Primary productivity and climate change in Austrian lowland rivers

Ottavia Zoboli, Katerina Schilling, Anna-Lena Ludwig, Norbert Kreuzinger, Matthias Zessner

Key words: stream metabolism; temperature; nutrients; phosphorus; climate change; primary productivity; eutrophication

Abstract

There is increasing evidence of water temperature being a key controlling factor of stream ecosystem metabolism. Although the focus of research currently lies on carbon emissions from fluvial networks and their potential role as positive climate feedback, it is likewise important to estimate the risk of eutrophication streams will be exposed to in the future. In this work, a methodological approach aimed to create a scientific basis for such assessment is developed and applied to two Austrian lowland rivers with significantly different characteristics. Gross primary productivity (GPP) is determined through the open diel oxygen method and its temperature dependence is quantified based on the metabolic theory of ecology. This relationship is combined with the outcomes of a climate change scenario obtained through a novel integrated modelling framework. The results indicate that in both rivers, a raise in atmospheric temperature by 1.5°C would provoke an increase of GPP by 7-9% and that such increase would not be limited by nutrients availability. The situation for the relatively shallow river appears more critical. Likely owing to more light availability, GPP values in summer are five times higher in the shallow river than in the deeper murky river. Further, phosphorus availability would also allow a greater increase of GPP under a scenario of higher temperature raise.

Introduction

There is a renewed interest in material and energy fluxes in freshwater ecosystems, driven by the overarching question of how they contribute to regional and global carbon (C) cycling (Hall et al., 2016). This has led to fundamental theoretical developments aimed to scale the metabolism from organisms to whole ecosystems (Enquist et al., 2003) and to efforts directed to identify and quantify key control factors. Crucial in the context of climate change is to understand how temperature influences stream metabolism. According to the metabolic theory of ecology, both ecosystem respiration (ER) and gross primary productivity (GPP) increase with rising stream temperature, and ER should increase faster than GPP owing to the higher temperature dependence of the respiration process compared to photosynthesis (Allen et al., 2005; Gillooly et al., 2001; López-Urrutia et al., 2006; Science, 2001; Yvon-

©IWA Publishing [2017]. The definitive peer-reviewed and edited version of this article
is published in Water Science & Technology, Volume 77, Issue 2, 417-425, 2017,
https://doi.org/10.2166/wst.2017.553 and is available at www.iwapublishing.com.
This is the accepted version.

Durocher et al., 2010). With an unprecedented experiment carried out in naturally heated geothermal streams, which allowed isolating the effect of temperature from other factors such as latitude, light or nutrient availability, Demars et al. (2011) demonstrated the role of temperature in whole-stream metabolism and the fact that ER is more strongly related to temperature than GPP. Based on these findings, they estimated that a 5°C global warming would cause an elevated negative net primary productivity (NEP), which would result in the doubling of global stream C emissions to the atmosphere. Demars et al. (2011) also observed that stream nutrient uptake velocity was significantly faster in warm streams than in cold ones and derived that stream nutrient processing would increase with global warming. They concluded that this would protect downstream ecosystems from eutrophication. However, it could be argued that faster nutrient processing and higher productivity with rising atmospheric temperatures may pose a risk to the health of the stream ecosystem itself. It seems thus meaningful and relevant to progress the study of the relationship between climate change and stream metabolism, with focus not only on the exchange of greenhouse gases but also on eutrophication. Further, climate change would not only affect atmospheric temperature, but would also profoundly alter, among others, rainfall-runoff patterns and agricultural productivity. Consequently, agricultural diffuse emissions of nutrients and river flow levels will also likely change. Therefore, predictions of how and how much stream metabolism would change with increasing temperatures ought to be combined with estimations of future summer low flows and nutrient availability.

This poorly understood and scarcely investigated aspect of the problem motivated the work presented here, which by means of two significantly different case studies pursues a twofold objective. The first goal is to analyze and quantify the relationship between primary productivity and temperature in Austrian lowland rivers. The second goal is to integrate such relationship within a climate change scenario developed for all Austrian river catchments by Schönhart et al. (Submitted) and Zessner et al. (2017a, 2017b), in which direct and indirect impacts of climate change on land use and surface waters are modeled and assessed through a novel integrated approach. More specifically, the theoretical future increase of primary productivity is quantified and potential limitations to such growth posed by future nutrient availability are investigated.

Materials and Methods

Study sites and datasets

Two study sites were selected, which aim to represent two distinct types of lowland rivers in Austria. The first is river Schwechat, which is a rather shallow stream with high visibility depth, and thus dominated by phytobenthos. It is a right tributary of the River Danube, located in eastern Austria. It is characterized by a total 70 km length, 1186 km^2 wide catchment, and downstream long-term mean annual flow of 8.2 m^{3}s^{-1} (BMLFUW, 2015). The Raba, another right tributary of the Danube River,

©IWA Publishing [2017]. The definitive peer-reviewed and edited version of this article
is published in Water Science & Technology, Volume 77, Issue 2, 417-425, 2017,
https://doi.org/10.2166/wst.2017.553 and is available at www.iwapublishing.com.
This is the accepted version.

represents instead deeper murky streams with predominant phytoplankton. It flows for approximately 250 km in the southeast of Austria. Its catchment area covers 1090 km^2 and its downstream long-term mean annual flow is 7.1 m^{3}s^{-1} (BMLFUW, 2015). Figure 1 shows the geographical position of these two rivers, the boundaries of their catchment areas as well as the location of the monitoring stations where the data used in this study were collected.

