession, the 1-station approach results in the dissolved oxygen signal integrating beyond the study reach of interest. Unfortunately, the authors cannot parse out restoration effects on ecosystem metabolism because the estimates of GPP and ER encompass all of the river reaches. If I understand correctly, the authors have the data to use a 2-station approach to estimate ecosystem metabolism. I strongly urge the authors to estimate reach specific ecosystem metabolism in order to quantitatively parse out the effects of restoration on ecosystem function.

RESPONSE:

We agree with the reviewer that it would be helpful to exactly quantify the metabolic rates of each of the investigated river reaches (D=degraded, R1=moderately restored, R2=intensively restored in our study). As explained in the original manuscript and in our response to Robert Pennington, these river reaches were too short to permit the application of the 2-station open-channel technique. Reach lengths chosen in our study represented typical spatial scales of river restoration practice (see lines 35/36 of the original paper). In fact, we are not aware of a single restored river section in Germany in which the 2-station open-channel method could be applied, as most sections are either too short or not homogeneous enough. We also stressed in the original manuscript that the used 1-station technique measured long upstream, degraded river reaches in addition to the river reaches of interest, and that the presented metabolic rates (measured with the 1-station method at the end of each experimental reach) and their successive increase have therefore to be considered as qualitative indicators of metabolism increase due to river restoration, rather than as the exact rates in the experimental reaches. Since the upstream river state was degraded, and calculations based on 1-station approach integrate upstream, degraded section with increasing lengths of restored sections (reaches R1 and R2) along the sampling stations, increase in metabolism can be considered as effect of restoration.

However, as the referee and Robert Pennington noted, the combined river reaches R1+R2 were long enough to permit the application of the 2-station open-channel method. Following this suggestion, we have now calculated the metabolic rates of the combined reach R1+R2 (see Fig. 1), and thereby we obtained metabolic rates that can be directly compared to metabolic rates of the upstream, degraded river (measured at station D with the 1-station open channel method). Results obtained with the 1-station and the 2-station method often agree remarkably well, and can therefore be compared (e.g., Bernot et al., 2010; Beaulieu et al., 2013).

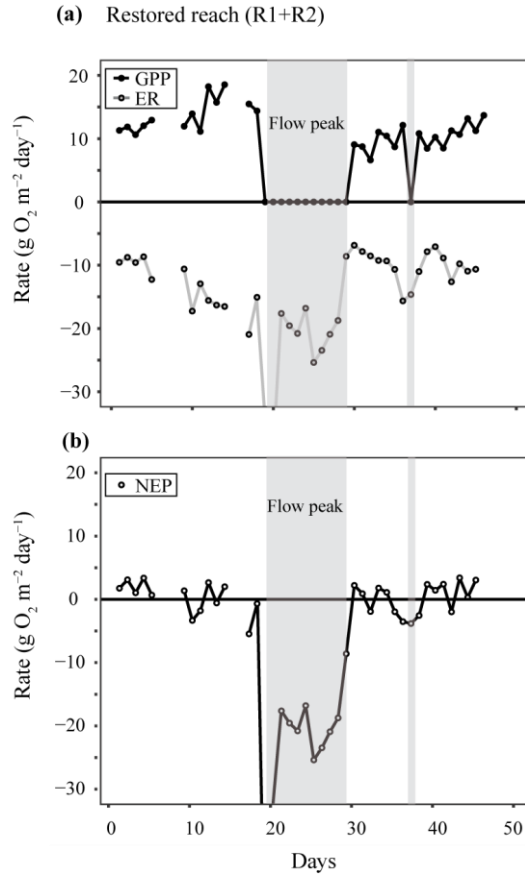


Fig. 1: Daily rates of (a) gross primary production (GPP: positive values, black line) and ecosystem respiration (ER: negative values, grey lines) and (b) net ecosystem production (NEP) calculated for the total restored reach (R1+R2) of the River Ruhr in summer 2014. Vertical grey bars indicate peak flow events.

Following the referee's suggestions, we also changed our statistical approach and now use an autoregressive approach to address the autocorrelation issue of time-series data. Briefly, we use the ARIMA function in [R] to identify an ARIMA model that best represents all time series (metabolic parameters at stations D, R1, R2, and reach R1+R2), estimate average parameter predictions and 95%-confidence limits for each time series based on these models, and use F-tests to test the hypothesis of differences among time series (compare Roley et al. 2014). Using this analysis, we still find an increase in river GPP, NEP and GPP:ER along the restored river section (D to R1 and R2; estimated by the 1-station method; see Fig. 2), as previously analyzed in the original submission by repeated-measures ANOVA. However, more importantly, GPP, ER, NEP, and GPP:ER were also higher (Fig. 2) in the total restored river reach (R1+R2) than in the upstream degraded river (station D).

Thus, we could quantitatively support our previous qualitative findings by estimating metabolism with the 2-station method for the combined restored reach R1+R2 (see Fig. 1). We believe that river metabolism increases due to hydromorphological restoration are now well supported in the revised paper.

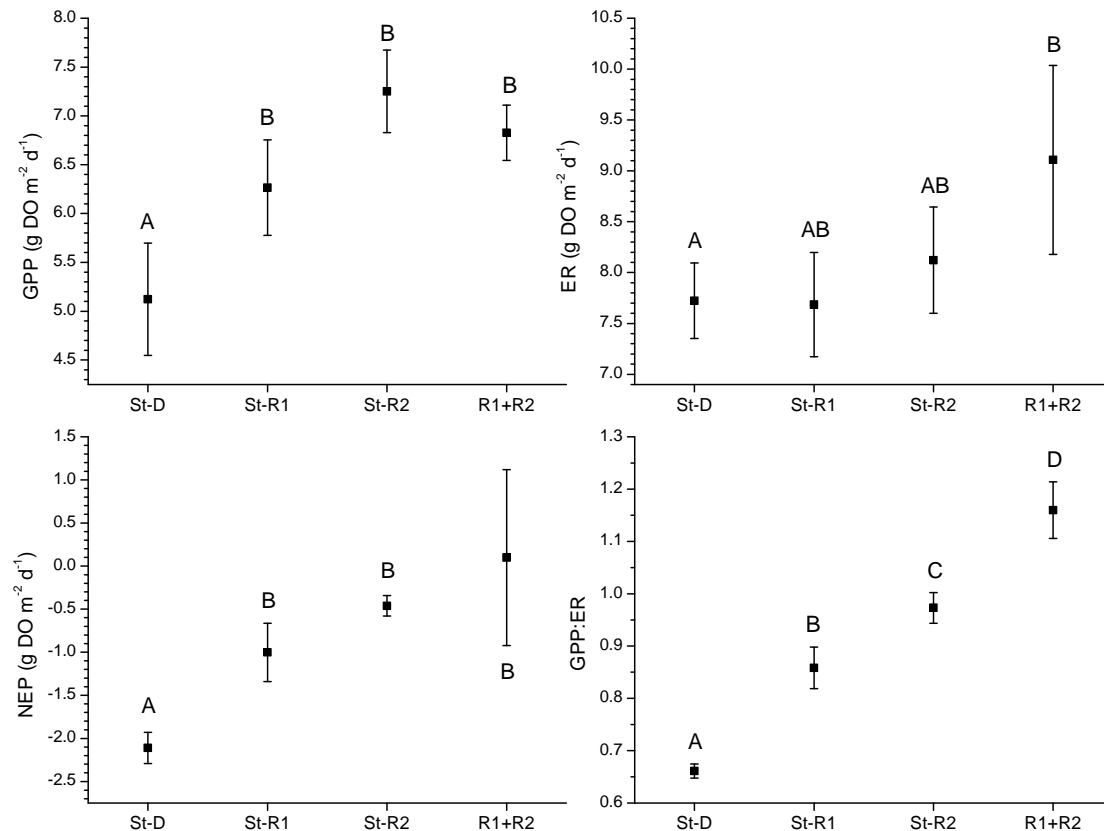


Fig. 2: Average predicted metabolic parameters and 95% confidence intervals of time series estimated by the 1-station open-channel-method at river stations D, R1, and R2, and by the 2-station open-channel-method for river reach R1+R2. F-tests for all variables were significant (GPP: $p < 0.001$; ER: $p < 0.05$; NEP: $p < 0.005$, GPP:ER: $p < 0.0001$). Different letters indicate differences according to Tukey's post-hoc test ($p < 0.05$).

COMMENT:

L31 – Hydromorphology is introduced here and mentioned throughout, but not defined. I think it would help the readers to clearly define hydromorphology early on in the manuscript. Specifically, why or how is hydromorphology linked to ecological status (as mentioned in the next sentence).

RESPONSE:

We agree and added the following definition to the revised paper: For example, the German national river habitat survey, which evaluates 31 hydromorphological parameters for 100 m river sections, concluded that the majority of German rivers is severely degraded (Gellert et al., 2014; UBA, 2013). As the river biota depend on suited habitats (Beisel et al., 2000; Schröder et al., 2013), about 85% of German rivers failed to reach the ‘good ecological status’ demanded by the WFD (EEA, 2012).

COMMENT:

L58 – I suggest changing ‘It measures ...’ to ‘Ecosystem metabolism is a measure of the production’

RESPONSE:

We agree and corrected this in the revised paper.

COMMENT:

L65 – Missing a ‘have’ – ‘The majority of these studies ‘have’ focused...’

RESPONSE:

We agree and corrected this in the revised paper.

COMMENT:

L66 – Dodds et al., Freshwater Science – estimated ecosystem metabolism in the Mississippi River reference to this study could be included. Also – Hall et al. L&O, measure GPP in the Colorado River.

RESPONSE:

We have included the mentioned studies in the revised manuscript.

COMMENT:

L84 – What do the authors mean by ‘hydrodynamics’? Beaulieu et al. 2013 measured ecosystem metabolism in an urban stream where storm events and periods of low to now flow had a strong effect on GPP and ER.

RESPONSE:

We agree and rewrote this sentence as follows: Increases in transient storage zones potentially enhance ER (Fellows et al., 2001) and nutrient processing (Valett et al., 1996; Gücker and Boëchat, 2004).

COMMENT:

L91 – The authors predicted that the restored reaches would result in higher biomass of primary producers. I am assuming this is due to increased light availability because of the widened channels. However, increased biomass of primary producers can also indicate eutrophication. I think within the context of this study, the authors attribute increased macrophytes, etc. to be a positive response to restoration (increased ecosystem function). But, increased macrophytes due to eutrophication or due to light alleviation can likely have opposite ecosystem function outcomes, I think it would be beneficial to mention or briefly discuss eutrophication versus a positive ecosystem function of increased autotrophic biomass.

RESPONSE:

We agree and discussed this issue in more detail in the revised paper. In the present case, there are no point or diffuse sources that lead to eutrophication effects in this river section. Thus, metabolic responses should be solely due to river restoration, i.e. wider channels (-> more light availability), shallower channels (-> better habitat for macrophytes), and lower current velocities (-> less hydraulic stress) as also discussed in lines 70 of the original manuscript.

COMMENT:

L101 – km to km²

RESPONSE:

In our version of the manuscript “km²” is correctly represented.

COMMENT:

L181 – L185 – I do not follow the reasoning for not using a 2-station approach to estimate ecosystem metabolism. What was the travel time between the two stations? As mentioned within the general comments – without having a reach specific estimation of ecosystem metabolism, the authors cannot infer differences in GPP and ER to restoration efforts.

RESPONSE:

We clarified this in the revised manuscript, also giving values for travel times. In our response to Robert Pennington, we already presented the corresponding calculations (based on travel times and reaeration coefficients) that show that the 3 experimental reaches are too short to permit the use of the 2-station method, and we discussed this issue in more detail in the revised manuscript. As for reach specific rates, we now present these rates for the combined restored reach R1+R2 (see previous response to the referees general comments and Figs 1 and 2). Nonetheless, we do not share the referee's view that increases in 1-station metabolism along the restored reach do not permit any conclusion about restoration effects: as mentioned in the original paper and in the response to the referee's general comments, we consider increased 1-station metabolism measured downstream of restored reaches a qualitative indicator, and the referee has not provided any argument as to why this conclusion may be flawed. As mentioned above, it is almost impossible to apply the 2-station method to restored river sections, as restored stretches (at least for larger rivers) are almost always too short or too inhomogeneous.

COMMENT:

L205 – Using night-time regression is ok here. However, I do agree with one of the open comments posted for this manuscript – given the high productivity in this river, it might be possible to model GPP, ER, and k. There are several packages becoming available that may help model ecosystem metabolism from oxygen data, including a 2-station approach. One package that is currently in development is StreamMetabolizer, for instance (<http://usgs-r.github.io/streamMetabolizer/>) or another package from Halbedel and Buttner 2014 (Methods in Ecology and Evolution).

RESPONSE:

We agree with the reviewer that this might be possible in the future. However, the mentioned MeCa toolbox by Halbedel and Büttner (2014) is a mere MatLab implementation of the classical method by Odum (1956) and does not allow for inverse modeling or regression approaches. We have actually used this Toolbox to model our data and results are exactly the same as those obtained by our Excel model; which should be case as we used exactly the same method and equations. Further, MeCa does not allow to model k from time series, but merely estimates k from empirical equations or a two-station propane addition experiment. As for StreamMetabolizer, we agree that this is a promising approach, but currently a tested and stable version of this software is not available. The authors' state: "This package is in development. We are using it for our own early applications and welcome bold, flexible, resilient new users who can help us make the package better." Thus, we believe that it is too early to publish results from this software.

COMMENT:

L225 – ANOVA with repeated measures is not appropriate for time-series data. I suggest using an analysis method that includes an auto-regressive term, perhaps generalized least squares or something similar (i.e. see Zuur, A., Ieno, E. N., Walker, N., Saveliev, A. A., & Smith, G. M. (2009). *Mixed Effects Models and Extensions in Ecology with R*. The Quarterly Review of Biology (Vol. 84, pp. 574–405). Springer Science & Business Media. <http://doi.org/10.1086/648138>).

RESPONSE:

We agree and have followed the suggested paper and used auto-regressive approach (see our previous response to the reviewer's first comment, and Fig. 2).

COMMENT:

L228 – For future analyses, the authors should justify why they would exclude days during or after storms where GPP was zero. The variation in daily rates of ecosystem metabolism within one river often exceeds or is the same of that from multiple sites (see Hall 2016, *Metabolism of Streams and Rivers*. In J. B. Jones & E. H. Stanley (Eds.), *Stream Ecosystems in a Changing Environment* (pp. 151–180). Elsevier. <http://doi.org/10.1016/B978-0-12-405890-3.00004-X>). I think excluding these days, other than not being able to estimate GPP or ER (which can occur with high stream discharge events) would skew the results by artificially reducing the variance.

RESPONSE:

We agree that storms are an important part of environmental variability and mentioned average metabolic rates including storm measurements in the revised paper. However, GPP was not detectable during storm events, and we cannot be sure whether GPP was really zero or very low, or whether high flows may have prevented the detection of GPP. We will add this information to the revised paper.

COMMENT:

L266-268: Why not report ranges of NEP here? Also, I understand the utility of GPP:ER ratios – but NEP can be informative as actual flux values.

