Primary productivity and climate change in Austrian lowland rivers
Ottavia Zoboli, Katerina Schilling, Anna-Lena Ludwig, Norbert Kreuzinger and Matthias Zessner

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 also important to estimate the risk of eutrophication streams will be exposed to in the future. In this work, a methodological approach is developed to create a scientific basis for such assessment and is 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. Results indicate that in both rivers, a 1.5°C warming would provoke an increase of GPP of 7–9% and that such an increase would not be limited by nutrient availability. The results further suggest that the situation for the relatively shallow river might be more critical, given that its GPP values in summer are five times higher than in the deeper murky river.

Key words | climate change, eutrophication, nutrients, primary productivity, stream metabolism, temperature

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 at scaling metabolism from organisms to whole ecosystems (Enquist et al. 2003) and to efforts directed at identifying and quantifying key control factors. Crucial in the context of climate change is understanding 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 (Science 2001; Gillooly et al. 2001; Allen et al. 2005; López-Urrutia et al. 2006; Yvon-Durocher et al. 2010). With an unprecedented experiment carried out in naturally heated geothermal streams, which allowed isolation of 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 inferred 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 therefore seems meaningful and relevant to progress the study of the relationship between climate change and stream metabolism, with a focus not only on the exchange of...
greenhouse gases but also on eutrophication. Furthermore, climate change would not only affect atmospheric temperature, but would also profoundly alter, among other things, 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 estimates 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 that 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 modelled 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 the River Schwechat, which is a rather shallow stream with high visibility depth, and thus dominated by phyto-benthos. It is a tributary of the River Danube, located in eastern Austria. It is characterized by a total length of 70 km, a 1,186 km² wide catchment, and downstream long-term mean annual flow of 8.2 m³ s⁻¹ (BMLFUW 2015). The Raba, another tributary of the River Danube, represents instead deeper murky streams with predominant phytoplankton. It flows for approximately 250 km in the southeast of Austria. Its catchment area covers 1,090 km² and its downstream long-term mean annual flow is 7.1 m³ s⁻¹ (BMLFUW 2015). Figure 1 shows the geographical position of these two rivers, the boundaries of their catchment areas and 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 (O₂) concentration and water temperature available for multiple years, which allowed the estimate 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 by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (Camhy et al. 2015; 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.

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. 2015). 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 (46.950185°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.

**Primary productivity and temperature dependence**

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:

\[
GPP(dt) = \frac{dC}{dt} - k(C_{Sat} - C) + ER + A
\]  

where \(GPP(dt)\) is the variation of GPP in time, \(dC/dt\) the rate of change of \(O_2\) concentration, \(k\) the reaeration coefficient (coefficient of gas exchange at the air-water interface), \(C_{Sat}\) the saturated dissolved \(O_2\) concentration as a function of water temperature, \(C\) the instant dissolved \(O_2\) concentration, \(ER\) the ER 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 & 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 studied, 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 using 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:

\[
\ln(GPP) = \ln(c) - \frac{1}{E} \left( \frac{1}{T} - \frac{1}{T_{Ref}} \right)
\]

(2)

where GPP is the gross primary productivity per unit area (g O₂ m⁻² d⁻¹), the intercept ln(c) is the normalized absolute GPP (g O₂ 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, respectively.

**Climate change scenario**

Zessner et al. (2017a) recently developed a novel integrated impact 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 exceeding environmental quality standards set for nutrient concentrations by the Water Framework Directive for surface waters. To do so, the framework combines runoff-prediction modelling (TUW model, Parajka et al. 2007; Top-kriging interpolation, Skøien & Blöschl 2007), mathematical optimization of agricultural land use (EPIC, Izaurralde et al. 2006; CropRota, Schönhart et al. 2011; PASMAgrid, Kirchner et al. 2016), and catchment-scale nutrient emissions modelling (USLE, Wischmeier & Smith 1978; MONERIS, Zessner et al. 2011). Both single models and the integrated framework were validated upon, among others, observed land use, crop production, fertilizer application, river discharges and river nutrient loads. The performance of the integrated modelling for calculating river nutrient loads (evaluated on 120 monitoring stations) shows a Nash-Sutcliffe Efficiency of 0.73 for nitrogen and 0.51 for phosphorus. In catchments with a high agricultural share, such as the one of the River Raba, the IIMF achieves better results, with only 30% of cropland and 25% 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 exceeding environmental quality standards for nutrient 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 warming 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, for rainfall-runoff current climate models provide highly uncertain and contrasting predictions. Therefore, Schönhart et al. (submitted) developed scenarios which differ from each other concerning rainfall-runoff changes: (i) scenario similar with a distribution of total precipitation similar to the past, (ii) scenario wet with a precipitation increase of 20%, and (iii) scenario dry with a decrease in precipitation of 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, i.e. the scenario in which Austrian rivers would become 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 in precipitation of 20%. The primary reason for this scenario being the most critical in view of the risk of exceeding environmental quality standards is that, although the reduction of run-off would lead to slightly lower diffuse nutrient emissions, this effect would be offset by the considerably higher in-stream nutrient concentrations in summer due to lower river discharges.