These two study sites were primarily chosen in light of high frequency measurements of oxygen (O_2) concentration and water temperature available for multiple years, which allowed the estimation of the dependence between primary productivity and temperature. These data were collected at two monitoring stations installed and operated by the Institute for Water Quality, Resource and Waste Management of the TU Wien, on commission of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (Camhy et al., 2013; Fuiko et al., 2016). In particular, the available datasets cover the period 2010-2012 for the river Schwechat and the period 2010-2016 for the river Raba. Table 1 shows the details of the collection and handling of these data.

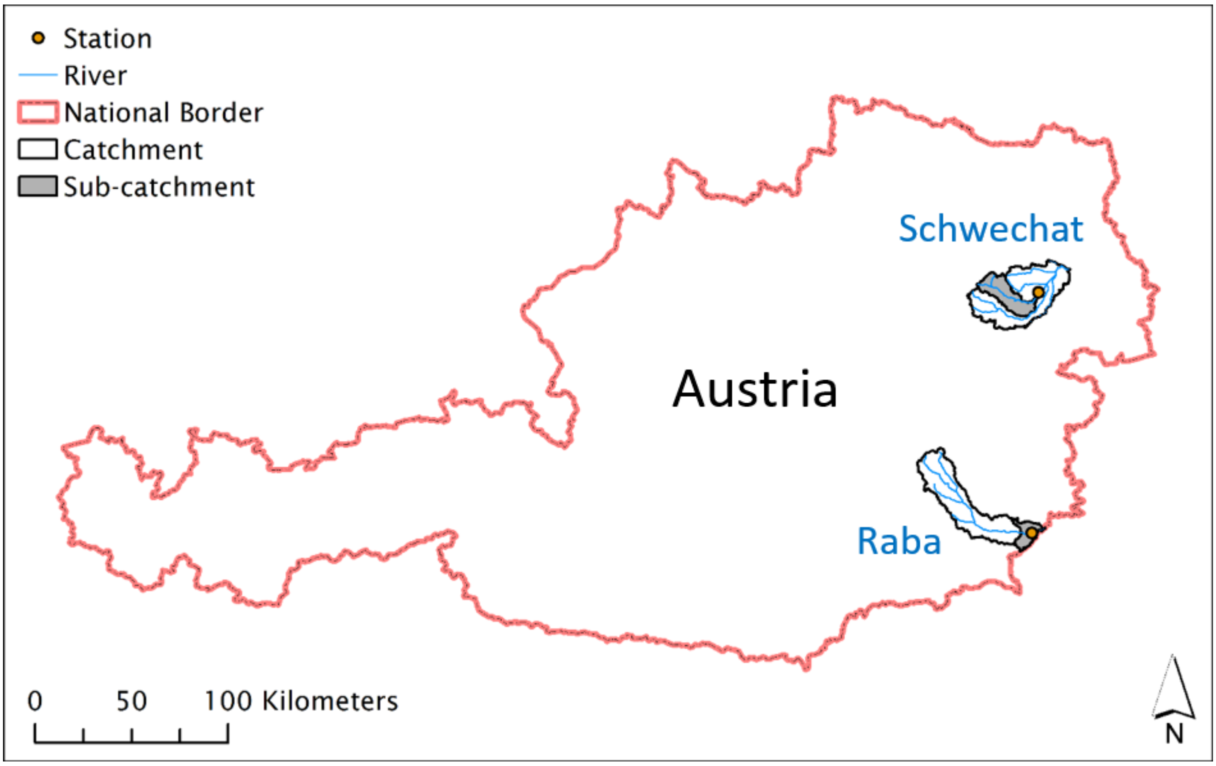

Figure 1: Map of the location of the rivers Schwechat and Raba in Austria. The map further indicates: i) the boundaries of the total river catchments, ii) the area of the sub-catchments on which this study focuses, and iii) the location of the two monitoring stations from which the data were obtained.

Table 1: Details of the continuous measurement of dissolved oxygen and temperature at the river Schwechat and Raba.

	Parameter	Sensor	Measurement range	Measurement frequency	Data handling
Schwechat	Oxygen (O_2)	Luminescence *(monthly calibration and maintenance)*	0,05 – 20 mg O_2/l	12 minutes	Plausibility check Calculation of mean hourly values
	Water temperature	NTC/Pt100 *(monthly calibration and maintenance)*	0 – 50 °C	12 minutes	Plausibility check Calculation of mean hourly values
Raba	Oxygen (O_2)	Luminescence *(monthly calibration and maintenance)*	0,05 – 20 mg O_2/l	12 minutes	Plausibility check Calculation of mean hourly values
	Water temperature	Pt100 *(monthly calibration and maintenance)*	0 – 50 °C	12 minutes	Plausibility check Calculation of mean hourly values

The station at the Schwechat (48.041663°N, 16.334211°W) was located approximately upstream-midstream of the whole catchment, but downstream of a well-studied sub-catchment (Camhy et al., 2013). Within this sub-catchment, the Schwechat shows an almost natural condition upstream, but highly modified hydrological characteristics midstream and downstream, where it also receives considerable discharges of treated municipal wastewater from two towns. Table 2 gives an overview of the emissions of total phosphorus (TP) in the sub-catchment, which are clearly dominated by discharges of wastewater treatment plants' effluents and by urban runoff.