RESPONSE:

We agree and presented NEP here in the revised paper. Furthermore, daily NEP is presented in Fig. 6 of the revised manuscript.

COMMENT:

L336: Given the methodological approaches using the 1-station method of estimating metabolism along with the use of ANOVA, differences in metabolism amongst the reaches is not presently supported.

RESPONSE:

By estimating metabolism with the 2-station method for the combined restored reach R1+R2 (see Fig. 1) and by comparing ARIMA function estimates (a) along the restored river section and (b) between the upstream degraded river and the restored reach R1+R2 (see Fig. 2), we believe that river metabolism increases due to restoration are now well supported in the revised paper.

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Valett, H.M., Morrice, J.A., Dahm, C.N., and Campana, M.E.: Parent lithology, surface-groundwater exchange, and nitrate retention in headwater streams. *Limnology and Oceanography*, 41, 333-345, 1996.

Detailed response to reviewer 2

COMMENT

This manuscript addresses a question of high importance – how might we use measurements of ecosystem processes to monitor the health of rivers? While there has been a push to include process measurements with other monitoring efforts (including those of restored sites), data showing how process measurements can actually be used to inform monitoring in rivers are few. Here the authors estimate ecosystem metabolism and hydromorphic characteristics of connected river reaches with (n=2, “R1” and “R2”) and without (n=1, “D”) a history of restoration efforts and provide evidence for higher rates of ecosystem metabolism (gross primary production and ecosystem respiration; GPP and ER) in restored versus degraded reaches. What this difference means in terms of “good” or “bad” rates remains unclear without longer-term before/after data. And while the motivation for this research is very timely and will be of broad interest, a few assumptions behind methods and presentation of results limit the impact of the manuscript in its current form.

RESPONSE

We agree with the reviewer that the incorporation of ecosystem processes in river monitoring is of high importance and we think that our revised paper will be of broad interest. By estimating metabolism with the 2-station method for the combined restored reach R1+R2 (see Fig. 1 in response to reviewer 1) and by comparing ARIMA function estimates (a) along the restored river section and (b) between the upstream degraded river and the restored reach R1+R2 (see Fig. 2 in response to reviewer 1), we believe that river metabolism increases due to restoration are now well supported in the revised paper.

As for the referee’s question as to what higher rates of GPP and ER mean in terms of “good” and “bad”: The restored sections (R1 and R2) have a higher structural quality according to the national river habitat survey protocol, and their better (=closer to natural conditions) morphological condition compared to the degraded “control” section has been characterized throughout the manuscript. As discussed in lines 371-374 of the original manuscript, higher rates of metabolism and the occurrence of dense macrophyte stands in restored river reaches may also increase the assimilation of dissolved nutrients (Fellows et al., 2006; Gücker et al., 2006) and the sedimentation of particulate nutrients (Schulz and Gücker, 2005), thereby positively affecting water quality. Accordingly, increased rates of GPP and ER should indicate a positive response to restoration in the case of the investigated river, as they occurred in reaches closer to local reference conditions. However, a general classification of metabolism increase as either “good” or “bad” in terms of “natural” and “unnatural” conditions is currently hardly possible as there is only limited knowledge about natural geographical gradients in river metabolism (especially for mid-sized and larger rivers) as discussed in lines 347-356 and 376-380 of the original manuscript. This highlights the importance of coupling functional measures, such as metabolism, with assessments of ecosystem structure in different biomes and ecoregions.

COMMENT

It is not clear from the descriptions in main text and supplements why the two restored reaches were separated from one another – beyond the fact that they were perhaps separate projects? While restoration effort was indeed larger in R2 than R1, it was not drastically so, especially given the larger reach area in R2 than R1. Further, using a single-station metabolism approach to estimate GPP and ER does not honor the boundaries set by the authors in naming R1 and R2 given the overlap in O₂ footprints upstream of researcher-defined reach boundaries. Based on author responses to earlier comments, it appears that combining R1 and R2 is a more suitable approach, despite losing a reach "replicate" of sorts. I hope the manuscript will be revised accordingly and the authors will confirm that combined R1-R2 rates are reasonable given what R1- and R2-only rates were.

RESPONSE

The larger area of R2 compared to R1 is a consequence of restoration effort (widening of the river channel and amount of soil removed) - accordingly, it is important to separate R1 and R2 to explain the local situation with two reaches restored with different restoration effort to the reader, even if these reaches do not match the dimensions of our experiments.

Restoration is most often implemented in short river stretches of approximately 1 km (as described in lines 35-36 of the original manuscript). The experimental reaches, therefore, reflected these typical spatial scales and we were able to combine the assessment of reach-scale structural characteristics with changes in metabolism. Despite the mismatch between lengths of river reaches evaluated and reaches exclusively affected by restoration, we found significant effects of reach-scale restoration on whole-river metabolism using the 1-station technique. We also stressed in the original manuscript that the used 1-station technique measured long upstream, degraded river reaches in addition to the river reaches of interest, and that the presented metabolic rates (measured with the 1-station method at the end of each experimental reach) and their successive increase have therefore to be considered as qualitative indicators of metabolism increase due to river restoration, rather than as the exact rates in the experimental reaches.

In response to the reviewers' concerns, we additionally calculated the metabolic rates of the combined reach R1+R2 with the 2-station method, and obtained metabolic rates that can be directly compared to metabolic rates of the upstream, degraded river (measured at station D with the 1-station open channel method). Results obtained with the 1-station and the 2-station method often agree well (e.g., Bernot et al., 2010; Beaulieu et al., 2013). Thus, we quantitatively supported our previous qualitative findings by estimating metabolism with the 2-station method for the combined restored reach R1+R2. We would like to stress that the good agreement of results of the 1-station and the 2-station method in restored reaches, i.e. that both clearly suggested metabolism increases due to restoration, may be an important finding for agency efforts to monitor restoration outcome, because the 1-station method may be more practical for routine measurements, while the 2-station technique is often considered a research method that is too complex for such purposes. Therefore, we believe that it is important to show and compare results from both techniques in our study.

COMMENT

Time series analyses could be a more powerful way quantify differing/strengths of controls on metabolism in R vs D reaches during the 50-day deployments. A more sophisticated analysis would enhance the contribution of the paper beyond means/ranges of GPP, ER, NEP. See Roley et al 2014 Freshwater Science for an example of this and a citation of general interest. If not used here, this is at least worth a mention for future research avenues.

RESPONSE

We changed our statistical approach and now use an autoregressive approach to address the autocorrelation issue of time-series data (see response to reviewer 1 for a more detailed description). However, this new approach only resulted in minor changes in results.

COMMENT

The importance of autochthonous production for ecosystem functioning” (19-20) is a very context-dependent statement that should be expressed with caution. What does an increase in GPP mean for ecosystem health? We see this response in the R2 reach (but D was 2nd highest in macrophytes, not R1?), and higher GPP is sometimes used as a sign of ecosystem degradation: excess primary production in response to nutrient loading. Units of N are in mg, so there may be environmental issues requiring mitigation beyond physical restoration by widening river channels. Without "pre" data for R reaches, one could argue that the restoration project provided more light + warmer temperatures needed for enhancement of macrophytes beyond “natural” conditions.

RESPONSE

We express increased abundance of macrophytes as positive effect of restoration (see Lorenz et al. 2012 J. Appl. Ecol.) rather than using it as indicator for high nutrient load and eutrophication. Restoration aimed to establish near-natural hydromorphology and biota. Thus, increased occurrence of macrophytes is positive effect in terms of near-natural state of the investigated river. See also response to comment of reviewer 1: We agree and discussed this issue in more detail in the revised paper. In the present case, there are no point or diffuse sources that lead to eutrophication effects in this river section. Thus, metabolic responses should be solely due to river restoration, i.e. wider channels (-> more light availability), shallower channels (-> better habitat for macrophytes), and lower current velocities (-> less hydraulic stress) as also discussed in lines 70 of the original manuscript. In R1 other autotrophs (e.g., periphyton) which have not been subject to mapping may have stimulated metabolism.

COMMENT

L2 - No comma needed after “Both”

RESPONSE

We agree and corrected this in the revised paper.

COMMENT

L - 49-50 – Should include a “but see: :” citation here to acknowledge that there have indeed been several previous studies even if this issue is not well-studied or settled.

RESPONSE

We have added this to lines 53ff of the original manuscript.

COMMENT

L - 53 – Delete “only”

RESPONSE

We corrected this in the revised paper.

COMMENT

L - 109 – It would be useful to give time frame of/since restoration here, not only in supplement.

RESPONSE

We agree and added this information in the next paragraph of the revised paper. Please see also response to reviewer 3.

COMMENT

L - 130 – What about water chemistry? Any differences among reaches? If restoration is indeed altering nutrient retention or removal, that should be reflected in downstream concentrations.

RESPONSE

It may well be possible that changes nutrient concentrations are measurable along the >2 km of restored river. However, we did not measure nutrient concentrations along the studied stream section, and therefore cannot comment on that.

COMMENT

L - 183-4 – Vague RE: which methods as written. Why not restate and give equations for this, k, and base metabolism calculation to allow readers to better assess the methods within the manuscript itself?

RESPONSE

We agree with the reviewer that it is interesting to have the mentioned equations and added them to the manuscript.

COMMENT

L - 225 – Good to see that the authors will update their statistical analyses in a revised manuscript.

RESPONSE

The detailed results from these analyses are in our response to reviewer 1.

COMMENT

L - 227 – Data from flood events are one of the most exciting things we can learn about from longer time series. I urge the authors not to exclude them from their analyses.

RESPONSE

We agree that floods and storms are an important part of environmental variability. However, GPP was not detectable during storm events, and we cannot be sure whether GPP was really zero or very low, or whether high flows may have prevented the detection of GPP. As reviewer 1 also stated, this often occurs with high stream discharge events. Thus, we show the data and discuss them in terms of environmental variability, but believe that it is more adequate not to analyze flood data statistically in terms of restoration effect.

COMMENT

L - 273 – “returned”

RESPONSE

We agree and corrected this in the revised paper.

COMMENT

L - 347 – Give some numbers to support this comparison in the main text. Fine to keep the citations/table in supplement.

RESPONSE

We agree and added more detailed information in the discussion.

COMMENT

L - 369 – “near-natural” is a very vague description and does not seem to be supported with data.

RESPONSE

We removed the term „near-natural“ conditions (“Thus, the restoration of short river reaches may have positive effects...”).

COMMENT

L - 380 – “as a functional indicator”.

RESPONSE

We agree and corrected this in the revised paper.

COMMENT

Table 2 – Check units. Superscripts for m didn’t appear in my version of the text.

RESPONSE

In our version of the manuscript superscripts are correctly represented. We confirmed this in the final version.

COMMENT

Fig 2 – Needed? There are many figures, and I didn’t feel that this was needed for main text. Supplemental figures are nice.

RESPONSE

We believe that these figures are important to understand our rationale. Moreover, as Biogeosciences is an online journal without figure limits, we thought that this would not be a problem.

COMMENT

App S5 – Possible to include Q for context? See also Genzoli & Hall 2016 FWS, Davis et al 2012 RRA, Dodds et al. 2013 FWS, Hall et al 2015 L&O.

RESPONSE

Yes, we included Q in spreadsheet (a) “river characteristics” of Appendix 5.

Detailed response to reviewer 3

COMMENT

This manuscript examines the response of ecosystem metabolism to river restoration by comparing ecosystem metabolism among three river reaches of a mid-size river: a degraded (unrestored) reach (D), a moderately restored (R1), and a substantially restored reach (R2). The use of ecosystem metabolism to determine the effects of river restoration is fairly novel. In that sense, the manuscript represents a relevant contribution to the challenge of incorporating measures of ecosystem functioning to river monitoring, and to river restoration in particular. The manuscript is well structured and written. In general, the results are clearly and transparently exposed, limitations indicated, and details nicely presented in the appendixes. My main concern with this manuscript relies on the fact the sampling design of this case study may not be the most appropriate for correctly answering the important question of whether river restoration caused a significant change in ecosystem metabolism. Ecosystem metabolism was measured in only one river, only after river restoration, and only during a certain period of the year (summer). Ideally, such a question should have been addressed by measuring in several rivers, before and after restoration (BACI design), and considering several periods of the year. None of these criteria is fulfilled, and therefore, the strength of the results and its potential extrapolation to more general responses are limited. This should be at least more explicitly acknowledged in a revised version of the manuscript.

RESPONSE

The comparison of restored with upstream degraded “control” sections (space-for-time substitution) is commonly used to quantify restoration effects as data on pre-restoration are rare (e.g., Hering et al. 2015 J. Appl. Ecol., Jähnig et al. 2011 J. Appl. Ecol.). Time of measurements is in accordance with the WFD compliant sampling period for structural measures such as macroinvertebrates and macrophytes. Consequently, our results can be linked to these measures (see lines 315-318). The measurements are extensive and time consuming and it was not the aim of our paper to replicate measurements in several rivers – this would have required a much simpler method, thus gaining limited insights into the underlying mechanisms. We would like to stress that our manuscript is the first measuring metabolic changes of medium-sized rivers following restoration. The lack of available data - especially for mid-sized and larger rivers - is discussed in lines 351-356 of the original manuscript.

COMMENT

I agree with the comments that have arisen in the open discussion regarding the use of the 1-station method. As indicated in those comments and responses, the authors should incorporate the 2-station method for the restored reaches (R1 + R2) to make

their statements more robust. These limitations in the metabolism estimations together with the issue in the general sampling design (previous paragraph) and the statistically significant but relatively minor changes in metabolic fluxes in restored relative to degraded reaches, makes the conclusions of a clear effect of the restoration on ecosystem metabolism not as clear as pointed out by the authors.

RESPONSE

Please see our response to reviewer 1. We do not consider significant GPP increases from ≈ 5 to ≈ 7 g DO m⁻² d⁻¹ and significant NEP increases from ≈ -2 to ≈ 0 g DO m⁻² d⁻¹ as minor changes from an ecosystem perspective.

COMMENT

I also think that the last part of the discussion could be greatly improved by making more explicit recommendations and by being more convincing about the advantages of incorporating metabolism and other functional measures to river monitoring.

RESPONSE

We agree with the reviewer that advantages of functional indicators for river monitoring are manifold and should be mentioned in studies, which are using functional measures in applied river research. However, we feel that this topic - and ecosystem metabolism in particular - has been widely discussed within the literature (see also references presented in line 382 of the original manuscript) and that a summary of the benefits of metabolism as a functional indicator is more appropriate as presented in lines 380 - 387 of the original manuscript. We think that a more extensive description would make the manuscript lengthier without giving new information.

COMMENT

L - 17-18: Unclear sentence. Rephrase.

RESPONSE

We changed the sentence as follows: "Restoration increased autotrophic processes, as indicated by higher GPP:ER rates measured at restored reaches".

COMMENT

L - 23-24: Any hints that this is occurring at the study site?

