Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 3, September 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I3/AF260320

Metabolic Adaptation of Indigenous Bacterial Communities to Organic Loading in Polluted Freshwater Ecosystems

[1*] Dmitri Volkov, Eurasian Institute for Technology Futures, Moscow, Russia.

[2] Elena Petrova, Eurasian Institute for Technology Futures, Moscow, Russia.

Abstract: Organic enrichment may lead to increased carbon consumption by bacteria in combination with enhanced oxygen demand in contaminated freshwater ecosystems. Understanding such behavior necessitates distinguishing between metabolism and the efficiency of biomass formation. The current paper formulates an explicit and transparent model relating the amount of available carbon, bacterial growth efficiency, and oxygen demand due to aerobic respiration. Freshwater research is considered to provide guidance for the choice of processes used, with numerical analysis based on explicitly postulated functions rather than measurements in the field. Five artificial scenarios of carbon concentration, ranging from 2 to 40 mg C L^{-1} are considered, taking into account the saturated uptake process, additional high concentration inhibition, and decreasing bacterial yield. Growth efficiency decreases from 42.86% to 22.50%. The initial oxygen demand rises from 2.53 mg O_2 L^{-1} d^{-1} for 2 mg C L^{-1} to 6.42 mg O_2 L^{-1} d^{-1} for 20 mg C L^{-1}, and declines to 5.66 mg O_2 L^{-1} d^{-1} for 40 mg C L^{-1}. Such results illustrate how low efficiency may go hand-in-hand with high oxygen consumption but do not prove adaptation, thresholds of local contamination, and restoration success. Comparative studies of bacterial production and respiration rates, chronic pollution experiments, and analysis of community structure need to be done in order to test the proposed explanation. This theoretical approach offers a consistent starting point for developing such studies.

Keywords: Bacterial Growth Efficiency; Dissolved Organic Carbon; Freshwater Pollution; Metabolic Response; Oxygen Demand; Indigenous Bacteria.

(Submitted: May 29, 2026; Revised: July 10, 2026; Accepted: August 31, 2026; Published: September 30, 2026)

I. Introduction

Indigenous bacterial communities help in the transformation of organic matter from freshwater into biomass and respiratory products. The chemical composition of the available material can also influence nutrient cycling and microbial interactions. Studies conducted in lakes with different sources of organic matter demonstrate the importance of considering carbon quality in addition to quantity when analyzing bacterial processes (Wan et al., 2023).

1.1 Organic Enrichment and the Interpretation of Metabolic Change

However, an increase in organic carbon does not indicate its biological destination. Some are used for growth, some will be respired, and some may be unavailable throughout the observation period. A study conducted in a tropical river shows the relationship between microbial processing and organic matter stoichiometry and hydrological environment, which proves that the equal importance of carbon concentration and elemental perspective is essential (Cuevas-Lara et al., 2024). It is important to consider not only how much carbon is processed but also how efficiently the process contributes to the growth of biomass. The bacterial growth efficiency indicates the proportion of carbon used for the purpose of production. In addition to the examination of a freshwater lake, grazing and viruses are other factors responsible for affecting the distribution of bacterial carbon. Substrate availability is thus one among several factors in the case. There is no meaning in attempting interpretation through the use of an organic pollution gradient alone (Pradeep Ram et al., 2024). Indigenous bacteria in this context refer to those bacteria which reside in the freshwater receiving environment prior to an enrichment event. Indigenous in this case does not mean that all bacteria identified arise within the receiving environment. Through experiments with terrestrial leaves, it is evident that some organisms brought along with them can be involved in the succession process (Vesamäki et al., 2024).

1.2 Aim and Analytical Contribution

It is to develop a testable relationship between organic enrichment, carbon distribution, and oxygen demand without assigning unmeasurable properties to a particular microbial community. The specific goals are to establish two metrics of metabolism, compute their values assuming certain facts, investigate sensitivity to high concentration inhibition, and indicate what evidence will validate their biological significance. The contribution is the interpretation framework and the scenario computation procedure rather than a new environmental data set. "Organic loading" in the title is used in a general environmental sense. The quantitative input is available organic carbon concentration, mg C L^{-1}. A concentration is an inventory; it is not a rate of mass flow per unit time. It can be converted into loading rate using discharge, volume of receiving water, detention time and the pattern of flow. The values of scenario levels, therefore, cannot be taken as discharge criteria.