The station at the Raba, which is still in operation, is located downstream (46.930185°N, 16.153495°W), shortly before the Austrian-Hungarian national border. Land use in the catchment of the Raba differs considerably from that of the Schwechat. Approximately 45% of the area is dedicated to arable land, 10% to grassland, and 40% is covered by forest, with only 5% occupied by urban areas. This is well reflected by the emissions of TP, which in this case consist predominantly of erosion from agricultural soils.

©IWA Publishing [2017]. The definitive peer-reviewed and edited version of this article
is published in Water Science & Technology, Volume 77, Issue 2, 417-425, 2017,
https://doi.org/10.2166/wst.2017.553 and is available at www.iwapublishing.com.
This is the accepted version.

Table 2: Emissions of total phosphorus (TP) via different pathways in the catchment of the Raba and in the two sub-catchments where the monitoring stations are located. These emissions were estimated through the MONERIS model by Zessner et al. (2017a) and Schönhart et al. (Submitted) and represent average values for the period 2005-2010. Note: for the river Schwechat, only the sub-catchment is shown, given that the rest of the catchment drains downstream of the station.

	Schwechat Station sub-catchment	**Raba Station sub-catchment**	**Raba Whole catchment**
Catchment area (km^2)	152.9	198.5	1089.8
TP emissions via atmospheric deposition (t TP y^{-1})	0.1	0.1	0.2
TP emissions via surface runoff (t TP y^{-1})	0.5	0.2	1.0
TP emissions via snowmelt (t TP y^{-1})	0.0	0.0	0.0
TP emissions via agricultural erosion (t TP y-1)	1.4	4.8	24.0
TP emissions via natural erosion (t TP y-1)	0.1	0.2	0.8
TP emissions via tile drainage systems (t TP y-1)	0.1	0.0	0.6
TP emissions via groundwater (t TP y-1)	0.4	0.7	3.4
TP emissions via urban runoff (t TP y-1)	8.0	0.4	7.5
TP emissions from point sources (t TP y-1)	13.6	0.0	5.5
Total TP emissions	24.2	6.4	43.0

Primary productivity and temperature dependence

Gross primary productivity (GPP) was estimated by means of the open diel oxygen method, whose theoretical foundations were originally developed by Odum (1956) and can be summarized through the following equation:

$$\mathrm{GPP}(\mathrm{d}t) = \frac{dC}{dt} - k(C_{Sat} - C) + ER + A \qquad \text{Eq. 1}$$

where GPP(dt) is the variation of GPP in time, dC/dt the rate of change of O_2 concentration, k the reaeration coefficient (gas exchange coefficient at the air-water interface), C_{Sat} the saturated dissolved O_2 concentration as a function of water temperature, C the instant dissolved oxygen concentration, ER the ecosystem respiration and A the accrual of groundwater. GPP, ER, A, and dC/dt are expressed in g O_2 L^{-1} h^{-1}, C and C_{Sat} in g O_2 L^{-1} and k in h^{-1}. The Hornberger-Kelly night time regression method (Hornberger and Kelly, 1975) was applied to calculate k and ER, whereas A could be neglected, and the hourly calculated GPP values were integrated to obtain daily GPP (g O_2 L^{-1} d^{-1}). Combining it with water depth at the river stretch, GPP expressed as oxygen production over unit area instead of unit volume was obtained (g O_2 m^{-2} d^{-1}).

The temperature dependence of GPP was determined through the model developed by Enquist et al. (2003) to scale biochemical kinetics from individual organisms to ecosystems. It is based on Arrhenius equations formally derived from the metabolic theory of ecology. As in Gillooly et al. (2001), the absolute metabolic flux was normalized to a reference temperature, to make it biologically more meaningful. Taking into account the location of the studied streams in a temperate climatic region, the reference temperature of 15°C was selected as in Demars et al. (2011). The following regression model was applied to determine the relationship between GPP and temperature:

$$\ln(GPP) = \ln(c) - E\frac{1}{\mathrm{k}}\left(\frac{1}{T} - \frac{1}{T_{Ref}}\right) \qquad \text{Eq. 2}$$

where GPP is the gross primary productivity per unit area (g O_2 m^{-2} d^{-1}), the intercept ln(c) is the normalized absolute GPP (g O_2 m^{-2} d^{-1}), the slope E the activation energy (eV), k the Boltzmann constant (in eV K^{-1}), and T and T_{Ref} the stream temperature and the reference temperature in Kelvin degrees, respectively.

Climate change scenario

Zessner et al. (2017a) recently developed a novel integrated modelling framework (IIMF) to assess the impacts of climatic and socio-economic drivers on land use and water quality. The novelty of their approach is the explicit consideration and quantification of the linkage between climate change, agricultural activities and surface water quality, which constitutes a step forward with respect to previous studies, which tended to separately assess the impact either of agriculture or of climate change on water resources. The specific goal was to estimate the emissions of nutrients and the risk of exceedance of environmental quality standards set for nutrients concentrations by the Water Framework Directive for surface waters. To do so, the framework combines runoff-precipitation modelling (TUW model, Parajka et al. 2007; Top-kriging interpolation, Skøien and Blöschl, 2007), mathematical optimization of agricultural land use (EPIC, Izaurralde et al., 2006; CropRota, Schönhart et al., 2011; PASMA[grid], Kirchner et al., 2016), and catchment-scale nutrient emissions modelling (USLE, Wischmeier and Smith, 1978; MONERIS, Zessner et al., 2011). Both single models and the integrated framework were validated upon, among others, observed land use, crop production, fertilizers application, river discharges and river nutrient loads. The performance of the integrated modelling for calculating river nutrient loads (evaluated upon 120 monitoring stations) shows a Nash-Sutcliffe Efficiency of 0.73 for nitrogen and 0.51 for phosphorus. In catchments with high agricultural share, such as the one of the river Raba, the IIMF achieves better results, with only 30% of cropland and 23% of permanent grassland dominated areas showing a deviation greater than 30% between modelled and observed loads (Zessner et al., 2017a).