RESPONSE

"High rates of metabolism and the occurrence of dense macrophyte stands may increase the assimilation of dissolved nutrients and the sedimentation of particulate nutrients, thereby positively affecting water quality." – This is our interpretation of possible consequences of the observed high metabolism rates, although we did not measure nutrients permanently. To highlight the speculative nature of this sentence we use the word "may".

COMMENT

L - 61-64: "natural changes" and "land-use change" are confusingly used in this sentence.

RESPONSE

We think the difference is clearly described by giving examples in the original manuscript (see lines 62 and 64). Natural changes refer to floods and droughts (e.g., Uehlinger, 2000) and land-use change refers to differences between pristine and agricultural streams (e.g., Gücker et al., 2009; Silva-Junior et al., 2014).

COMMENT

L - 79: Any reference?

RESPONSE

“Moreover, the reconnection of rivers with their floodplains by creating shallower river profiles and removing bank fixations may enhance inundation frequency, and hence resource transfers from land to water” - This is our interpretation of possible consequences of the hydromorphological restoration (reconnection of river and floodplain by creating shallower river profiles and removing bank fixations) although we are not aware of a reference. To highlight the speculative nature of this sentence we use the word “may”.

COMMENT

L - 89: Do you mean “contiguous” instead of “continuous”?

RESPONSE

We agree and corrected this in the revised paper.

COMMENT

L - 91: Here I miss some predictions regarding the expected differences between R1 and R2. It seems important to justify the examination of two levels of restoration.

RESPONSE

We expected (i) hydromorphological river characteristics, i.e. habitat composition and hydrodynamics, to change following restoration, with the magnitude of change depending on restoration effort (e.g. width and diversity of the river channel, and abundance of primary producers, as well as sizes and locations of transient storage zones in the two restored river reaches compared to the degraded reach).

COMMENT

L - 110-115: I suggest including here information on when the restoration was done. It seems important to know how much time has passed from restoration to measurements.

RESPONSE

We agree and added this information in the revised paper. See also response to reviewer 2.

COMMENT

L - 138: Unclear at which flow conditions these measures were done.

RESPONSE

We agree and added this information in the revised paper.

COMMENT

L - 195: It seems odds that some measures were done in 2013 and others in 2014. How may this have influenced your results?

RESPONSE

The purpose of our study was to quantify structural changes following restoration at the reach scale and examine the related effects on metabolism. Considering that there were no major meteorological differences between these years, that structural differences between D, R1 and R2 (effort) were very similar between years, and that measurements were performed in the same season at similar discharge conditions, we believe that interannual variability is a minor confounding factor in our study.

Detailed response to Robert Pennington

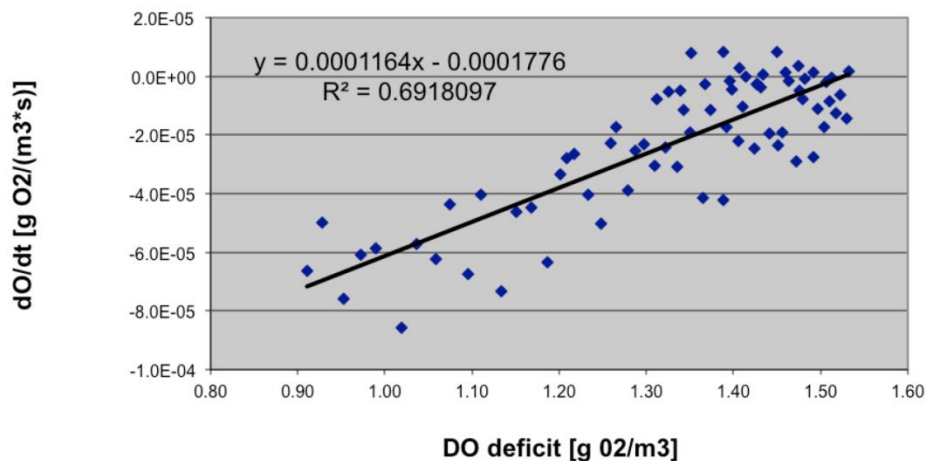
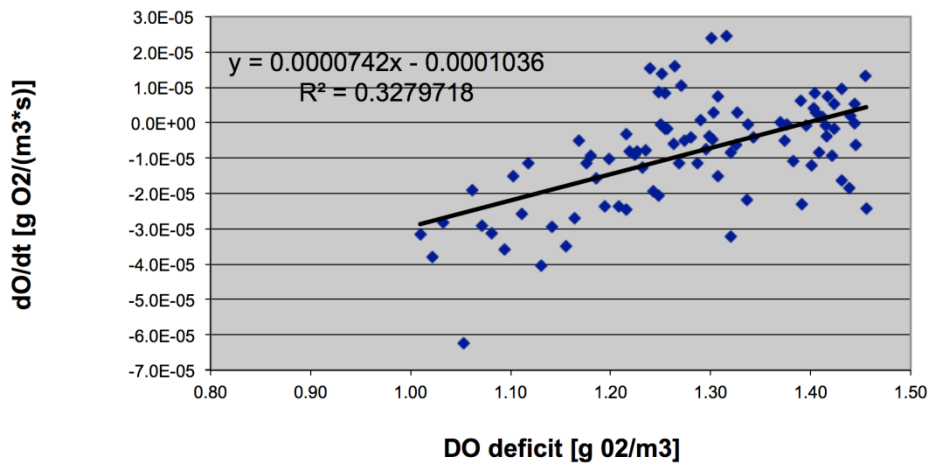
We agree with you that the estimation of the reaeration rate is probably the most critical step in the estimation of open-channel metabolism, and deserves further discussion. In order to present a short and concise paper, we tried not to overburden our paper with methodological details, but we are happy to discuss your suggestion (see point-by-point response below) and to add this information to our paper.

COMMENT:

One point I would like to see more complete discussion of is how the aeration rates were calculated. It would be nice to see a plot of $dDO/dt = ER + K(DO_deficit)$ for a few nights that were considered significant.

RESPONSE:

The nighttime regression procedure is a rather standard technique, widely used in open-channel metabolism studies (e.g., Young & Huryn, *Ecol. Appl.* 9: 1359-1376). This technique is particularly suitable for rivers with considerable GPP that causes considerable daytime DO increases, and stable nighttime DO plateau. It is suitable for streams with $K_{oxy} < 0.5 \text{ m h}^{-1}$, such as the investigated river (see Demars et al., *Limnol. Oceanogr.: Methods* 13, 356–374). Below we show two plots (the better fit with $p < 0.01$ and $R^2 = 0.69$ and the worse one with $p < 0.05$ and $R^2 = 0.33$) from the first two sampling weeks at station R2 to give an impression about the variability in the encountered nighttime patterns. The regression slope corresponds to the K_{oxy} (in $1/s$) in these representations. In our study, we only considered significant nighttime regressions ($p < 0.05$).



COMMENT:

Adding confusion to the aeration rate discussion is the reported units of appendix S2 in g O₂/(m³*s). Is this a typo? Why not use the same units as the text in 1/day (line 215)?

RESPONSE:

Yes, this is a typo. The y-axis units for plots in S2 should be 1/day. Thank you!

COMMENT:

Also, given the relatively low aeration rate and high productivity, why not use a parameter fitting approach to model metabolism and aeration rate? It seems a more robust approach than the nighttime regression method.

RESPONSE:

Inverse modeling approaches, such as BaMM (Holtgrieve et al., Limnol. Oceanogr., 55: 1047–1063) and BASE (Grace et al., Limnol. Oceanogr.: Methods 13: 103–114) require PAR irradiance input data for the simultaneous estimation of reaeration and metabolism. Unfortunately, we do not have adequate PAR data available for the studied river. Whether inverse modeling yields more reliable reaeration estimates than the nighttime regression method (and under which circumstances?) has not been

tested in the literature to our knowledge. In our opinion, the best approach would be to obtain reaeration rates from different methods (gas tracer experiments, nighttime regression, inverse modeling) in future studies. However, we believe that our reaeration estimates (ranging from about 6/d to 16/d across 3 sampling stations and 50 sampling days) are realistic estimates for the investigated river.

COMMENT:

Your study finds very high GPP and ER estimates compared to others. This could be a direct result of an overestimate of the aeration rate. I find that a more robust method, or convincing discussion of the aeration rate, is necessary to support these findings. If an entirely new analysis applying a parameter fitting model is perhaps infeasible, empirical values from hydrodynamics and morphology would be helpful.

RESPONSE:

To our knowledge, the nighttime regression technique has not been shown to be less robust than other methods in the literature. We see the available methods rather as complementary techniques. For example, gas tracer approaches are considered a direct and reliable method to measure reaeration, but represent only a temporal snapshot, and can yield unreliable results if conservative tracer dilution is not adequately quantified. The nighttime regression method estimates reaeration over a longer time scale and has been found to work well in less turbulent, productive streams, but is often not very useful in turbulent, shaded headwater streams. Inverse modeling may be the most integrative approach, but measured diel DO and temperature data can sometimes be uninformative and prior information (such as field tracer studies) is needed (see Holtgrieve et al., *Limnol. Oceanogr.*: Methods 14: 110–113). However, if not established for a specific sampling site, empirical equations may be the most uncertain option to estimate reaeration, as results of different empirical equations vary widely (at least 40-125% error in estimates, see Demars et al., *Limnol. Oceanogr.*: Methods 13, 356–374). Considering two contrasting hydromorphological parameter sets from our study (20 June 2014, low discharge, 9.1 m³/s; and 12 July 2014, high discharge 32.7 m³/s), reaeration rates estimated by the two most commonly used empirical equations indeed varied considerably, but yielded consistently higher reaeration rates than our nighttime regressions for these days (Table 1).

Table 1: Comparison of reaeration coefficients estimated in this study with those estimates from empirical models for the same reaches.

Reach	Owens 1974 (surface renewal model) K_{oxy}^{20} (/d)	Tsivoglou & Neil 1976 (energy dissipation model) K_{oxy}^{20} (/d)	Nighttime regression K_{oxy}^{20} (/d)
Low Q			
D	29	42	11
R1	51	36	9
R2	17	19	7
High Q			
D	48	127	11
R1	30	73	9
R2	15	45	9

Therefore, we do not think that overestimations of reaeration rates explain the high metabolic rates in our study. As discussed in the paper, we measured river metabolism during the peak of macrophyte growth in summer. This may explain the high rates of GPP and R in our study, and consequently, lower rates may be expected in other seasons.

COMMENT:

Also, would it be possible to apply the two-station method if you combined reaches? My rough calculations indicate a reach length of about 3000 meters would be appropriate from your hydraulics and aeration rate.

RESPONSE:

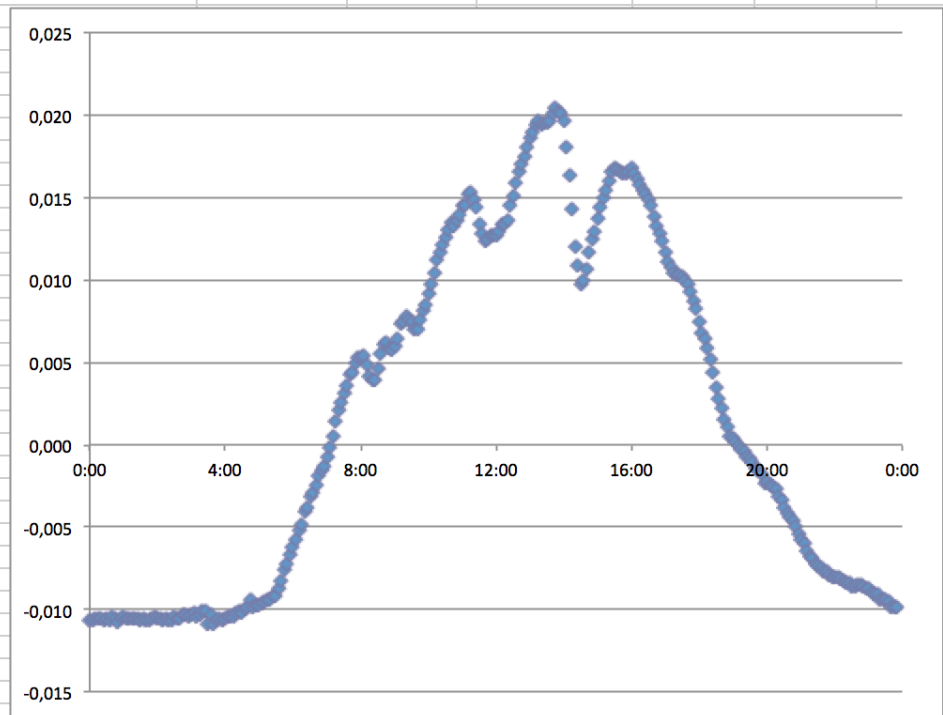
According to Demars et al. (Limnol. Oceanogr.: Methods 13, 356–374), the 2-station method is applicable to reach lengths 0.4 v/k to 1.0 v/k. In our reach system, this range corresponds to:

D	3283 - 8280 m
R1	2765 - 6912 m
R2	1624 - 4061 m

R1+R2	2199 - 5497 m
all 4 reaches	2482 - 6205 m

Thus, we cannot evaluate separate reaches in our study, but are at the lower end of this range (slightly above 0.4 v/k) for all 4 reaches combined and for R1+R2, and can therefore estimate 2-station metabolism for these combinations. Combining all reaches is of limited use for the aim of our paper to evaluate restoration effects, but combining restored reaches R1 and R2 indeed provides useful information. In response to your comment, we evaluated 2-station metabolism for R1+R2. Below please find the results of the application of the 2-station method for the first sampling day (June 20, 2014). Rates of GPP were only slightly higher for the combined reaches R1+R2 using the 2-station method than for the longer reach evaluated by the 1-station method at station R2 (that included a longer unrestored upstream section), i.e. 11.4 vs. 8.8 g DO m⁻² d⁻¹. Rates of R, were only slightly lower with the 2-station method, i.e. 9.6 vs. 11.2 g DO m⁻² d⁻¹. These results further support our hypothesis of increased river metabolism due to restoration. In the revised manuscript, we used the 2-station method systematically for the combined reaches R1+R2 for all sampling days.

Ecosystem Respiration	9.59	g O ₂ /m ² d			
Gross Primary Production	11.36	g O ₂ /m ² d			
Net Ecosystem Production	1.76	g O ₂ /m ² d			
P:R	1.18				



(values on y axis in g DO m-2 d-1 /1000)

REFERENCES:

- Demars et al., Limnol. Oceanogr.: Methods 13, 356–374.
Holtgrieve et al., Limnol. Oceanogr., 55: 1047–1063.
Holtgrieve et al., Limnol. Oceanogr.: Methods 14: 110–113.
Grace et al., Limnol. Oceanogr.: Methods 13: 103–114.