II. Literature Review

Nutrient enrichment can modify microbial communities along distinct paths depending on degradation and recovery processes. Studies of urban rivers suggest the presence of hysteretic and asynchronous dynamics in microbial assemblages, implying that recovery of biota cannot follow the same pathway as degradation (Shang et al., 2024). This suggests the need for multiple samples in the process of nutrient enrichment followed by relief, rather than a one-time sampling from enriched and non-enriched sites. Both organic and inorganic additions of phosphorus can lead to different bacterioplankton responses. In an experiment of a freshwater microcosm, phosphorus addition was shown to affect bacterial abundance and communities, making the consideration of nutrient enrichment explicit necessary (Tu et al., 2025). This implies that carbon addition needs to be considered along with nitrogen and phosphorus in enrichment experiments.

The physical environment may also limit metabolic rates. A study conducted on a boreal stream involves both laboratory experiments and whole-stream metabolism and shows that temperature and flow are significant regulators of organic carbon turnover (Iannucci et al., 2024). This leads to the need for distinguishing between the inherent ability to process material and the actual rate achieved under certain residence time, temperature, or mixing regimes. The current computations assume these variables to be constant and thus represent a limited comparison. Light provides another way. Field studies on freshwater aerobic anoxygenic photoheterotrophic bacteria show that light-dependent energy gain affects carbon fluxes and decreases respiration in comparison with the dark state (Piwosz et al., 2022). This means that respiration measurement in the absence of light represents a specific experiment condition rather than the full daily activity of the naturally light-exposed population. The quality of carbon may influence nutrient availability. Experimental results from a lake at a high altitude demonstrate different behaviors of bacteria when subjected to algal and soil organic matter, as well as the combined effect of carbon and nutrients (Dory et al., 2024). The same concentration-response relationship cannot fit all substrate combinations. The constants in this equation should be conditional on the source and fraction analysis of available carbon.

2.1 Stress Interactions and Temporal Variability

Non-linear metabolism could occur in freshwater ecosystems as well. However, the exact response of metabolism depends on the stressor applied. There are experiments on freshwater ecosystem gradient showing the stimulation by followed stress and different responses depending on changes in oxygen levels (DeVilbiss et al., 2024). This serves as evidence of process-driven research but cannot explain if organic carbon will show the same behavior or verify the use of inhibition chosen here. The timing of disturbance is essential as well. Rainfalls even smaller than in the case of drought can influence stream sediment respiration resulting in organic carbon emission (Coulson et al., 2022). Thus, sampling may not catch the moment when bacteria exhibit metabolic response. On the larger level, there is the presence of observed de-oxygenation in temperate lakes which stresses the ecological significance of oxygen measurement in

carbon processing (Jane et al., 2021). This is not enough to define the universal load value for bacteria acclimation.

The analytic problem being tackled here is that of separating carbon allocation from oxygen consumption in a single calculable equation. The relevant literature demonstrates the ecologic significance of this relationship but fails to provide a parameter set for the scenario suggested. The model exposes the assumptions being made as well as possible observations that would falsify the assumptions. It does not imply that the pairing of production and respiration is novel or ubiquitous.

III. Materials and Methods

3.1 Study Design and Evidence Status

This is a deterministic scenario analysis based on selected recent research. No freshwater samples, bacterial isolates, sequencing libraries, or laboratory incubations were created. Selected published studies are relevant to the decomposition of freshwater organic matter, carbon partitioning of bacteria, or environmental constraints. Such a targeted selection is not a systematic review or a meta-analysis, nor is any effect size computed. All numbers are based on the equations and parameters listed below.

Five available carbon scenarios are S = 2, 5, 10, 20, and 40 mg C L^{-1}. This range covers a twentyfold difference for comparison purposes only; they are not actual measurements or pollution categories. Temperature, nutrients, light, bacterial standing stock, and oxygen availability are considered fixed boundary conditions. Effective volume capacity is the number of bacteria with unchanged standing stock over a brief period of an assay.

3.2 Carbon Uptake Function

Carbon conversion rate potential U is computed as follows: U is computed as saturating substrate times high concentration inhibition:

$$U(S) = V \times S/(K + S) \times exp(-S/H) \quad (1)$$

In this case, U is presented in mg C L^{-1} d^{-1}; V = 6 mg C L^{-1} d^{-1} is the assumed volumetric capacity; K = 5 mg C L^{-1} is the half-saturation coefficient of the substrate component; and H = 60 mg C L^{-1} is the assumed baseline inhibition coefficient. Every ratio in the equation is dimensionless. The exponential multiplier is an assumption that indicates an aggregate limitation related to enrichment. Equation (1) is a phenomenological equation. The inhibition term in this equation can only show co-varying constraints for the level of a proposed model, but it cannot show a causal mechanism. The oxygen limitation is not considered in this equation since the calculation of oxygen demand will be performed under the condition of aerobic potential. Where the oxygen is limiting, there should be an oxygen limitation equation.