Based on the IIMF, Schönhart et al. (Submitted) estimated for all Austrian river catchments the emissions of nutrients and the risk of exceedance of environmental quality standards for nutrients concentrations deriving from a set of different scenarios of climatic and socio-economic changes. All scenarios consider an increase of average atmospheric temperature by 1.5°C, which would correspond to a rise of average stream-water temperature by 1°C. The average 1.5°C temperature increase for the time span 2010-2040 was derived by the work of Strauss et al. (2013), based on high resolution observations of significant increasing temperature trends in the network of Austrian monitoring stations. Contrary to temperature, current climate models provide highly uncertain and contrasting predictions for what concerns rainfall-runoff. Therefore, Schönhart et al. (Submitted) developed scenarios which differ from each other concerning rainfall-runoff changes: i) Scenario *similar* with a distribution of total precipitations similar to the past, ii) scenario *wet* with a precipitation increase by 20%, and iii) scenario *dry* with a decrease of precipitation by 20%. Further, these climatic scenarios were combined with different socio-economic scenarios of agricultural activity, which were developed with the active involvement of stakeholders. These distinguish between a business-as-usual situation and the implementation of an agricultural policy considerably more driven by water protection goals.

For the present work, the worst-case scenario was selected, that is to say the scenario in which Austrian rivers would result more vulnerable to eutrophication. In Schönhart et al. (Submitted), this is represented by the "IMPact_dry" scenario, which assumes business-as-usual agro-environmental policies and a reduction of precipitation by 20%. The primary reason for this scenario being the most critical in view of the risk of exceedance of environmental quality standards is that, although the reduction of run-off would lead to slightly lower diffuse nutrients emissions, this effect would be offset by the considerably higher in-stream nutrients concentrations in summer due to lower river discharges.

Nutrient uptake

The extended Redfield ratio (Redfield et al., 1963) depicts the general molar relationship between O_2 production and the uptake of C, nitrogen (N) and phosphorus (P) during the process of photosynthesis in the aquatic environment and is as follows: $C:N:P:-O_2 = 106:16:1:138$. Given that GPP is a measure of primary productivity expressed as oxygen production, this relationship can be conveniently applied to estimate the consumption requirements of P, which is typically the limiting nutrient in freshwater environments, as function of increasing GPP. The calculated temperature dependence provides an estimate of the theoretical increased amount of oxygen production per each temperature increase by 1°C. Through the extended Redfield ratio, this amount is translated into the theoretical increased requirement of phosphorus as function of the rising temperature. Since the ratio $P:-O_2 = 1:138$ is a molar relationship, whereas GPP and P uptake are given in grams per area and time, an intermediate step of molar conversion is performed.

The integrated modelling framework described in the previous chapter delivers estimates of nutrients loads and concentrations at the sub-catchment scale, i.e. estimates of the phosphorus that would be available for primary production. For the calculation of P uptake through increasing GPP, it is assumed that GPP is homogeneous across the area of the main channel within the considered sub-catchments (equal to 0.23 km^2 for the Schwechat and to 0.30 km^2 for the Raba).

Results and Discussion

Primary productivity and temperature dependence

Figure 2 (a-c) depicts the estimated GPP in the Schwechat for the years 2010-2012. As expected, GPP follows a pattern similar to that of temperature, with values ranging from close to null in winter up to 50-100 g O_2 m^{-2} day^{-2} in summer. The regression model determining the GPP temperature dependence has a relatively high r^2 of 0.66 and is statistically highly significant ($p \leq 0.001$, Figure 2d), thus indicating that the temperature is a meaningful predictor, which can explain a substantial part of the variation of GPP. The activation energy, i.e. the slope of the regression model, is equal to 0.65 eV ± 0.02 eV (1 eV = 96.5 KJ mol^{-1}).