Hydromorphological restoration stimulates river ecosystem metabolism

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Keywords: river restoration, ecosystem function, functional indicators, gross primary production, ecosystem respiration

Abstract

Both ecosystem structure and functioning determine ecosystem status and are important for the provision of goods and services to society. However, there is a paucity of research that couples functional measures with assessments of ecosystem structure. In mid-sized and large rivers, effects of restoration on key ecosystem processes, such as ecosystem metabolism, have rarely been addressed and remain poorly understood. We compared three reaches of the third-order, gravel-bed river Ruhr in Germany: two reaches restored with moderate (R1) and substantial effort (R2) and one upstream degraded reach (D). Hydromorphology, habitat composition and hydrodynamics were assessed. We estimated gross primary production (GPP) and ecosystem respiration (ER) using the one-station open-channel diel dissolved oxygen change method over a 50-day period at the end of each reach. Moreover, we estimated metabolic rates of the combined restored reaches (R1+R2) using the two-station open-channel method. Values for hydromorphological variables increased with restoration intensity ($D < R1 < R2$). Restored reaches had lower current velocity, higher longitudinal dispersion and larger transient storage zones. However, fractions of median travel time due to transient storage were highest in R1 and lowest in R2, with intermediate values in D. The share of macrophyte cover of total wetted area was highest in R2 and lowest in R1, with intermediate values in D. Station R2 had higher average GPP and ER than R1 and D. The combined restored reaches R1+R2 also exhibited higher GPP and ER than the degraded upstream river (station D). Restoration increased river autotrophy, as indicated by elevated GPP:ER, and NEP of restored reaches. Temporal patterns of ER closely mirrored those of GPP, pointing to the importance of autochthonous production for ecosystem functioning. In conclusion, high reach-scale restoration effort had considerable effects on river hydrodynamics and ecosystem functioning, which were mainly related to massive stands of macrophytes. High rates of metabolism and the occurrence of dense macrophyte stands may increase the assimilation of dissolved nutrients and the sedimentation of particulate nutrients, thereby positively affecting water quality.

1. Introduction

River restoration is a pivotal element of catchment management to counteract anthropogenic degradation and depletion of river health and water resources, and to increase overall biodiversity and ecosystem services provisioning (Bernhardt et al., 2005; Strayer and Dudgeon, 2010). Based on legislative frameworks such as the EU Water Framework Directive (WFD) and the Clean Water Act in the United States, large investments have been made to restore rivers. In Europe, degraded river hydromorphology is considered one of the central impacts to the ecological status of rivers (EEA, 2012; Hering et al., 2015). For example, the German national river habitat survey, which evaluates hydromorphological parameters for 100 m river sections, concluded that the majority of German rivers is severely degraded (Gellert et al., 2014; UBA, 2013). As the river biota depend on suited habitats (Beisel et al., 2000; Schröder et al., 2013), about 85% of German rivers failed to reach the ‘good ecological status’ demanded by the WFD (EEA, 2012). Accordingly, most restoration projects target the hydromorphological improvement of rivers. The majority of restoration measures is implemented at the reach-scale, covering short river stretches typically of one km or less (Bernhardt et al., 2005; Palmer et al., 2014). A variety of reach-scale measures have been implemented (Lorenz et al., 2012): for instance, restoration activities along mountainous rivers in central Europe mainly targeted re-braiding and widening of streams, leading to greater habitat and hydrodynamic heterogeneity (Jähnig et al., 2009; Poppe et al., 2016). In combination with other characteristics of the river ecosystem – e.g., light, organic matter, nutrient availability, temperature, hydrologic and disturbance regimes – such hydromorphological changes likely affect biological community composition and ecosystem functioning, including ecosystem metabolism (Bernot et al., 2010; Tank et al., 2010).

The assessment of restoration effects has mainly focused on responses of aquatic organisms, such as fish (e.g., Roni et al., 2008; Haase et al., 2013; Schmutz et al., 2016), benthic invertebrates (e.g., Jähnig et al., 2010; Friberg et al., 2014; Verdonschot et al., 2016), and macrophytes (e.g., Lorenz et al., 2012; Ecke et al., 2016). Recently, increasing attention has also been given to the response of floodplain organisms (e.g., Hering et al., 2015; Göthe et al., 2016; Januschke and Verdonschot, 2016), while functional characteristics, i.e. the rates and patterns of ecosystem processes, have rarely been

addressed. Ecosystem functions are life-supporting processes that are directly linked to ecosystem services, i.e. the benefits people obtain from the environment (Palmer and Filoso, 2009). Thus, an emerging interest in river restoration research is to incorporate the recovery of ecological functioning (Palmer et al., 2014). However, few studies have considered the response of river ecosystem functioning and functional metrics to restoration (e.g., Lepori et al., 2005; Bunn et al., 2010; Kupilas et al., 2016). Consequently, the effects of restoration on key ecosystem processes remain poorly understood.

Ecosystem metabolism, i.e. the combination of gross primary production (GPP) and ecosystem respiration (ER), is a fundamental ecosystem process in rivers. Ecosystem metabolism is a measure of the production and use of organic matter within a river reach by all biota. Therefore, it provides key information about a river's trophic and energetic base (relative contribution of allochthonous and autochthonous carbon) (Young et al., 2008; Tank et al., 2010; Beaulieu et al., 2013). The majority of stream ecosystem metabolism work has investigated natural changes, such as effects of floods and droughts (e.g., Uehlinger, 2000), seasonal or inter-annual changes (e.g., Uehlinger, 2006; Beaulieu et al., 2013), interbiome differences (e.g., Mulholland et al., 2001), or land-use change (e.g., Gücker et al., 2009; Silva-Junior et al., 2014). The majority of these studies have focused on smaller streams, while only few studies measured metabolism of larger streams and rivers (e.g., Uehlinger, 2006; Dodds et al., 2012; Hall et al., 2015; Hall et al., 2016). The response of stream metabolism to hydromorphological changes, e.g. through river widening, is almost unknown, especially for larger rivers (but see Colangelo, 2007).

The widening of the riverbed enhances habitat complexity and diversity of the river channel and the riparian zone (Jähnig et al., 2010; Januschke et al., 2014; Poppe et al., 2016). Moreover, channel widening also favors macrophytes and other autotrophs through the creation of shallow, slow flowing areas and backwaters (Lorenz et al., 2012). Further, it increases light availability and water temperature, which have been identified as major factors controlling river metabolism, especially primary production (Uehlinger, 2006; Bernot et al., 2010; Tank et al., 2010). Accordingly, these changes potentially lead to enhanced in-stream autotrophic processes.

Restoration also increases the retention of allochthonous organic matter (Lepori et al., 2005; Lepori et al., 2006; Flores et al., 2011). Moreover, the reconnection of rivers with their floodplains by creating shallower river profiles and removing bank fixations may enhance inundation frequency, and hence resource transfers from land to water. In combination, these changes can favor heterotrophic activity in the river. Restoration also affects hydrodynamics and surface water-ground water interactions of streams (Becker et al., 2013): for instance, widening of the stream channel reduces flow velocity and the creation of backwaters and pools possibly leads to changes in the size and location of transient storage zones (Becker et al., 2013). Increases in transient storage zones potentially enhance ER (Fellows et al., 2001) and nutrient processing (Valett et al., 1996; Gücker and Boëchat, 2004).

The objective of this study was to quantify reach-scale restoration effects on hydromorphology, habitat composition and hydrodynamics, as factors potentially affecting river ecosystem function, by comparing three contiguous stream reaches (two restored and one upstream non-restored reach) of a mid-sized mountain river in Germany and to determine the corresponding responses of river metabolism. We expected (i) hydromorphological river characteristics, i.e. habitat composition and hydrodynamics, to change following restoration, with the magnitude of change depending on restoration effort (e.g. width and diversity of the river channel, and abundance of primary producers, as well as sizes and locations of transient storage zones in the two restored river reaches compared to the degraded reach). Further, we expected (ii) ecosystem metabolism to respond with increased metabolic rates, i.e. enhanced GPP and ER, mainly as a result of increased abundances of primary producers.

2. Methods

2.1 Study site

This study was conducted in the upper River Ruhr (Federal State of North Rhine-Westphalia, Germany, Fig. 1, Table 1) a tributary to the Rhine. The third-order Ruhr is a mid-sized mountain river with gravel and cobbles as bed sediments. The catchment area upstream of the study site is 1060 km², about 64 % of which is forested, 28 % is arable land and pasture, and 8 % is urban area (located

mainly in the floodplains). The study site is at an altitude of 153 m a.s.l. and the mean annual discharge was $21.3 \text{ m}^3 \text{ s}^{-1}$ between 2004 and 2009. The Ruhr is draining one of the most densely populated areas of Europe; however, population density of the upstream catchment area is low ($135.3 \text{ inhabitants/km}^2$ upstream of the study site). Due to manifold uses, the river's hydromorphology has been largely modified by impoundments, residual flow sections, bank fixation as well as industrial and residential areas in the floodplain. More recently, the hydromorphology of several river sections has been restored.

Restoration aimed to establish near-natural hydromorphology and biota. Restoration measures were implemented between 2007 and 2009 and included 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. Moreover, the physical stream quality was enhanced by generating secondary channels and islands, adding instream structures, such as woody debris, and creating shallow habitats providing more space for autotrophs (see Appendix S1 in Supporting Information).

We separated the restored reach into two reaches of approximately similar lengths (1210 and 1120 m) with obvious differences in morphological stream characteristics due to differing restoration effort (R1: moderate restoration effort and R2: high restoration effort). Briefly, in R2 a larger amount of soil was removed and the costs for the implementation of measures were higher than in R1 (see Appendix S1). In R2 the bank fixation was removed at both shorelines and the river was substantially widened and secondary channels and islands were created, while the removal of bank fixation and widening in R1 mainly focused on one side due to constraints posed by a nearby railroad (see Appendix S1). The restored reaches were compared to a degraded "control-section" of 850 m length located upstream of the restored reaches (D). The degraded reach was characteristic for the channelized state of the River Ruhr upstream of the restoration site, and reflected the conditions of the restored sections prior to restoration: The reach was a monotonous, channelized and narrowed river section with fixed banks and no instream structures. A 650 m-long river section separating the degraded from the restored river reach was excluded from the investigations, as its hydromorphology was deviating due to

132 constructions for canoeing and a bridge. As the three sections were neighboring each other, differences
133 in altitude, slope, discharge and catchment land cover between reaches were negligible.

134 2.2 *Hydromorphology and habitat composition*

135 Physical stream quality was quantified from aerial photos. High-resolution photos of the restored
136 reaches were taken in summer 2013 using a Falcon 8 drone (AscTec, Germany). Aerial photos of the
137 degraded reach from the same year at similar discharge conditions were provided by the Ministry for
138 Climate Protection, Environment, Agriculture, Conservation and Consumer Protection of the State of
139 North Rhine-Westphalia. Photos were analyzed in a geographical information system (ArcGIS 10.2,
140 ESRI). For each reach, we measured the width of the wetted channel every 20 m along cross-sectional
141 transects at low flow conditions and calculated mean width and its variation (reach D: n = 42, R1: n =
142 59, R2: n = 54). For each reach, we recorded thalweg lengths, the area of the wetted stream channel,
143 the floodplain area (defined as bank-full cross-sectional area), and the area covered by islands, woody
144 debris, and aquatic macrophyte stands (Fig. 2). Subsequently, the share of macrophyte stands of the
145 total wetted area was calculated for each reach. Additionally, macrophytes were surveyed according to
146 the German standard method (Schaumburg et al., 2005a; b) in summer 2013. A 100 m reach was
147 investigated by wading through the river in transects every 10 m, and walking along the riverbank
148 (Lorenz et al., 2012). All macrophyte species were recorded and species abundance was estimated
149 following a 5-point scale developed by Kohler (1978), ranging from “1 = very rare” to “5 = abundant,
150 predominant”. The empirical relationship between the values of the 5-point Kohler scale (x) and the
151 actual surface cover of macrophytes (y) is given by the function $y = x^3$ (Kohler and Janauer, 1997;
152 Schaumburg et al., 2004). Using this relationship, we x^3 -transformed the values of the Kohler scale
153 into quantitative estimates of macrophyte cover for the studied 100 m reaches.

154 2.3 *Hydrodynamics*

155 Stream hydrodynamics were estimated using a conservative tracer addition experiment with the
156 fluorescent dye Amidorhodamine G. Across the river width, we injected the dissolved dye in a
157 distance sufficiently upstream to the first study reach to guarantee complete lateral mixing at the first

sampling station. Breakthrough curves of the tracer were continuously measured in the main current at the upstream and downstream ends of all three reaches (Fig. 1). Concentration of dye was recorded at a resolution of 10 s at the most upstream and downstream sampling stations using field fluorometers (GGUN-FL24 and GGUN-FL30, Albillia, Switzerland). At the other sampling stations (start and end of each investigated river reach) water samples were taken manually at 2 min intervals. The samples were stored dark and cold in the field and subsequently transported to the hydrogeochemical laboratory of the Ruhr University Bochum. Amidorhodamine G concentrations of water samples were measured with a fluorescence spectrometer (Perkin Elmer LS 45; detection limit of 0.1 ppb) and standard calibration curves prepared from the tracer and river water. Field fluorometers were calibrated prior to experiments with the same standard calibration procedure.

Subsequently, we used the one-dimensional solute transport model OTIS-P (Runkel, 1998) to estimate parameters of river hydrodynamics for each reach from the breakthrough curves: advective velocity, longitudinal dispersion, stream channel and storage zone cross-sectional areas, and storage rate. We further calculated fractions of median travel time due to transient storage (F_{med}^{200}) based on the hydrodynamic variables obtained from transport modeling (Runkel, 2002). Additionally, Damköhler numbers were estimated for each reach (Harvey and Wagner, 2000).

2.4 Discharge

Discharge data were provided by the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Production, Germany (Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen) for a gauging station situated at the downstream end of the study site. At this station, discharge was constantly recorded at 5-min intervals.

2.5 Ecosystem metabolism

We estimated river dissolved O₂ (DO) metabolism using the ‘open-channel one-station and two-station diel DO change techniques’ (Odum, 1956; Marzolf et al., 1994; Young and Huryn, 1998; Roberts et al., 2007). We initially chose the one-station method to estimate metabolic rates at the downstream end of each reach (stations D, R1, and R2), as the individual studied reaches were too short for a reliable

estimation of ecosystem metabolism with the two-station technique, due to high current velocities and low reaeration rates. According to Demars et al. (2015), the two-station method is applicable to reach lengths $0.4 v/k$ to $1.0 v/k$. For our reaches of the Ruhr, this range corresponds to 3283 - 8280 m for reach D, 2765 - 6912 m for reach R1, 1624 - 4061 m for reach R2, and 2199 - 5497 m for the combined reach R1+R2. Thus, the quantification of metabolism using the two-station method was only possible for the combined reach R1+R2 with a reach length of 2330 m.