**Nutrient uptake**

The extended Redfield ratio (Redfield et al. 1963) depicts the general molar relationship between O₂ production and uptake of C, nitrogen (N) and phosphorus (P) during the process of photosynthesis in the aquatic environment and is as follows: C:N:P = O₂ = 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 a function of increasing GPP. The calculated temperature dependence provides an estimate of the theoretical increased amount of oxygen production each time the temperature increases by 1°C. Through the extended Redfield ratio, this amount is translated into the theoretical increased requirement of phosphorus as a function of rising temperature. Since the ratio P:O₂ = 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 section delivers estimates of nutrient loads and concentrations at the sub-catchment scale, i.e. estimates of the phosphorus that would be available for primary production. The modelled PO₄-P concentration for the reference period in the sub-catchment of the Schwechat studied is 0.12 mg L⁻¹, whereas the observed mean concentration (as reported in the Supplementary Information, available with the online version of this paper) was 0.08 mg PO₄-P L⁻¹. The modelled concentration in the selected climate change scenario was 0.14 mg PO₄-P L⁻¹. In order to better align the results to the actually observed conditions, in this study a mean concentration of 0.10 mg PO₄-P L⁻¹ is assumed for the climate change scenario, which corresponds to the sum of the observed mean value and the difference between the model results for the reference period and the climate change scenario.

As far as the Raba is concerned, the performance of the model in depicting the observed concentration is better than for the Schwechat, with the modelled value being 0.06 mg PO₄-P L⁻¹ and the observed value 0.05 mg PO₄-P L⁻¹. Given that the modelled concentration for the climate change scenario is 0.08 mg PO₄-P L⁻¹ and to ensure methodological consistence in the analysis of the two rivers, the concentration used in this study for the climate change scenario is 0.07 mg PO₄-P L⁻¹.

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 sub-catchments studied (equal to 0.23 km² for the Schwechat and to 0.30 km² for the Raba).

**RESULTS AND DISCUSSION**

**Primary productivity and temperature dependence**

Figure 2(a)–(c) depict 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 nil in winter up to 50–100 g O₂ m⁻² day⁻¹ 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 2(d)), 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).

As shown in Figure 3(a)–3(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 3(h)). Nevertheless, a major difference was detected in the range of GPP rates, with values not exceeding 20 g O₂ m⁻² day⁻¹ in summer. Further, the Raba shows also a lower slope, i.e. activation energy, of 0.55 eV ± 0.01 eV.

The Supplementary Information (available with the online version of this paper) provides an overview of the average values of basic chemical parameters in the two rivers during the periods studied. The comparison shows that the two rivers, within the those periods, 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. This consideration is supported by the comparison of the total suspended solids (TSS) values measured at baseflow conditions, which are reported in the Supplementary Information. Whereas the Schwechat showed, in the period studied, mean and 90%ile TSS values of 6.5 mg L⁻¹ and 12 mg L⁻¹ respectively, the same values in the Raba were 24 mg L⁻¹ and 53 mg L⁻¹ respectively. This is also in line with the large differences in the relevance of phosphorus emissions in the two catchments shown in Table 2. Whereas in the Schwechat they are clearly dominated by effluent discharges of wastewater treatment plants, in the Raba it is agricultural erosion that plays a major role. In both cases, the calculation of the temperature dependence of GPP is highly sensitive to the time of 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 4(a)), which would imply a lower increase of GPP as function of warming. With a value of 0.35, the

![Figure 3](https://iwaponline.com/wst/article-pdf/77/2/417/242528/wst077020417.pdf)

**Figure 3** | GPP and stream water temperature in the River Raba in the years 2010-2016 (a)–(g); GPP response to temperature (h).
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. Enquist et al. 2003; Demars et al. 2011). 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 that are dominant through different periods of the year present distinct biological characteristics and distinct responses to changes in temperature (Wu et al. 2011).