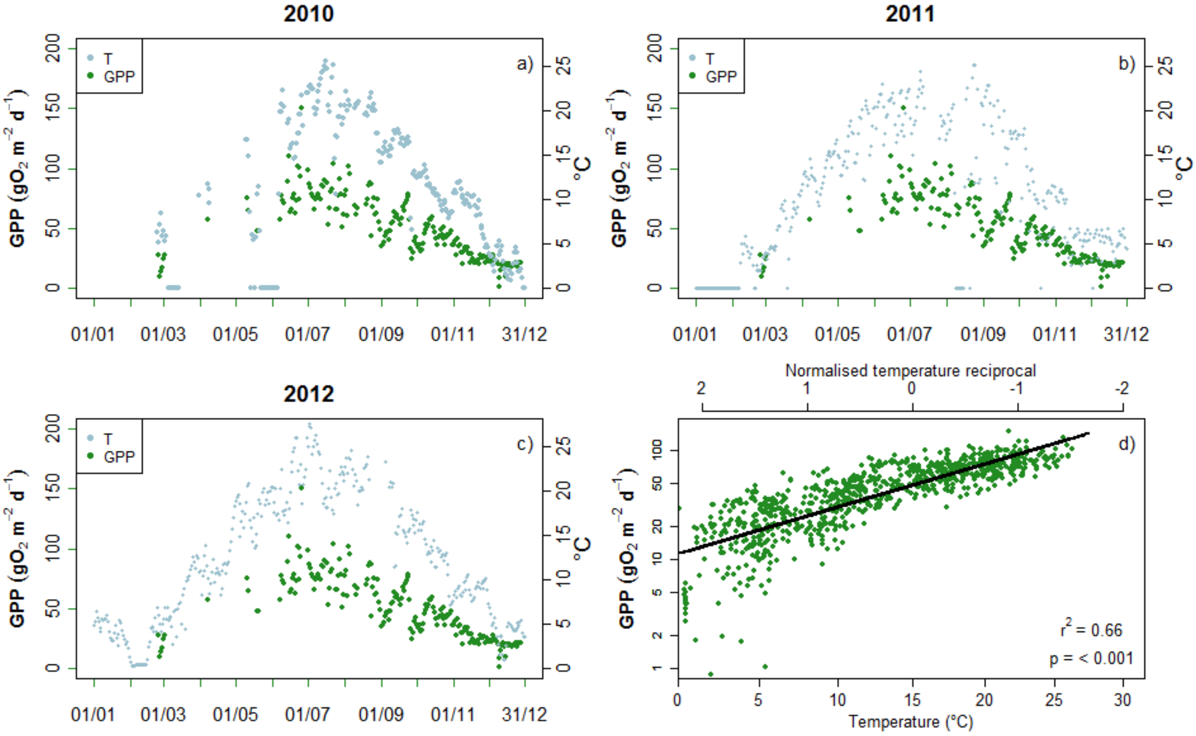

Figure 2: GPP and stream water temperature in the river Schwechat in the years 2010-2012 (a-c); GPP response to temperature (d).

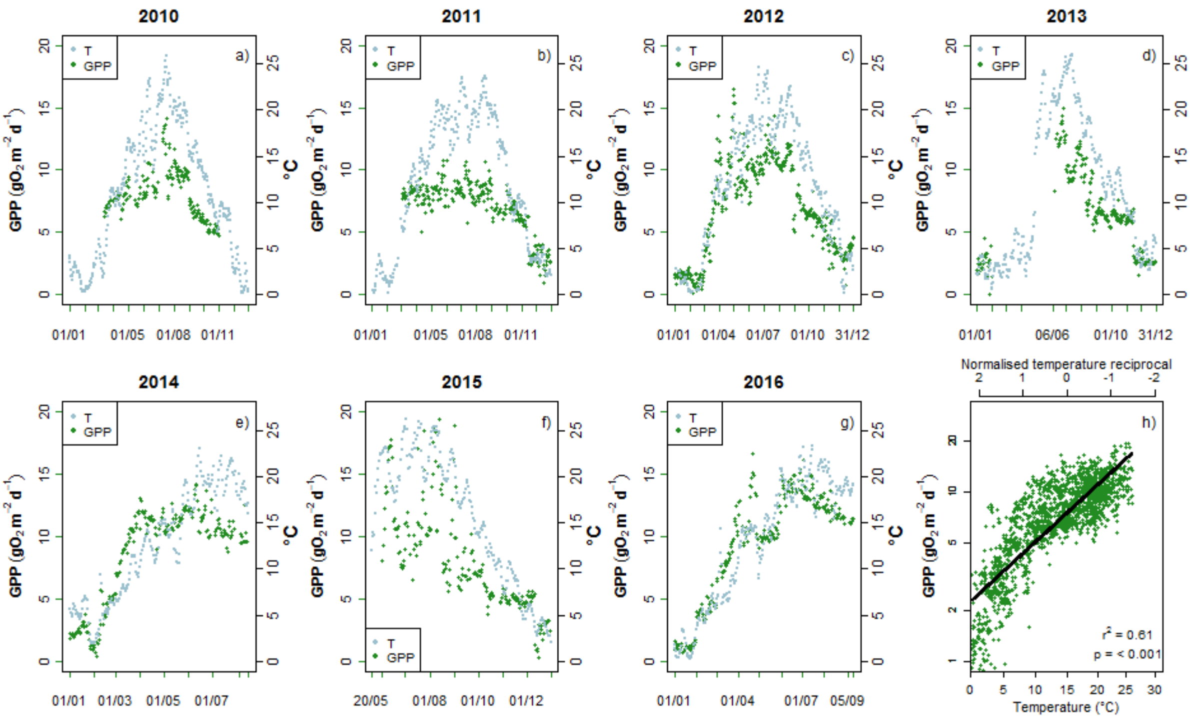

Figure 3: GPP and stream water temperature in the river Raba in the years 2010-2016 (a-g); GPP response to temperature (h).

As shown in Figure 3(a-g), the GPP calculated for the Raba for the years 2010-2016 also followed a pattern very similar to that of stream temperature. The regression between the two variables was found to be highly significant and with an r^2 equal to 0.61 (Figure 3h). Nevertheless, a major difference was detected in the extent of GPP rates, with values not exceeding 20 g O_2 m^{-2} day^{-2} in summer. Further, the Raba shows also a lower slope, i.e. activation energy, of 0.55 eV ± 0.01 eV. The Appendix in the Supplementary Information provides an overview of the average values of basic chemical parameters in the two rivers during the considered periods. The comparison shows that the two rivers, within the considered period, did not show major differences concerning e.g. concentrations of organic matter, nutrients, dissolved oxygen and pH. Therefore, the difference in the magnitude of GPP rates may be primarily attributed to the fact that in the Schwechat light availability is much higher than in the Raba.