Reach lengths influencing the one-station diel dissolved O_2 change technique in our study were typically much longer than the experimental reaches, due to high current velocities and low reaeration (>10 km; estimated according to Chapra and Di Torro, 1991). Following methods in Demars et al. (2015), metabolism estimates at the downstream sampling station R2 were only to 35% influenced by the restored river sections, but to 65% by upstream degraded river sections. Accordingly, differences in metabolic rates among sampling stations at the end of restored and impacted experimental reaches as estimated in our study should be viewed as qualitative indicators of restoration effects, rather than measured metabolic rates of the experimental reaches. To quantitatively support our qualitative findings, we additionally used the two-station method for the combined restored river reach R1+R2, which was long enough for the application of the two-station open-channel method. The selected methods are based on the assumption that changes in DO within a parcel of water traveling downstream can be attributed to metabolism (photosynthesis and respiration) and to gas exchange between water and atmosphere, given that no significant groundwater dilution of river water occurs along the studied river:

$$dDO/dt = GPP - ER - (K_{oxy} * D)$$

where dDO/dt is the change in dissolved oxygen concentration ($mg\ O_2\ L^{-1}\ s^{-1}$), GPP is the gross primary production ($mg\ O_2\ L^{-1}\ s^{-1}$), ER is the ecosystem respiration ($mg\ O_2\ L^{-1}\ s^{-1}$), K_{oxy} is the reaeration coefficient (s^{-1}), and D is the oxygen deficit or surplus in the river (i.e., the difference between the measured oxygen concentration and the value at saturation; $mg\ O_2\ L^{-1}$). The change in DO was estimated as the difference between consecutive 5-min readings of the same probe for the one

station method and as the difference between upstream (top of reach R1) and downstream probes (end of reach R2) for the two station method (Roberts et al., 2007; Beaulieu et al., 2013).

In two consecutive field campaigns in summer 2014, DO and water temperature were continuously measured at the downstream ends of the three reaches and at the top of reach R1 at 5-min intervals for 50 days. The DO probes with data loggers (O₂-Log3050-Int data logger Driesen + Kern GmbH, Germany) were installed in the thalweg of the river in the middle of the water column. The DO probes were calibrated in water-saturated air prior to measurements. Additionally, probes were cross-calibrated for one hour at a single sampling station in the river before and after the measurements. We used the data of this comparison to correct for residual differences among probes (Gücker et al., 2009). This procedure assured that differences between probes were only due to differences in DO and water temperatures and not to analytical errors. In previous laboratory tests, the probes showed no drift and were thus not corrected for drift during the measurement campaigns (Almeida et al., 2014).

In parallel to DO and water temperature, atmospheric pressure was recorded (Hobo U20-001-04; Onset Computer Corporation). We used atmospheric pressure and water temperature data to calculate the oxygen saturation. Reaeration coefficients (K_{oxy}^{20} ; standardized for 20°C) were estimated using the nighttime regression approach (Young and Huryn, 1999). For the downstream stations of all three sampling reaches, we calculated reaeration coefficients (K_{oxy}) as the slope of regressions between DO change rates ($d\text{DO}/dt$; $\text{mg O}_2 \text{ L}^{-1} \text{ s}^{-1}$) and DO deficits (D ; $\text{mg O}_2 \text{ L}^{-1}$) at night (night hours were defined as the period 1 h after sunset to 1 h before sunrise):

$$d\text{DO}/dt = K_{\text{oxy}} * D + \text{ER}$$

We only considered significant nighttime regressions ($p < 0.05$). Reaeration coefficients for days without significant regressions were estimated as the average value of the coefficients of the days before and after, as we did not observe K_{oxy}^{20} - discharge relationships in our data (see Appendix S2) that could have been used to estimate K_{oxy}^{20} values for days without reliable estimates. Estimated reaeration coefficients were low and ranged from 5 to 15 d^{-1} in our study (see Appendix S2). Subsequently, we calculated ER and GPP as described in detailed elsewhere (Marzolf et al., 1994;

Young and Huryn, 1998; Roberts et al., 2007) from the recorded nighttime river water DO deficit and the daytime DO production, respectively, corrected for atmospheric reaeration (see Appendix S3). Metabolic rates obtained by this method closely matched those obtained with the estimator of Reichert et al. (2009). Ground water dilution was not detected, i.e. discharge differences among the investigated river reaches were within the ranges of method uncertainty of discharge measurements, and was thus not considered into our estimates. Metabolism measurements from days at which floating macrophytes accumulated around probes and affected DO measurements were eliminated from the dataset.

2.6 Data analysis

We used the ARIMA function in [R] to identify an ARIMA model that best represented all time series (metabolic parameters at stations D, R1, R2, and reach R1+R2), estimated average parameter predictions and 95%-confidence limits for each time series based on these models, and used F-tests to test the hypothesis of differences among time series (compare Roley et al., 2014). Data recorded at the time of flooding events were omitted from analyses, because GPP was not detectable, and we cannot be sure whether GPP was indeed zero or very low, or whether high flows prevented the detection of GPP. Overall, data of $n = 32$ days were used in the analyses. Repeated measures ANOVAs and Tukey's HSD post-hoc tests were used to test for differences in water temperature among river reaches. Conventional one-way ANOVA was used to test for differences in river width, comparing the transect measurements performed in the three river reaches. All statistical analyses were conducted in [R] (R Development Core Team, 2007).

3. Results

3.1 Hydromorphology and habitat composition

Restored river reaches were morphologically more complex and had significantly wider wetted channels (ANOVA and Tukey post-hoc test, $P < 0.05$) and more variable channel width than the degraded reach (Table 2). Furthermore, the restored reaches had larger wetted channel areas, floodplain areas, island areas and patches of woody debris than the degraded river reach (Table 2). The

intensively restored reach R2 showed the highest values for hydromorphological variables (Table 2).
The share of macrophyte cover of total wetted area was also highest in R2.

3.2 Hydrodynamics

The reaches differed in hydrodynamic parameters: The restored reaches had lower flow velocity and higher longitudinal dispersion, cross-sectional areas of the advective channel, and storage zone cross-sectional areas than the degraded reach (Table 2). Storage rate and fractions of median travel time due to transient storage (F_{med}^{200}) was highest in R1 and lowest in R2, with intermediate values for D (Table 2). Damköhler numbers between 0.5 and 5.0 indicated reliable transient storage parameter estimates for the reaches (Harvey and Wagner, 2000; Table 2). Tracer breakthrough curves estimated by transport modelling closely corresponded to measured tracer concentrations (Fig. 3).

3.3 Discharge and water temperature

Mean discharge during the first weeks of measurement was $8.4 \text{ m}^3 \text{ s}^{-1}$. The hydrograph was characterized by a large summer flow peak and two minor peaks during the study period (Fig. 4 a). During the flow peaks discharge rapidly increased 3.5- to 7-fold, relative to the mean flow. Trends in water temperature over time were very similar for the three river reaches and are exemplarily shown for R2 (Fig. 4 b). Overall, restored reaches had higher mean daily water temperatures than the degraded reach, with R2 having higher mean daily water temperatures compared to R1 (repeated measures ANOVA, $P < 0.0001$; and Tukey's HSD post-hoc tests, $P < 0.0005$).

3.4 Ecosystem metabolism

We observed significant effects of reach-scale restoration on metabolic rates estimated at the end of the restored river sections (R1 and R2 compared to D; estimated by the one-station method) and between the upstream degraded river (station D) and the combined restored reaches R1+R2 (estimated with the two-station method). According to the ARIMA function estimates, we found higher river GPP, NEP and GPP:ER at the restored river sections (R1 and R2 versus station D; estimated with the one-station method; Fig. 5). Moreover, GPP, ER, NEP, and GPP:ER were also higher (Fig. 5) in the total restored river reach (R1+R2; estimated with the two-station method) than in the upstream

degraded river (measured at section D with the one-station method). These findings indicate an increase in the river's metabolism following restoration.

The three sampling stations at the downstream ends of the reaches generally exhibited similar metabolism patterns (Fig. 6). Rates of GPP and ER ranged from 2.59 to 13.06 and -4.96 to -17.52 g O₂ m⁻² day⁻¹ at sampling station D, from 2.33 to 12.36 and -4.04 to -14.02 g O₂ m⁻² day⁻¹ at station R1, and from 3.61 to 17.64 and -5.91 to -24.71 g O₂ m⁻² day⁻¹ at station R2. Daily rates of GPP were highest shortly before the main summer flow peak at all sampling stations (Fig. 6 a). GPP was not detectable during the summer flow peaks. ER generally mirrored the GPP patterns, but showed distinct peaks at the beginning of the summer flow peak. ER exceeded GPP during all but one day at R1 and two days at R2. Consequently, NEP (net ecosystem production) was negative during most of the measured period, i.e. reaches were heterotrophic (Fig. 6 b). NEP ranged from -4.61 to -0.47 g O₂ m⁻² day⁻¹ at station D, from -4.29 to 0.22 g O₂ m⁻² day⁻¹ at station R1, and from -8.24 to 0.14 g O₂ m⁻² day⁻¹ at station R2. The average GPP:ER ratio ranged from 0.66 to 0.97 across all sampling stations, also indicating that the Ruhr was moderately heterotrophic. General patterns in daily rates of both GPP and ER also seemed to be influenced by flow peaks. GPP and ER were both suppressed immediately following the flooding events. The ensuing recovery patterns for GPP and ER were similar for all investigated sampling stations: depending on magnitude of flow, GPP and ER were suppressed for several days, but steadily returned to pre-disturbance conditions. The total restored river reach (R1+R2, two-station method) showed temporal metabolism patterns comparable to those estimated at the three sampling stations with the one-station method (Fig. 6). However, NEP of the total restored river reach (R1+R2) was positive and average GPP:ER ratio higher than 1 during most of the sampling period, indicating a slight change in the river's metabolic balance following restoration.

4. Discussion

Restoration of river hydromorphology usually covers short river stretches of less than one km and is expected to increase the river's habitat and hydrodynamic heterogeneity. Together, these changes may stimulate ecosystem metabolism, i.e. whole-stream rates of GPP and ER, as well as affect the river's metabolic balance. Increases in river metabolism, in turn, may result in increased rates of other

ecosystem processes, such as secondary productivity and whole-stream nutrient processing (Fellows et al., 2006; Gücker and Pusch, 2006).

4.1 Hydromorphological characteristics

Recent monitoring and evaluation of restoration projects report positive effects on hydromorphology and habitat composition (Jähnig et al., 2009; Jähnig et al., 2010; Poppe et al., 2016). Similarly, we found greater habitat complexity of restored reaches, as indicated by wider and more diverse river channels. The reach with the highest restoration effort (R2), was characterized by the highest values and heterogeneity of hydromorphological variables; this suggests that restoration effort is indeed crucial for restoration success. According to Lorenz et al. (2012), the success of restoration in mid-sized to larger rivers can also be indicated by increased cover, abundance and diversity of macrophytes as they benefit from more natural and diverse substrate, and the variability in flow. Consequently, the higher share of macrophyte cover of total wetted area in R2 also highlighted the higher morphological quality of this reach.

Moreover, there were no point sources or changes in land use along the studied river section, and therefore, increases in P and N concentrations, and associated eutrophication effects in the studied river section seem unlikely (compare Table 1). Thus, higher macrophyte biomass and metabolic responses are likely to be a result of river restoration, i.e. wider channels increasing light availability, shallower channels providing better habitats for macrophytes, and lower current velocities decreasing hydraulic stress.

Changes in hydromorphology and habitat composition influenced hydrodynamics: we observed lower current velocity, higher longitudinal dispersion and larger transient storage zones in the restored reaches. This corresponds with the larger river width and wetted channel area, and the increased abundance of morphological features such as woody debris, islands and macrophyte patches.

However, F_{med}^{200} , i.e. the relative importance of transient storage for whole-stream hydrodynamics, was highest in R1 and lowest in R2, with intermediate values for D. Accordingly, there appeared to be an inverse relationship between F_{med}^{200} and the share of macrophyte cover of total wetted area, which

was highest in R2 and lowest in R1, with intermediate values in D. These findings suggest that the dense stands of macrophytes in R2 particularly altered stream hydrodynamics: macrophyte patches built large surface transient storage areas and potentially changed the locations of transient storage zones from the hyporheic zone to the surface water column. Macrophyte fields in R2 may have even been so dense that large parts of them were representing hydrodynamic dead zones. A similar effect was found in streams restored by implementing steering structures to enhance stream quality: the restored reaches were dominated by surface transient storage exchange (Becker et al., 2013). Furthermore, the sedimentation of fine sediment within dense macrophyte stands may further decrease exchange with the hyporheic zone.

4.2 Functional characteristics

Metabolism was measured over a 50-day period to obtain representative data, allowing for comparisons among sampling stations. Furthermore, this time series allowed for the analysis of environmental variability, such as flow peaks. The results were obtained for the summer period, i.e. the time of maximum biomass, which is also relevant for the WFD compliant sampling period (e.g., Haase et al., 2004; Schaumburg et al., 2004; EFI+ CONSORTIUM, 2009). Therefore, results obtained in this study are directly comparable to the river status derived from biological assessment.

In general, the three sampling stations showed similar patterns in metabolism, as our one-station metabolism approach measured a long upstream river section in addition to the experimental reaches. Rates of ER mirrored those of GPP, suggesting that autotrophic respiration largely drove temporal patterns in ER, despite an overall ratio of GPP:ER < 1 and a slightly negative NEP during most of the measurement period. Similar patterns were found in streams in the US (Beaulieu et al., 2013; Hall et al., 2016). The average GPP:ER ratio was significantly higher downstream of the restored reaches in our study (0.86 and 0.97, respectively) and in the combined restored reach (1.16) than in the upstream degraded river (0.66), indicating an increase in autotrophic processes following restoration. The only moderate heterotrophic state of the river together with ER closely tracking GPP indicated the importance of autochthonous production for the metabolism. This is further supported by the comparison of pre- and post-peak flow ER (Fig. 6). McTammany et al. (2003) suggested that higher

inputs of allochthonous material may occur after flooding events, subsequently supporting high rates of ER. In line with this, we expected high rates of ER during the last third of the sampling period, especially in restored reaches with a potentially high POM trapping efficiency. However, ER was lower compared to pre-flow peak conditions, with ER still mirroring GPP, thus indicating the coupling of autochthonous production with ER even after floods. This implies that restoration (reconnection of river and floodplain) did not increase resource transfer into the channel to such an extent that it influenced river metabolism.

We observed significantly higher GPP and ER at station R2 compared to the other stations. Metabolism of R1 did not markedly differ from D, corresponding with consistently higher values of hydromorphological variables in R2 only. Given the previously discussed importance of autochthonous production for the metabolism, habitat enhancement supporting the growth of macrophytes is likely the cause for higher GPP and ER in R2. Consequently, only high restoration effort bringing a restored reach close to reference conditions led to pronounced effects on ecosystem metabolism. Restoration effects were mainly related to the growth of aquatic macrophytes, which formed dense stands that augmented ecosystem metabolism. We acknowledge that metabolism was measured during summer, i.e. the time of maximum biomass of aquatic macrophytes. Therefore, high GPP and ER measured in this campaign might be restricted to this season and effects will be lower during winter times when macrophyte abundance will be low.