**Primary productivity under climate change scenario**

The results of the modelled average response of GPP to temperature presented in Figure 2(d) lead to the estimate that in the Schwechat a rise of stream temperature of 1 °C would lead to an increase in GPP of approximately 9%. Following the calculation steps described in the ‘Materials and Methods’ section, this result was combined with the concentration of PO$_4$-P (0.10 mg L$^{-1}$) estimated for the sub-catchment of the River Schwechat studied under the selected climate change scenario and it was estimated that per 1 °C water temperature increase an additional concentration of 0.090 mg PO$_4$-P L$^{-1}$ would be taken up. This implies that the remaining concentration of PO$_4$-P, about 0.01 mg L$^{-1}$, would not be strictly limiting for further algal or plant growth, but it would not allow another 9% increase if the temperature were to rise by more than 1 °C, unless warming also induced a sharp acceleration of nutrient processing and release. If only the period April–September were taken into account instead, the response to warming would approximately correspond to a 5% GPP increase per degree Celsius. This would mean on the one hand a lower relative impact of warming on primary productivity. On the other hand, however, this would also imply a more modest nutrient uptake and the possibility of further GPP increases if the temperature rose by more than 1 °C.

As far as the Raba is concerned, the modelled response of the GPP, according to the results presented in Figure 3(h), would approximately correspond to a 7.5% increase per each additional degree Celsius. The combination of this result with the PO$_4$-P concentration estimated for the climate change scenario in the sub-catchment of the monitoring station, namely 0.07 mg PO$_4$-P L$^{-1}$, would imply that the 0.050 mg PO$_4$-P L$^{-1}$ necessary to allow the modelled increase would be largely available. These results also indicate that, following this additional uptake, PO$_4$-P in-stream concentration would be about 0.04 mg L$^{-1}$. This means that, contrary to the situation in the River Schwechat, enough P would be available for further intensification of primary productivity in case of a temperature rise above 1 °C. As depicted in Figure 4(b), however, owing to the high variability of the data, the response of GPP to temperature change in the Raba during the summer months shows a statistically weak relationship. This outcome, combined with the much lower magnitude of primary production in the river, suggests that the River Raba might be less vulnerable.

![Figure 4](https://iwaponline.com/wst/article-pdf/77/2/417/242528/wst077020417.pdf)
to increased eutrophication problems under the selected climate change scenario than the River Schwechat.

These estimates are affected by a considerable degree of uncertainty stemming mainly from three sources. First, as thoroughly discussed by Demars et al. (2015) and Demars & Manson (2015), the calculation of GPP using the open diel oxygen method can be subject to large uncertainties primarily due to the difficulties in determining 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 PO₄-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 estimates 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 limiting) the modelled increase of algal and plant growth.

CONCLUSIONS

In this work, the 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 O₂ m⁻² day⁻¹ were reached in summer, in the deeper murky river with predominant phytoplankton the calculated GPP in the same period did not exceed 20 g O₂ m⁻² day⁻¹.

These results were combined with the outcomes of an integrated model, which provided discharge and PO₄-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 of 1 °C as it would not be limited by phosphorus availability. An important finding is, however, the different scenario that would follow the additional uptake of nutrients caused by the increasing GPP. In the shallow river, PO₄-P would reach very low concentrations, which would be limiting for further primary production. Therefore, if the average atmospheric temperature were to rise more by than 1.5 °C, an increase of primary productivity of more than 9% would be likely prevented by low nutrient availability. The results depict a very different situation for the deeper and murky river dominated by phytoplankton. Here, it was estimated that PO₄-P concentrations would allow an increase of GPP well beyond 7% if the stream temperature were to rise by more than 1 °C. These results highlight the importance of considering not only temperature but also nutrient availability in the modelling of the potential impact of climate change on primary productivity in freshwater ecosystems.

This contribution puts forward a methodological approach aimed at providing a scientific basis for enabling 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, under the sixth Austrian Climate Research Programme, funded the project.

REFERENCES