In both cases, the calculation of the temperature dependence of GPP is highly sensitive to the considered period of the year. Figure 4 shows the results of the regression analysis performed on the data from April to September aggregated for all available years. Within this limited period, the response of GPP to temperature in the Schwechat was noteworthy, but with a more modest slope of 0.34 eV ± 0.02 eV (Figure 4a), which would imply a lower increase of GPP as function of rising temperature. With a value of 0.35, the coefficient of determination r^2 was lower too, but still within the range found in other studies which determined the temperature dependence of stream metabolism exclusively in summer months (e.g. Demars et al., 2011; Enquist et al., 2003). As for the Raba, on the contrary, a tendency of increasing GPP is still observable, but stream temperature does not seem to be the critical controlling factor in this period. This might have different explanations. In the first place, as mentioned above, light availability could be critical in the Raba. Therefore, fluctuations of turbidity, which are prominent in spring and summer, could explain part of the GPP variability. Another possible reason is the fact that the different algae species, which are dominant through different periods of the year, present distinct biological characteristics and distinct responses to changes in temperature (Wu et al., 2011).

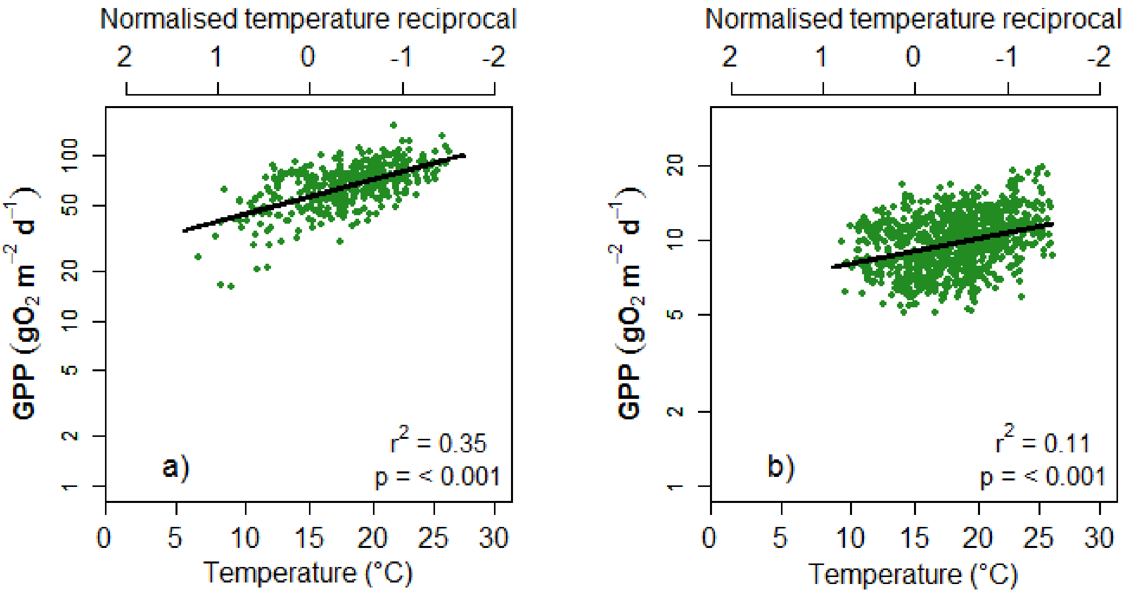

Figure 4: GPP response to temperature in the period April-September: a) in the Schwechat, data aggregated for years 2010-2012; b) in the Raba, data aggregated for the years 2010-2016.

Primary productivity under climate change scenario

The results of the modelled average response of GPP to temperature presented in Figure 2d lead to estimate that in the Schwechat an increase of 1 °C in stream temperature would lead to an increase of GPP of approximately 9%. Following the calculation steps described in the "Materials and Methods" chapter, these results were combined with the concentration of PO_4-P (0.114 mgL^{-1}) modelled for the considered sub-catchment of the river Schwechat under the selected climate change scenario and it was estimated that per 1°C water temperature increase an additional concentration of 0.090 mgL^{-1} would be uptaken. This implies that the remaining concentration of PO_4-P, in the range of 0.024 mgL^{-1}, would not be limiting for further algal or plant growth. If only the period April-September were taken into account instead, the response to rising temperature would approximately correspond to a 5% GPP increase per Celsius degree. This would mean a lower impact of rising temperature on primary

©IWA Publishing [2017]. The definitive peer-reviewed and edited version of this article
is published in Water Science & Technology, Volume 77, Issue 2, 417-425, 2017,
https://doi.org/10.2166/wst.2017.553 and is available at www.iwapublishing.com.
This is the accepted version.

productivity. It would not alter, however, the main conclusion, i.e. that P availability in this river would not be limiting the increase of GPP also in case of the temperature rising above 1°C.