Ecosystem metabolism of the sampling stations at the restored reaches and of the combined restored river reaches was expected to be at similar levels to those of natural rivers reported in the literature. Therefore, we compared GPP and ER of our sampling stations to those of rivers comparable in size (discharge between 5 - 50 m³ s⁻¹; see Appendix S4, S5). GPP and ER estimated in this study were among the highest values reported for similar sized rivers; especially those of the sampling station R2 and the combined restored reach. 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. Interestingly, 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

394 compared to natural ones may be common. However, there is a tremendous variability in ecosystem
395 metabolism among natural river reaches in the literature (see Appendix S4, S5). Considering the
396 limited knowledge about natural geographical gradients in river metabolism, it was not possible to
397 assess if values obtained for restored reaches indicate natural conditions in a broader geographic
398 context. In future analyses of restoration effects on fluvial metabolism, local reference conditions
399 should therefore be assessed whenever possible.

400 Our experimental reaches reflected typical spatial scales on which restoration measures are
401 implemented. However, individually, these reaches were too short to feasibly use the two-station diel
402 DO change method (see 2.5). Accordingly, we used the one-station approach to assess reach-scale
403 restoration effects on ecosystem metabolism of longer river sections (>10 km). Following methods in
404 Demars et al. (2015), we evaluated to which extent these metabolism estimates reflected the restored
405 river sections. Measurements at sampling station R1 and R2 were only to 16% and 24%, respectively,
406 influenced by the restored experimental reaches directly upstream. However, station R2 was to 35%
407 influenced by the combined reaches R1+R2, and thus to 65% by upstream degraded river sections.
408 Despite this mismatch between lengths of river reaches evaluated and reaches exclusively affected by
409 restoration, we found significant effects of reach-scale restoration on whole-river metabolism.
410 Interestingly, our study therefore also shows that high restoration effort in short river reaches (1 to 2
411 km) had considerable effects on total whole-river metabolic rates of river stretches exceeding the
412 length of the actually restored reaches (>10 km), and that the one-station method may therefore be an
413 interesting option to qualitatively assess restoration effects in field situation, in which the two-station
414 method is not feasible.

415 To quantitatively support these qualitative findings, we estimated metabolism of the combined
416 restored reaches R1+R2, which were long enough to permit the application of the two-station method.
417 The obtained metabolic rates should be directly comparable to metabolic rates of the upstream,
418 degraded river (measured at station D with the one-station method) as results obtained with the one-
419 station and the two-station methods often agree remarkably well (e.g., Bernot et al., 2010; Beaulieu et
420 al., 2013). The total restored reach (R1+R2) showed higher GPP, ER, NEP, and GPP:ER than the

upstream degraded river. Thus, these results support the findings derived from the one-station method, indicating an increase in the river's metabolism and metabolic balance associated with restoration.

Thus, the restoration of short river reaches may have positive effects on downstream river sections regarding diel DO variability and carbon spiraling. High rates of metabolism and the occurrence of dense macrophyte stands in restored river reaches may also increase the assimilation of dissolved nutrients (Fellows et al., 2006; Gücker et al., 2006) and the sedimentation of particulate nutrients (Schulz and Gücker, 2005), thereby positively affecting water quality.

4.3 Recommendations for restoration monitoring

For most regions and river types, data is missing that could be used to establish limits of good, moderate or poor river conditions. However, based on data from mainly small streams, Young et al. (2008) proposed a useful framework to assess functional stream health using GPP, ER, NEP and GPP:ER. Consequently, metabolic rates for different river types should be surveyed to allow the incorporation of ecosystem metabolism of mid-sized and large rivers as functional indicator in this framework. Our study stresses the benefits of metabolism as a functional indicator complementing the monitoring of restoration projects (compare Young et al., 2008; Bunn et al., 2010): Temporally high-resolution and automated monitoring, that integrates biotic and abiotic variables over time and across habitats may increase our understanding of the effects of river restoration and might help identifying initial changes after restoration. Incorporating functional indicators into monitoring programs may enable a more holistic assessment of river ecosystems and elucidate responses to restoration (and also impairment), which may be related to ecosystem structure and function.

Acknowledgements

We thank D. Dangel, K. Gees, M. Gies, A. Gieswein, K. Kakouei, B. Rieth, L. Rothe, C. Sondermann, M. Sondermann, and colleagues from the Ruhr University Bochum for their help during the tracer experiment. We thank L. Wenning and J. Herold for their assistance in many of our field trips, R. Dietz and D. Hammerschmidt for supporting our research, and the NZO GmbH for providing aerial photos. We thank B. Demars for helpful comments on a previous version of this manuscript. We also

447 gratefully acknowledge a PhD fellowship of the German Environment Foundation (Deutsche
448 Bundesstiftung Umwelt, DBU) to B.K. and a productivity grant by the Brazilian National Council for
449 Scientific and Technological Development (CNPq 302280/2015-4) to B.G.. This study was financially
450 supported by the EU-funded project REFORM (Restoring rivers FOR effective catchment
451 Management), European Union's Seventh Programme for research, technological development and
452 demonstration under Grant Agreement No. 282656.

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645 **Table 1:** River and study site characteristics

River characteristics	
Catchment size (km ²)	4485
Stream length (km)	219
River type	Gravel-bed
Stream order	3
Ecoregion	Central Highlands
Study site characteristics	
Latitude (N) *	51.44093
Longitude (E) *	7.96223
Catchment size (km ²)	1060
Altitude (m a.s.l.)	153
Mean annual discharge (m ³ s ⁻¹)	21.3
Catchment geology	siliceous
Restoration length (km)	2.3
Restoration date	2007-2009
Main restoration action	riverbed widening
pH **	8.3
Electric conductance ** (μ S cm ⁻¹)	340
Total nitrogen ** (mg L ⁻¹)	2.7
NO ₃ -N ** (mg L ⁻¹)	2.53
NH ₄ -N ** (mg L ⁻¹)	< 0.1
Total phosphorus ** (mg L ⁻¹)	0.07
Total organic carbon ** (mg L ⁻¹)	2.3

* center of reach

** data from ELWAS-WEB (online information system maintained by The Ministry for Climate Protection, Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia; sampling date: 26.6.2012).

649 **Table 2:** Morphological and hydrodynamic characteristics of the investigated river reaches

Variable	degraded reach (D)	1. restored reach (R1)	2. restored reach (R2)
Thalweg length (m)	850	1210	1120
Width (m)	22.5	28.2	36.6
Width variation * (m)	3.3	6.3	10.5
Wetted channel area (m ²)	19,114	34,604	41,673
Floodplain area (m ²)	27,363	30,630	34,218
Island area (m ²)	0	2,666	12,381
Woody debris (m ²)	0	467	691
Macrophyte coverage (%)	4.8	1.7	19.8
Flow velocity (m s ⁻¹)	0.95	0.8	0.47
Longitudinal dispersion, D (m ² s ⁻¹) **	0.28	0.59	10.21
Channel cross-sectional area, A (m ²) **	12.11	14.96	27.05
Storage zone cross-sectional area, A_s (m ²) **	2.38	4.48	3.16
Storage rate, α (s ⁻¹) **	4.9×10^{-4}	7.4×10^{-4}	2.0×10^{-4}
Transient storage, F_{med}^{200} (%)	1.6	3.9	0.8
Damköhler number	2.8	4.8	4.4

* Width variation calculated as standard deviation; degraded: n = 42, restored 1: n = 59, restored 2: n = 54

** Data on hydrodynamic characteristics represent the final parameters obtained by one-dimensional transport modelling using OTIS-P.

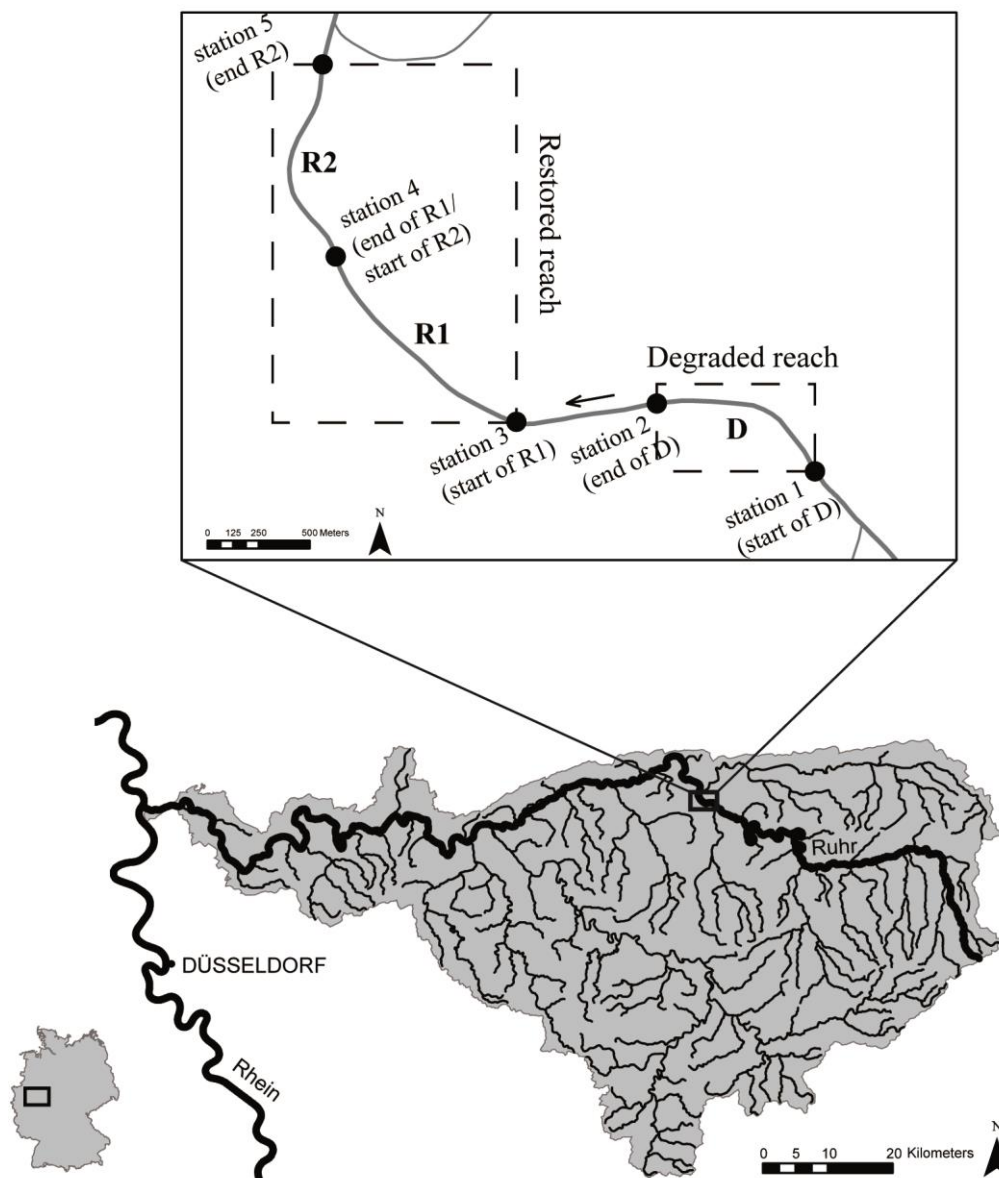
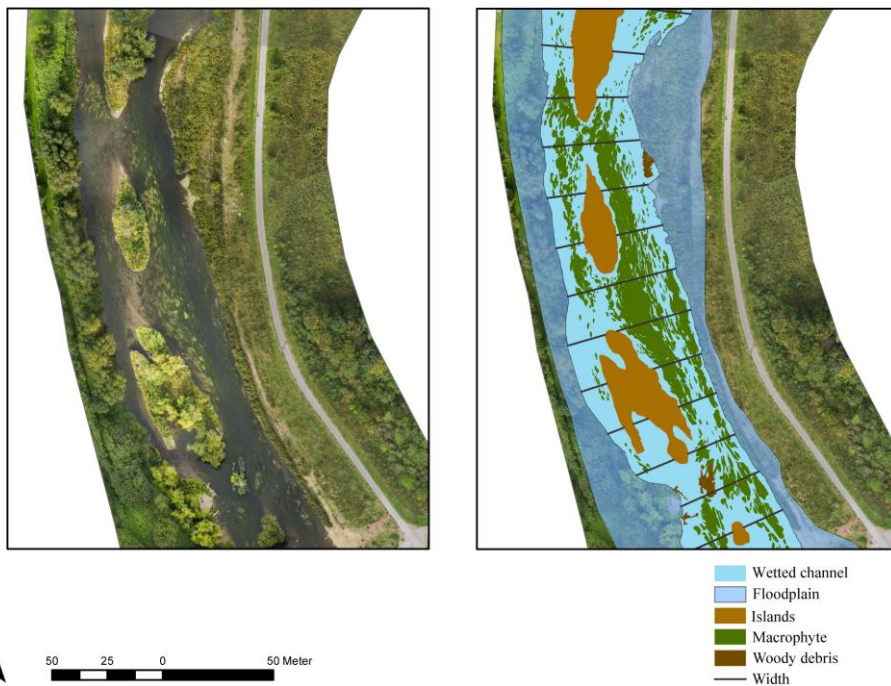


Fig. 1: Location of the study site in the upper catchment of the River Ruhr in Germany. Stations represent start and end of the investigated river reaches (degraded, 1st restored and 2nd restored reach).



50 25 0 50 Meter

Wetted channel
Floodplain
Islands
Macrophyte
Woody debris
Width

Fig. 2: Analysis of aerial photos. A representative river section of the 2nd restored reach is shown.

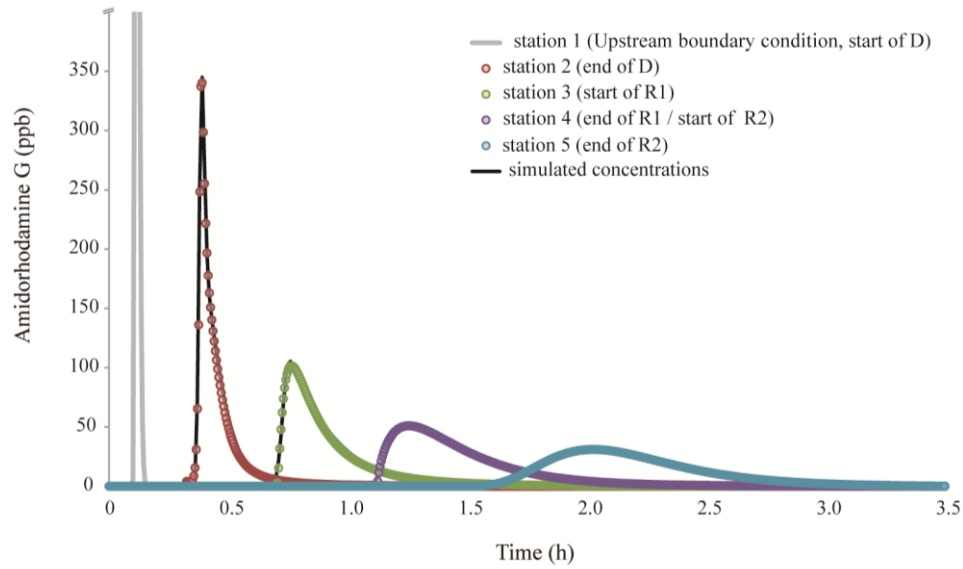


Fig. 3: Tracer breakthrough curves for the conservative tracer addition experiment in the River Ruhr. Upstream boundary condition based on concentrations at sampling station 1 (start of degraded reach, D, grey solid line), observed concentrations at sampling stations 2 (end of degraded reach, empty circles), 3 (start of 1st restored reach, R1, empty squares), 4 (end of 1st restored reach, start of 2nd restored reach, R2, empty triangles), 5 (end of 2nd restored reach, crosses), and simulated concentrations based on final parameter estimates with OTIS-P (solid lines).

