

We would like to thank Anonymous Referee 1 for his helpful comments. We address these comments below in a detailed point-by-point response.

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).

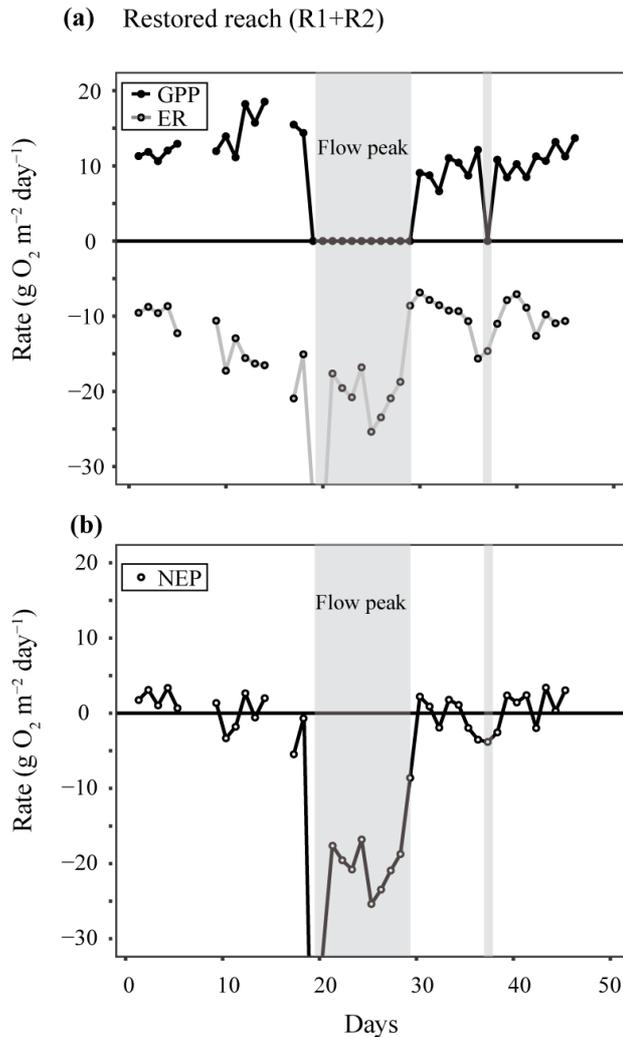


Fig. 1: Daily rates of (a) gross primary production (GPP: positive values, black line) and ecosystem respiration (ER: negative values, grey lines) and (b) net ecosystem production (NEP) calculated for the total restored reach (R1+R2) of the River Ruhr in summer 2014. Vertical grey bars indicate peak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