As far as the Raba is concerned, the modelled response of the GPP, according to the results presented in Figure 3h, would approximately correspond to a 7.5% increase per each additional Celsius degree. The combination of this result with the PO_4-P concentration modelled for the climate change scenario in the sub-catchment of the monitoring station, namely 0.033 mg PO_4-P L^{-1}, would imply that the 0.030 mg PO_4-P L^{-1} necessary to allow such modelled increase would be available. Nevertheless, these results also indicate that, following such additional uptake, PO_4-P in-stream concentration would be in the range of 0.003 mgL^{-1}. This means that, contrary to the situation in the river Schwechat, unless nutrients processing and release sharply accelerated too with rising temperature, in the river Raba the remaining phosphorus concentration would be limiting for further intensification of primary productivity. Further, as depicted in Figure 4b, owing to high variability of the data, the response of GPP to temperature change in the Raba during summer months shows a statistically weak relationship. These two outcomes both suggest, therefore, that the river Raba might be less vulnerable to increased eutrophication problems under the considered climate change scenario than the river Schwechat.

These estimations are affected by a considerable degree of uncertainty mainly stemming from three sources. First, as thoroughly discussed by Demars et al. (2015) and Demars and Manson (2013), the calculation of GPP using the open diel oxygen method can be subject to large uncertainties primarily due to the difficult determination of the aeration coefficient. Second, the Redfield ratio, employed to estimate the incremental phosphorus uptake required by rising GPP, despite being a generally valid relationship, can present deviations in different aquatic environments. Last, the discharges and PO_4-P concentrations at low flow conditions predicted for the climate change scenario are the result of an integrated stepwise modelling with multiple assumptions and consequent inherent uncertainties.

These results shall thus not be considered as precise predictions, but rather as approximate estimations of the degree to which primary productivity could be influenced by the rise of temperature and of the potential role played by phosphorus availability in limiting or not the modelled increase of algal and plant growth.

Conclusions

In this work, the gross primary productivity (GPP) and its response to stream temperature were determined for two lowland Austrian rivers with distinct characteristics. In both rivers, the relationship between GPP and temperature was found to be significant and equal to an approximate increase of 7-9% per degree Celsius. However, whereas in the rather shallow river, characterized by high visibility depth and dominated by phytobenthos, high GPP values of about 100 g O_2 m^{-2} day^{-2} were reached in summer, in the deeper murky river with predominant phytoplankton the calculated GPP in the same period did not exceed 20 g O_2 m^{-2} day^{-2}.

These results were combined with the outcomes of an integrated model, which provided discharge and PO_4-P concentration levels for a climate change scenario potentially critical for eutrophication of terrestrial water bodies. The results suggest that in both study sites GPP could increase by 7-9% as consequence of a rise in water temperature by 1°C. An important finding is however the different situation that would follow the additional uptake of nutrients caused by the increasing GPP. In the deeper murky river, PO_4-P would reach very low concentrations, which would be limiting for further primary production. Therefore, if the average atmospheric temperature were to rise more than 1.5°C, an increase of primary productivity by more than 7% would be likely prevented by low nutrients availability. The results depict a very different situation for the shallower and clearer river dominated by phytobenthos. Here, it was estimated that PO_4-P concentrations would allow an increase of GPP well beyond 9% if stream temperature were to raise more than 1°C. These results highlight the importance of considering not only temperature but also nutrients availability in the modelling of the potential impact of climate change on primary productivity in freshwaters.

This contribution puts forward a methodological approach aimed to provide a scientific basis, which shall enable the assessment of potential risks of eutrophication and/or of failed achievement of environmental standards for freshwater ecosystems.

Acknowledgements

This work was part of the "Aqua-Stress" Project: Water resources under climatic stress. An integrated assessment of impacts on water availability and water quality under changing climate and land use (N° KR13AC6K11034). The Climate and Energy Fund, within the sixth Austrian Climate Research Program, funded the project.

©IWA Publishing [2017]. The definitive peer-reviewed and edited version of this article
is published in Water Science & Technology, Volume 77, Issue 2, 417-425, 2017,
https://doi.org/10.2166/wst.2017.553 and is available at www.iwapublishing.com.
This is the accepted version.

References

Allen, A.P., Gillooly, J.F., Brown, J.H., 2005. Linking the global carbon cycle to individual metabolism. Functional Ecology 19, 202–213. doi:10.1111/j.1365-2435.2005.00952.x

BMLFUW, 2015. Hydrographisches Jahrbuch Österreich 2013. Bundesministerium für Land- Und Forstwirtschaft, Umwelt und Wasserwirtschaft.

Camhy, D., Ertl, T., Fuiko, R., Gamerith, V., Gruber, G., Hofer, T., Höller, M., Kinzer, C., Kleidorfer, M., Kornfeind, L., Leonhardt, G., Muschalla, D., Pressl, A., Rauch, W., Steffelbauer, D., Steger, B., Svardal, K., Urich, C., Winkelbauer, A., Winkler, S., 2013. Integrierte Betrachtung eines Gewässerabschnitts auf Basis kontinuierlicher und validierter Langzeitmessreihen. Bundesministerium für Land- Und Forstwirtschaft, Umwelt und Wasserwirtschaft, Vienna.