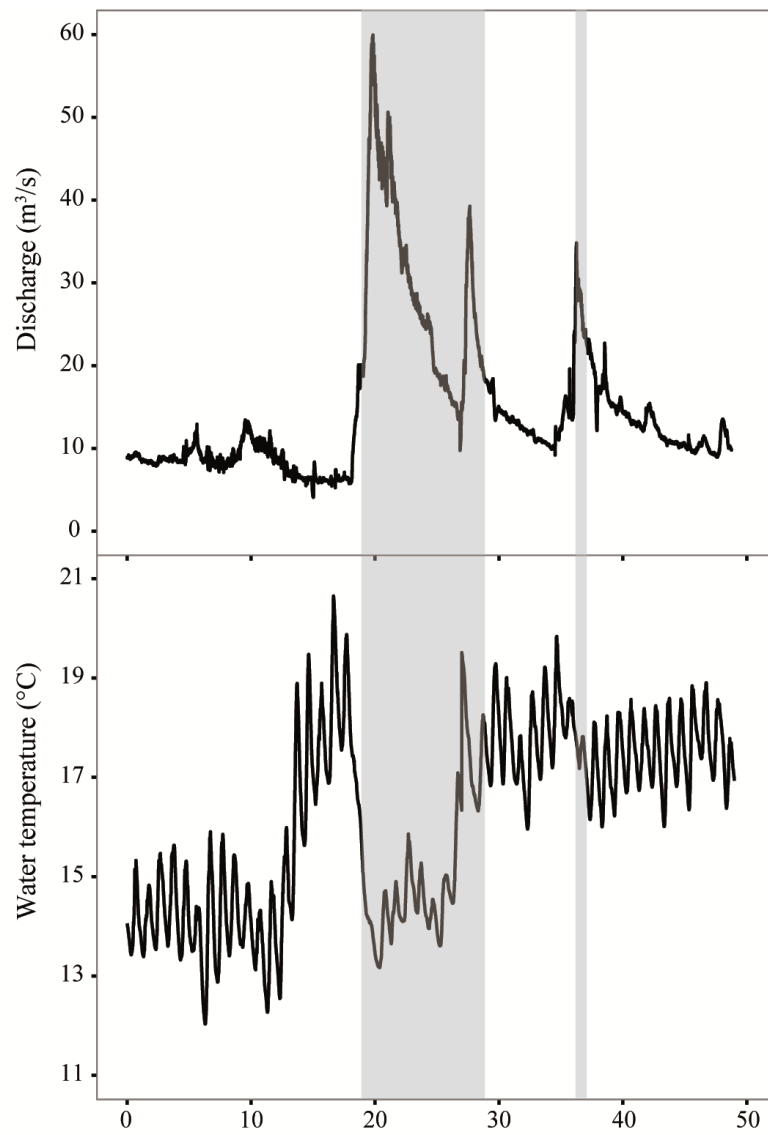


Fig. 4: (a) discharge and (b) water temperature in the River Ruhr during the study period in summer 2014. Trend in water temperature during study period is exemplarily shown for the 2nd restored reach (R2).

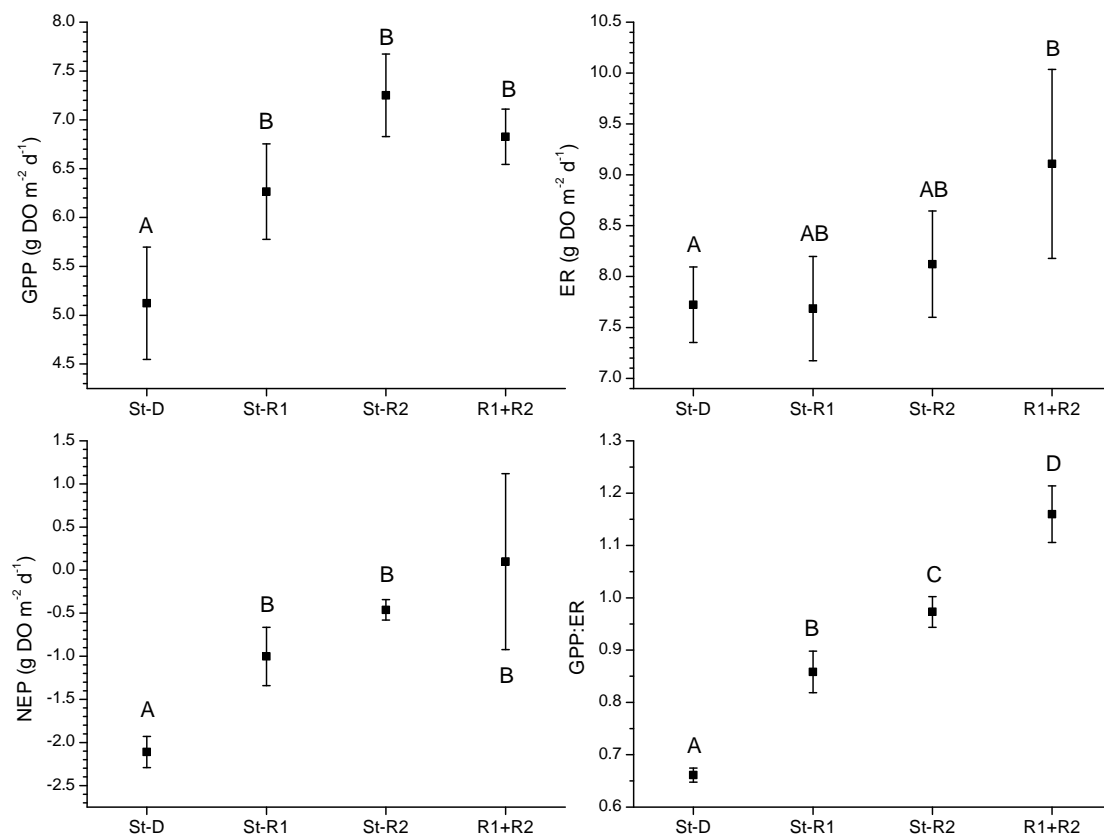


Fig. 5: Average predicted metabolic parameters and 95% confidence intervals of time series estimated by the 1-station open-channel-method at river stations downstream of reaches D, R1, and R2, and by the 2-station open-channel-method for river reach R1+R2. F-tests for all variables were significant (GPP: $p < 0.001$; ER: $p < 0.05$; NEP: $p < 0.005$, GPP:ER: $p < 0.0001$). Different letters indicate differences according to Tukey's post-hoc test ($p < 0.05$).

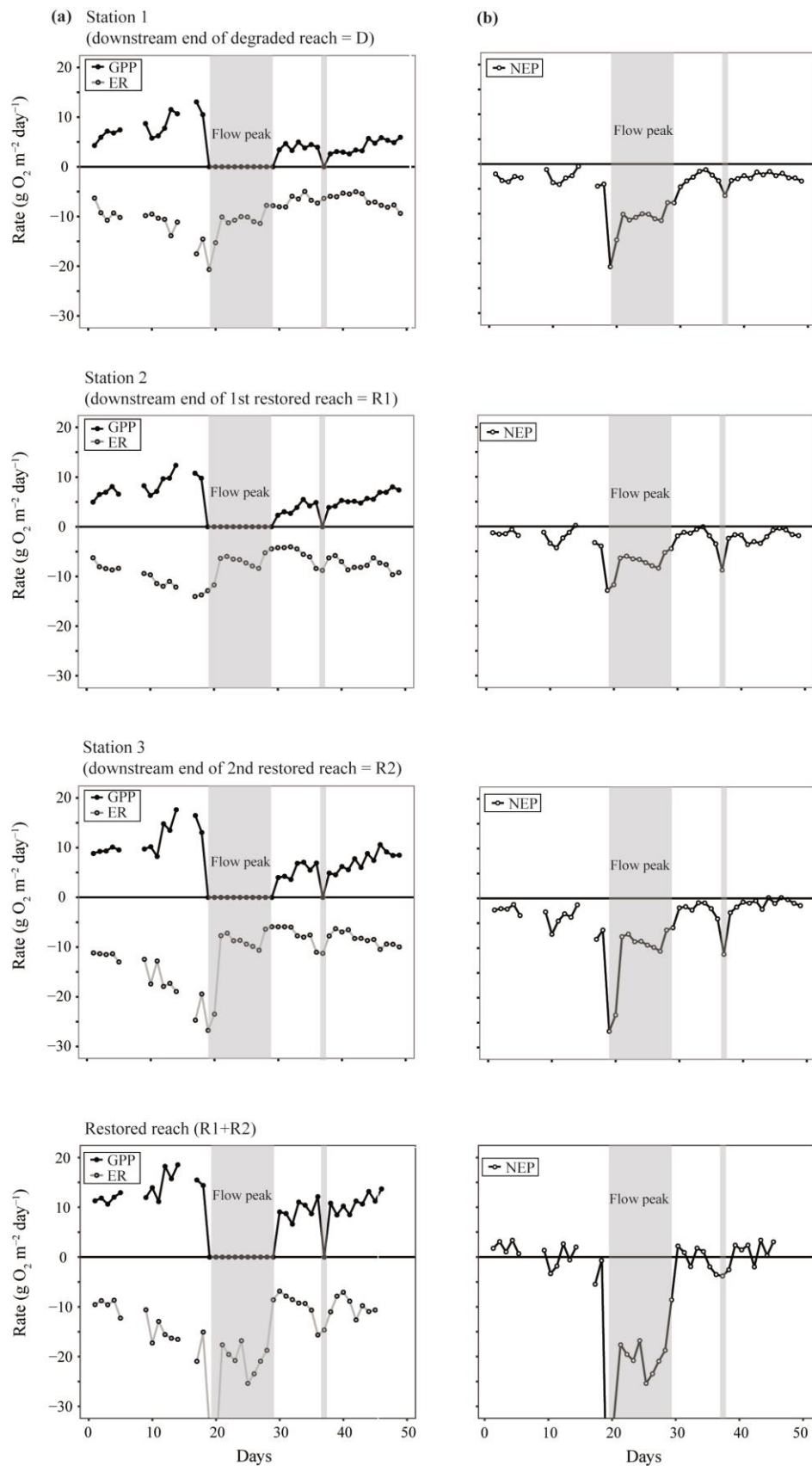


Fig. 6: Daily rates of (a) gross primary production (GPP: positive values, black line) and ecosystem respiration (ER: negative values, grey lines) and (b) net ecosystem production (NEP) measured at the downstream ends of the investigated reaches (degraded = D; 1st restored = R1; 2nd restored = R2) and for the combined reaches R1+R2 of the River Ruhr in summer 2014. Vertical grey bars indicate peak flow events.

Appendix 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).