3.3 Growth Allocation Function

The allocation of carbon processing into bacterial production can be described with the use of equation (2):

$$Y(S) = Y_{\max}/(1 + S/J) \quad (2)$$

The assumed maximum yield value is Y_{max} = 0.45, and the allocation constant is J = 40 mg C L^{-1}. These numbers are parameters of a particular scenario and do not constitute any estimates derived from the studies cited above. Higher concentration decreases Y by definition. Thus, lower efficiency in the results indicates the consequence of this hypothesis.

3.4 Carbon Balance and the Two-Outcome Metrics

Production P and respiratory carbon loss R divide the potential processed carbon. They have the same units U and adhere to the explicit carbon balance equation (3):

$$P = YU; \quad R = (1 - Y)U; \quad P + R = U \tag{3}$$

The partition does not include any storage process, extracellular product formation, or mortality. These factors would need to be included for a more prolonged incubation period. The limited balance ensures that the same carbon is not double-counted in both the growth and respiration losses.

$$BGE = 100 \times P/(P + R) = 100Y \tag{4}$$

The first outcome measure is bacterial growth efficiency BGE, as a percentage, presented in table 1. In a subsequent experiment, P and R will be measured independently and then used to calculate BGE using equation (4-5). In the case under consideration, the equality BGE = 100Y can be derived immediately from the imposed allocation function. BGE is a fraction of carbon allocation and must not be considered the percentage of environmental carbon pool depletion.

$$Q = (32/12) \times R/RQ. \tag{5}$$

The second outcome is aerobic oxygen demand, Q, in mg O2 L^-1 d^-1, which is illustrated in figure 1. Respiratory quotient, RQ, is defined as the molar ratio of carbon dioxide output to oxygen intake and is assumed constant at 1. Constant 32/12 is used for converting respiratory carbon mass to oxygen mass according to the RQ. Nitrification, sediment demand, photoreactions, and respiration of other organisms are excluded from the computation. Thus, this is neither the overall oxygen consumption of the ecosystem nor a five-day biological oxygen demand test.

3.5 Sensitivity Analysis and Verification

The inhibition level H is varied to 40 and 80 mg C L^{-1}, whereas all other parameters are kept constant. This alternative evaluates the sensitivity to weak or strong inhibition within the chosen family of models. This is not a confidence interval or a probability distribution. The computations are done on a continuous concentration grid between 0 and 40 mg C L^{-1} for the figure and at the five specified levels for presentation. The verification conditions are $U \geq 0$, $0 \leq Y \leq 1$, $P + R = U$, and $Q = 0$ if $S = 0$. All the numbers are computed prior to rounding and presented to two decimal digits. No statistical significance testing, standard errors, biological replicates, or confidence intervals are shown because the deterministic scenarios have no sampling variation.

IV. Results

4.1 Growth Efficiency Across the Synthetic Carbon Gradient

Table 1 shows the first performance measure. The computed BGE decreases from 42.86% at 2 mg C L^{-1} to 22.50% at 40 mg C L^{-1}. This represents an absolute drop of 20.36 percentage points and a relative decrease of 47.50%. In between these two concentrations, i.e., at 20 mg C L^{-1}, the simulated community devotes 30.00% of their processed carbon to production, and the rest for respiration.

Table 1: Calculated Bacterial Growth Efficiency under Synthetic Available-Carbon Scenarios. Values are Model Outputs Rather than Observations

Scenario	Available carbon S (mg C L^{-1})	Bacterial growth efficiency (%)
A	2	42.86
B	5	40.00
C	10	36.00
D	20	30.00
E	40	22.50

The assumed allocation function provides a gradual decrease, rather than a sharp change point. For 5 and 10 mg C L^{-1}, BGE is 40.00% and 36.00%, respectively. No scenario gives a threshold that differentiates

between an adapted and a damaged community. This table represents a continuous mathematical equation whose biological meaning would be dependent on independently measured production and respiration.