Demars, B.O. l., Russell Manson, J., Ólafsson, J.S., Gíslason, G.M., Gudmundsdóttir, R., Woodward, G., Reiss, J., Pichler, D.E., Rasmussen, J.J., Friberg, N., 2011. Temperature and the metabolic balance of streams. Freshwater Biology 56, 1106–1121. doi:10.1111/j.1365-2427.2010.02554.x

Demars, B.O.L., Manson, J.R., 2013. Temperature dependence of stream aeration coefficients and the effect of water turbulence: A critical review. Water Research 47, 1–15. doi:10.1016/j.watres.2012.09.054

Demars, B.O.L., Thompson, J., Manson, J.R., 2015. Stream metabolism and the open diel oxygen method: Principles, practice, and perspectives. Limnol. Oceanogr. Methods 13, 356–374. doi:10.1002/lom3.10030

Enquist, B.J., Economo, E.P., Huxman, T.E., Allen, A.P., Ignace, D.D., Gillooly, J.F., 2003. Scaling metabolism from organisms to ecosystems. Nature 423, 639–642. doi:10.1038/nature01671

Fuiko, R., Kornfeind, L., Schilling, K., Weilguni, S., Winkelbauer, A., 2016. Nachhaltige Wassergütewirtschaft Raab. Online - Monitoring. Bundesministerium für Land- Und Forstwirtschaft, Umwelt und Wasserwirtschaft, Vienna.

Gillooly, J.F., Brown, J.H., West, G.B., Savage, V.M., Charnov, E.L., 2001. Effects of Size and Temperature on Metabolic Rate. Science 293, 2248–2251. doi:10.1126/science.1061967

Hall, R.O., Tank, J.L., Baker, M.A., Rosi-Marshall, E.J., Hotchkiss, E.R., 2016. Metabolism, Gas Exchange, and Carbon Spiraling in Rivers. Ecosystems 19, 73–86. doi:10.1007/s10021-015-9918-1

Hornberger, G.M., Kelly, M.G., 1975. Atmospheric reaeration in a river using productivity analysis. J Environ Eng Div Proc Am Soc Civ Eng.

Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J., Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling 192, 362–384. doi:10.1016/j.ecolmodel.2005.07.010

Kirchner, M., Schönhart, M., Schmid, E., 2016. Spatial impacts of the CAP post-2013 and climate change scenarios on agricultural intensification and environment in Austria. Ecological Economics 123, 35–56. doi:10.1016/j.ecolecon.2015.12.009

López-Urrutia, Á., Martin, E.S., Harris, R.P., Irigoien, X., 2006. Scaling the metabolic balance of the oceans. PNAS 103, 8739–8744. doi:10.1073/pnas.0601137103

Odum, H.T., 1956. Primary Production in Flowing Waters1. Limnol. Oceanogr. 1, 102–117. doi:10.4319/lo.1956.1.2.0102

Parajka, J., Merz, R., Blöschl, G., 2007. Uncertainty and multiple objective calibration in regional water balance modelling: case study in 320 Austrian catchments. Hydrol. Process. 21, 435–446. doi:10.1002/hyp.6253

Redfield, A.C., Ketchum, B.H., Richards, F.A., 1963. The influence of organisms on the composition of sea-water. The Sea 26–77.

is published in Water Science & Technology, Volume 77, Issue 2, 417-425, 2017,

https://doi.org/10.2166/wst.2017.553 and is available at www.iwapublishing.com.

This is the accepted version.

Schönhart, M., Schmid, E., Schneider, U.A., 2011. CropRota – A crop rotation model to support integrated land use assessments. European Journal of Agronomy 34, 263–277. doi:10.1016/j.eja.2011.02.004

Schönhart, M., Trautvetter, H., Parajka, J., Blaschke, A.P., Hepp, G., Kirchner, M., Mitter, H., Schmid, E., Strenn, B., Zessner, M., Submitted. Modelled impacts of policies and climate change on land use and water quality in Austria. Agricultural Systems.

Science, A.A. for the A. of, 2001. Corrections and Clarifications. Science 294, 1463–1463. doi:10.1126/science.294.5546.1463

Skøien, J.O., Blöschl, G., 2007. Spatiotemporal topological kriging of runoff time series. Water Resour. Res. 43, W09419. doi:10.1029/2006WR005760

Strauss, F., Formayer, H., Schmid, E., 2013. High resolution climate data for Austria in the period 2008–2040 from a statistical climate change model. Int. J. Climatol. 33, 430–443. doi:10.1002/joc.3434

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses - a guide to conservation planning. Predicting rainfall erosion losses - a guide to conservation planning.

Wu, N., Schmalz, B., Fohrer, N., 2011. Distribution of phytoplankton in a German lowland river in relation to environmental factors. J Plankton Res 33, 807–820. doi:10.1093/plankt/fbq139

Yvon-Durocher, G., Jones, J.I., Trimmer, M., Woodward, G., Montoya, J.M., 2010. Warming alters the metabolic balance of ecosystems. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2117–2126. doi:10.1098/rstb.2010.0038

Zessner, M., Kovacs, A., Schilling, C., Hochedlinger, G., Gabriel, O., Natho, S., Thaler, S., Windhofer, G., 2011. Enhancement of the MONERIS Model for Application in Alpine Catchments in Austria. International Review of Hydrobiology 5, 541–560. doi:10.1002/iroh.201111278

Zessner, M., Schönhart, M., Parajka, J., Trautvetter, H., Mitter, H., Kirchner, M., Hepp, G., Blaschke, A.P., Strenn, B., Schmid, E., 2017a. A novel integrated modelling framework to assess the impacts of climate and socio-economic drivers on land use and water quality. Science of The Total Environment 579, 1137–1151. doi:10.1016/j.scitotenv.2016.11.092

Zessner, M., Schönhart, M., Parajka, J., Trautvetter, H., Mitter, H., Kirchner, M., Hepp, G., Blaschke, A.P., Strenn, B., Schmid, E., 2017b. Aqua-Stress - Water resources under climatic stress. An integrated assessment of impacts on water availability and water quality under changing climate and land use. Klima Energie Fonds, Vienna.