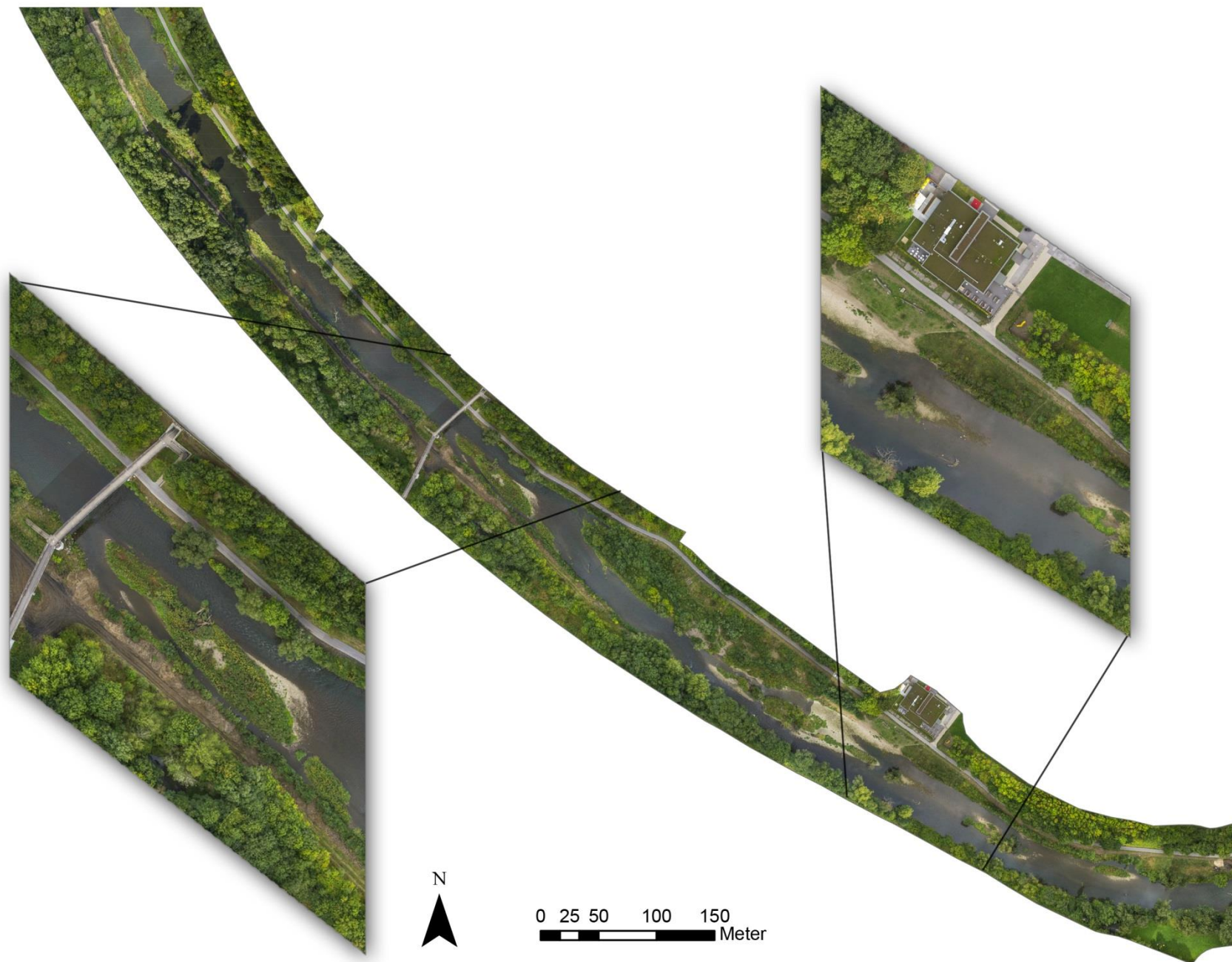


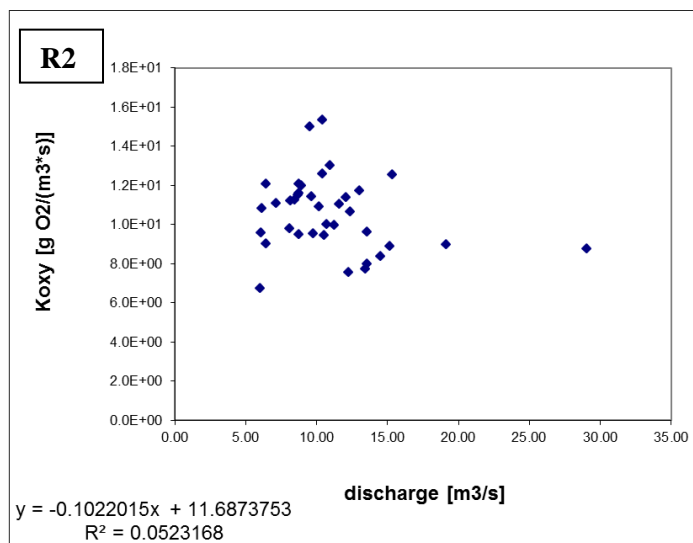
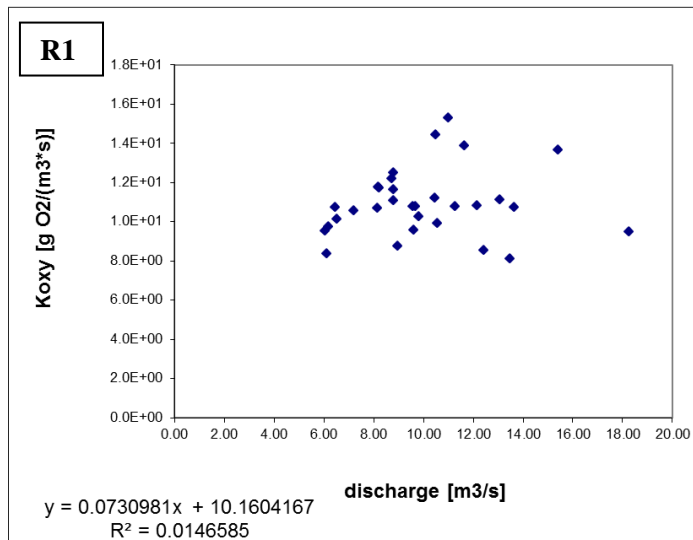
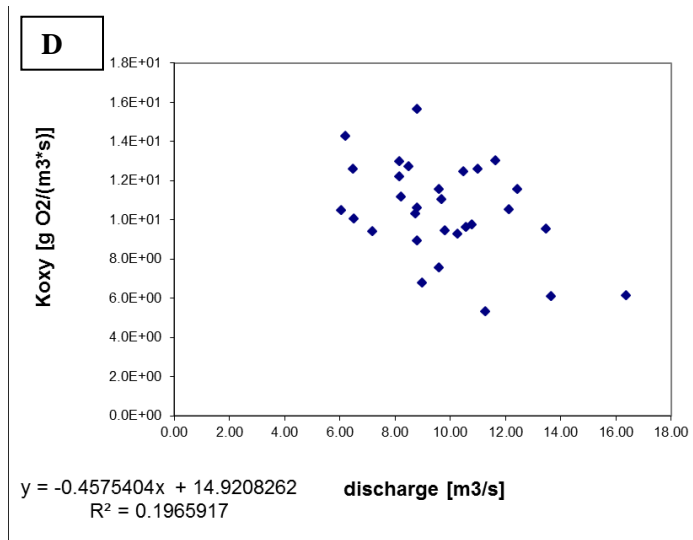
Fig. S7: 1st restored reach (R1) (photo by NZO GmbH, Germany).



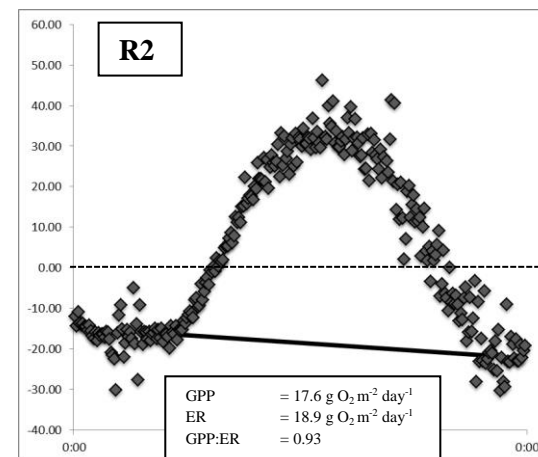
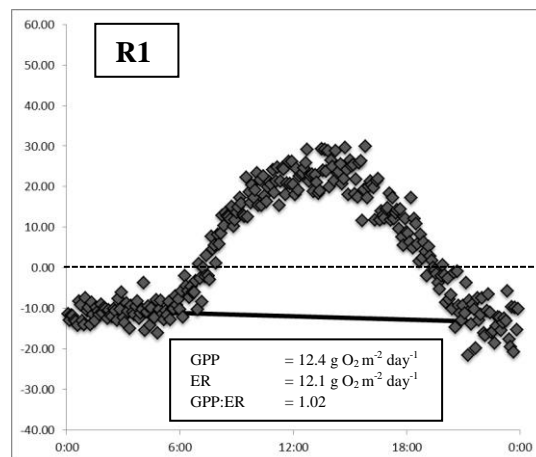
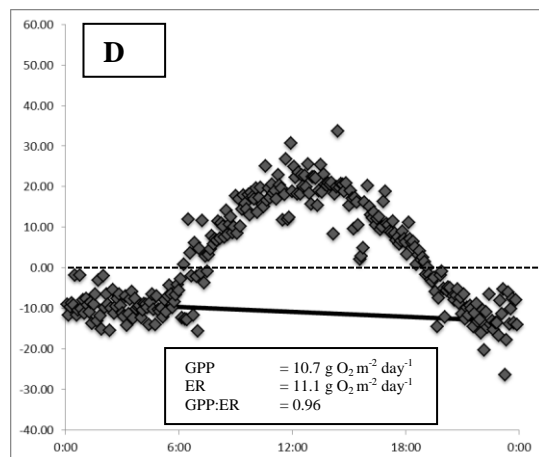
Fig. S8: 2nd restored reach (R2) (photo by NZO GmbH, Germany).

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

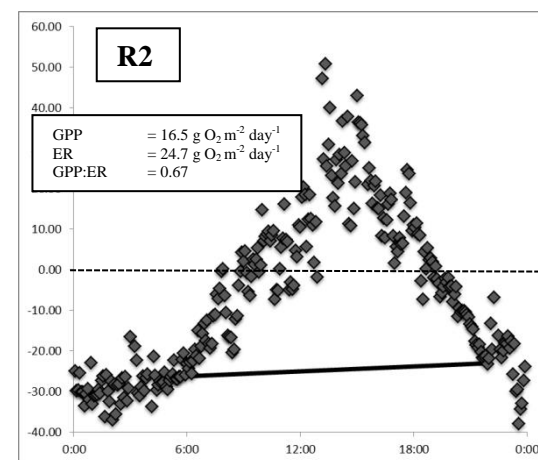
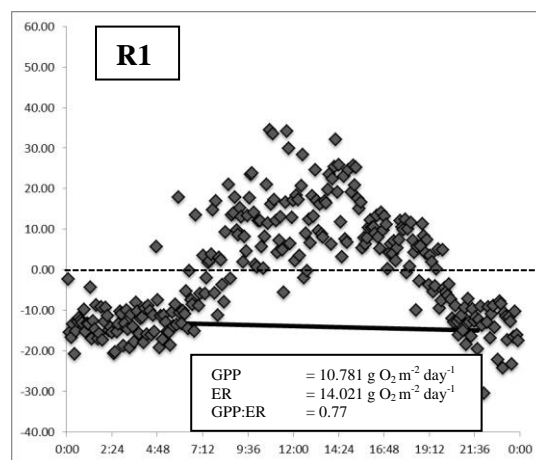
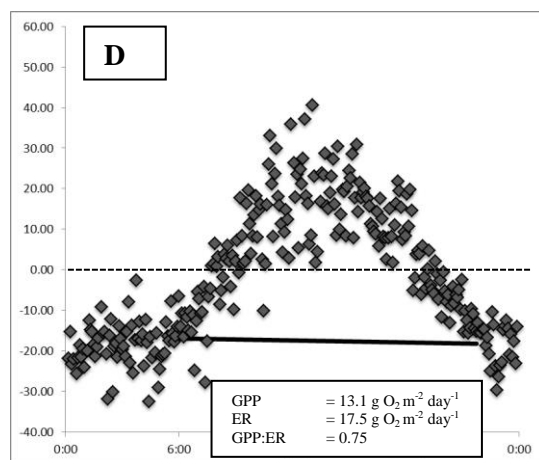
All regressions with $P > 0.05$



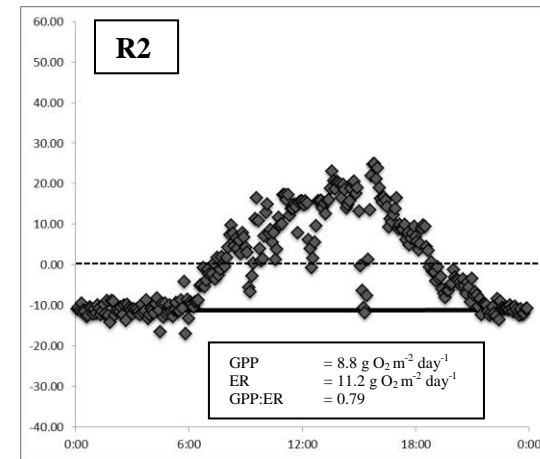
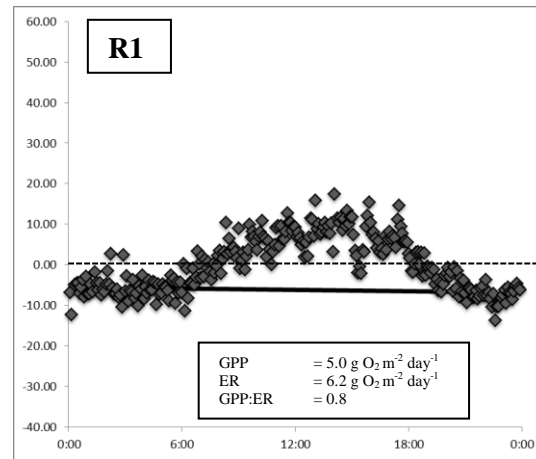
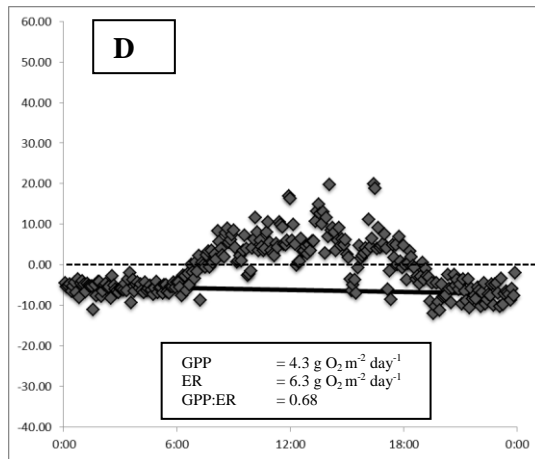
Appendix S3: Diurnal patterns of ecosystem metabolism in the sampling stations at D, R1 and R2 for days on which GPP and ER were among the highest respectively lowest rates measured



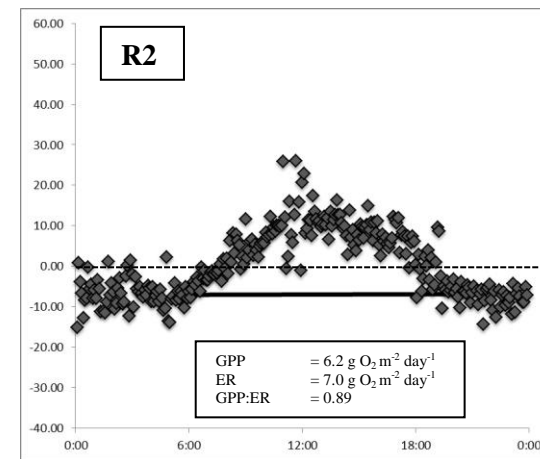
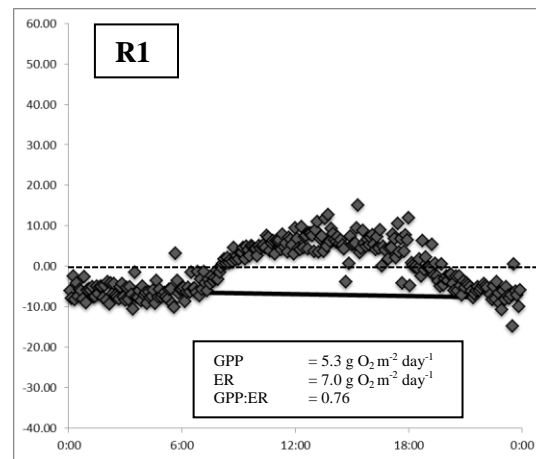
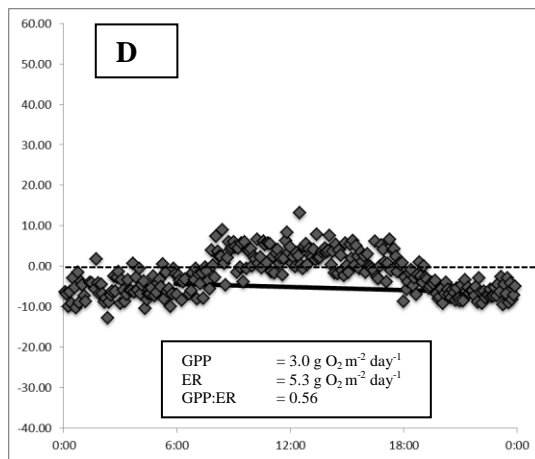
Day 17



Day 1



Day 40



Appendix 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 m³ 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:

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- 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.
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Appendix 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	Relatively 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

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

Sampled river		Metabolism				Reference
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)	
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. <i>Freshwater Biology</i> , 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. <i>Journal of Geophysical Research</i> , 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. <i>Limnology</i> , 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. <i>Journal of the North American Benthological Society</i> , 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. <i>Journal of the North American Benthological Society</i> , 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. <i>Journal of the North American Benthological Society</i> , 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. <i>Journal of the North American Benthological Society</i> , 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. <i>Journal of the North American Benthological Society</i> , 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. <i>Journal of the North American Benthological Society</i> , 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. <i>Freshwater Biology</i> , 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. <i>Marine and Freshwater Research</i> , 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. <i>Marine and Freshwater Research</i> , 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. <i>Freshwater Biology</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Ecosystems</i> , 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. <i>Hydrobiologia</i> , 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. <i>Hydrobiologia</i> , 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. <i>Hydrobiologia</i> , 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. <i>Hydrobiologia</i> , 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. <i>Limnol. Oceanogr.</i> , 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. <i>Ecosystems</i> , 19, 73-86.