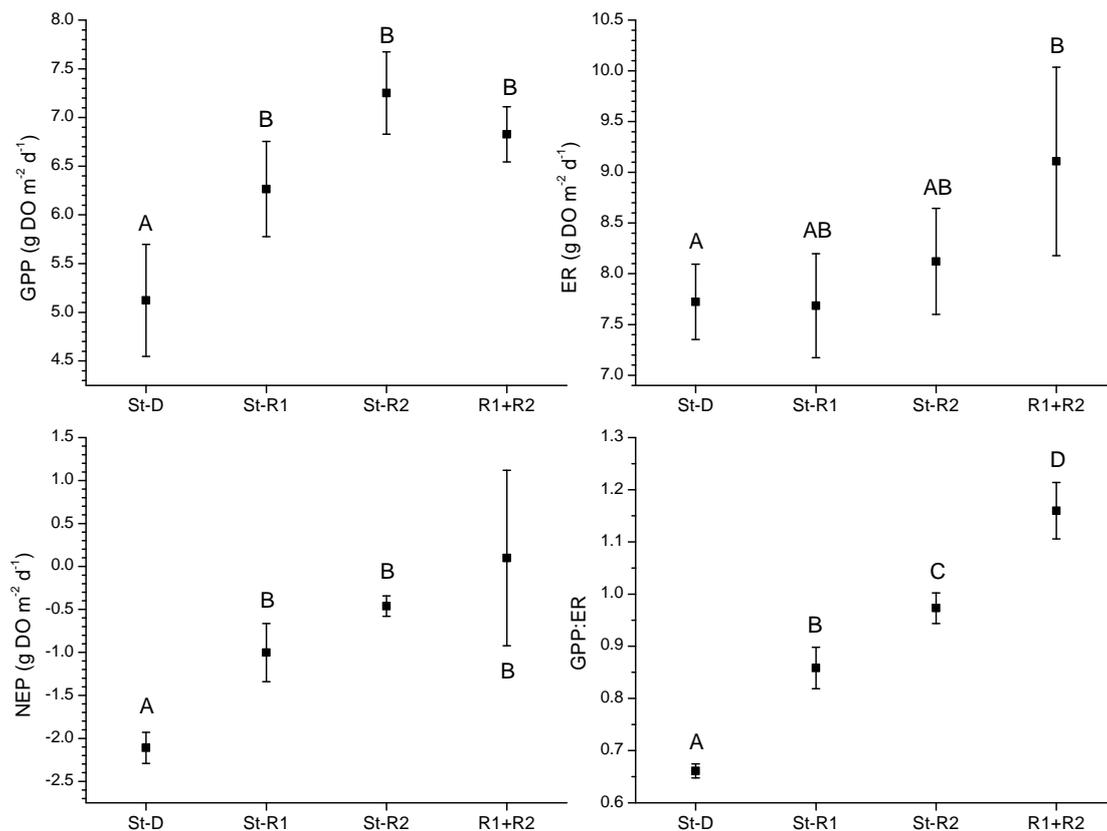


Fig. 2: Average predicted metabolic parameters and 95% confidence intervals of time series estimated by the 1-station open-channel-method at river stations D, R1, and R2, and by the 2-station open-channel-method for river reach R1+R2. F-tests for all variables were significant (GPP: $p < 0.001$; ER: $p < 0.05$; 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 will add the following definition to the revised paper: For example, the national river habitat survey in Germany, which evaluated hydromorphology using 31 parameters related to the longitudinal profile, channel development, bed structure, cross profile, bank structure and adjacent land use on the scale of 100 m long river sections, concluded that the majority of German rivers was severely degraded while achieving a 'good chemical status' (Gellert et al., 2014; UBA, 2013). As the river biota depend on certain morphological and substrate features (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 will correct this in the revised paper.

COMMENT:

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

RESPONSE:

We agree and will correct 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 will rewrite 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 will discuss 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 will clarify this in the revised manuscript, also giving values for travel times. In our previous 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 will discuss 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 will also mention 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 will present NEP here in the revised paper. Furthermore, daily NEP is presented in Fig. 5 of the original 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.

REFERENCES:

- Beaulieu, J.J., Arango, C.P., Balz, D.A. and Shuster, W.D.: Continuous monitoring reveals multiple controls on ecosystem metabolism in a suburban stream. *Freshwater Biology*, 58, 918–937, 2013.
- Beisel, J.-N., Usseglio-Polatera, P. and Moreteau, J.-C.: The spatial heterogeneity of a river bottom: a key factor determining macroinvertebrate communities. *Hydrobiologia*, 422/423, 163–171, 2000.
- Bernot, M.J., Sobota, D.J., Hall, R.O., Mulholland, P.J., Dodds, W.K., Webster, J.R. et al.: Inter-regional comparison of land-use effects on stream metabolism. *Freshwater Biology*, 55, 1874–1890, 2010.
- EEA (European Environment Agency): European Waters – Assessment of Status and Pressures. EEA Report No. 8, EEA, Copenhagen. 96 pp., 2012.
- Fellows, C.S., Valett, H.M. and Dahm, C.N.: Whole-stream metabolism in two montane streams: Contribution of the hyporheic zone. *Limnology and Oceanography*, 46, 523–531, 2001.
- Gellert, G., Pottgiesser, T. and Euler, T.: Assessment of the structural quality of streams in Germany—basic description and current status. *Environmental Monitoring and Assessment*, 186, 3365–3378, 2014.
- Gücker, B. and Boëchat, I.G.: Stream morphology controls ammonium retention in tropical headwaters. *Ecology*, 85, 2818–2827, 2004.
- Halbedel, S. and Büttner, O.: MeCa, a toolbox for the calculation of metabolism in heterogeneous streams. *Methods in Ecology and Evolution*, 5, 971–975, 2014.
- Odum, H.T.: Primary production in flowing waters. *Limnology and Oceanography*, 2, 102–117, 1956.
- Roley, S.S., Tank, J.L., Griffiths, N.A., Hall, R.O. and Davis, R.T.: The influence of floodplain restoration on whole-stream metabolism in an agricultural stream: insights from a 5-year continuous data set. *Freshwater Science*, 33, 1043–1059, 2014.
- Schröder, M., Kiesel, J., Schattmann, A., Jähnig, S., Lorenz, A.W., Kramm, S., Keizer-Vlek, H., Rolaufts, P., Graf, W., Leitner P. and Hering, D.: Substratum associations of benthic invertebrates in lowland and mountain streams. *Ecological Indicators*, 30, 178–189, 2013.
- UBA (Federal Environment Agency): Water Resource Management in Germany Part 1: Fundamentals. Bonn, 2013.

https://www.umweltbundesamt.de/sites/default/files/medien/378/publikation/n/wawi_teil_01_englisch_barrierefrei.pdf (accessed November, 25th, 2016).

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.