4.2 Carbon Partitioning Behind the Efficiency Response

On the basis of the baseline assumptions, the potential carbon processing increases from about 1.66 mg C L^{-1} d^{-1} for 2 mg C L^{-1} to 3.44 mg C L^{-1} d^{-1} for 20 mg C L^{-1}. For 40 mg C L^{-1}, the potential carbon processing decreases to 2.74 mg C L^{-1} d^{-1}. This kind of processing response is the result of the competition between substrate saturation and the applied inhibition multiplier. The BGE at the highest concentration level, therefore, correlates with a lower processing rate compared to the intermediate scenario. These values help differentiate between allocation and total activity. A small growth fraction, on the other hand, does not say anything about the size of the amount being respired. Multiplication of the total processing rate is necessary to find the carbon loss through respiration and the potential oxygen demand.

4.3 Potential Oxygen Demand and Parameter Sensitivity

The second parameter for measuring results is depicted in figure 1. Baseline values of potential oxygen demand are 2.53, 4.42, 5.78, 6.42, and 5.66 mg O_2 L^{-1} d^{-1} for five levels of rising carbon concentration. Potential oxygen demand for 20 mg C L^{-1} is 2.54 times higher than the demand at 2 mg C L^{-1}. The next decline in 40 mg C L^{-1} is 11.85%, although BGE is decreased as seen in table 1.

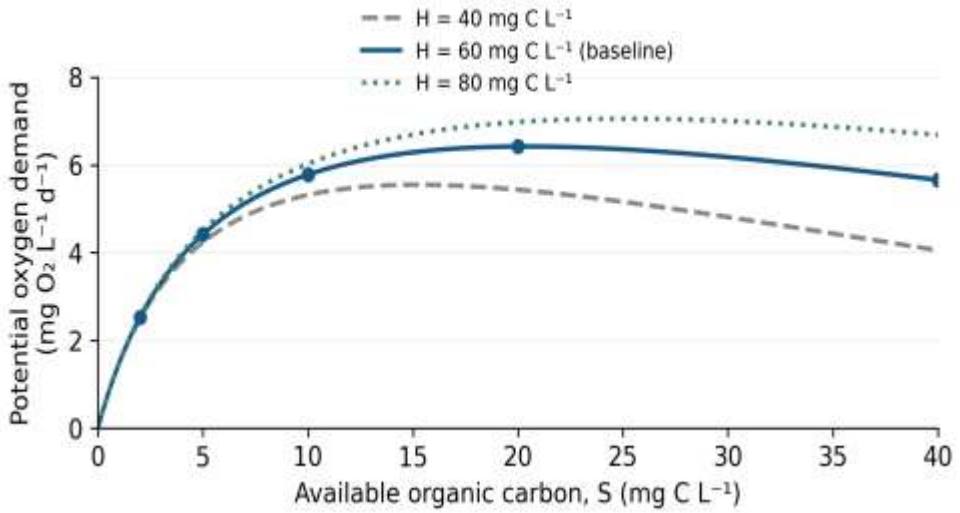


Figure 1: Potential Aerobic Oxygen Demand Across a Synthetic Available-Carbon Gradient

The baseline curve has H = 60 mg C L^{-1}; the others change in H only. Labels denote the five baseline cases. All curves are deterministic computations, not observations or confidence bands. Source: Equations (1) – (5). When H = 40 mg C L^{-1}, switching H from 60 to 40 mg C L^{-1} reduces demand from 5.66 to 4.05 mg O_2 L^{-1} d^{-1}. Switching H up to 80 mg C L^{-1} increases it to 6.69 mg O_2 L^{-1} d^{-1}. This produces a difference of 2.64 mg O_2 L^{-1} d^{-1} at the same carbon concentration. BGE is equal in these cases because equation (2) doesn't include H.

4.4 Joint Interpretation of the Two Metrics

However, the situation which has the lowest BGE does not show the highest demand for oxygen. In the case of high amounts of carbon, assuming the inhibition takes place lowers the processing level enough to compensate for the higher ratio of respiration. An oxygen consumption drop in such situations would thus be unclear without any measurement of the production level and determination of the remaining carbon amount. It could indicate lowered metabolic activity instead of better environmental conditions. This is implied by the given equations.

V. Discussion

5.1 Metabolic Adjustment and the Evidence Required for Adaptation

The scenario analysis distinguishes between two possible interpretations that are usually lumped together under metabolic adaptation. A temporary shift in allocation may reflect physiology while a long-lasting improvement in efficiency due to exposure would require the time component to be tested. Community replacement is a way to maintain a bulk process while altering its agents. The current model has no history of exposure, inheritance, turnover of the population, or specific traits of the taxa, therefore it can reflect the metabolic response hypothesis, but cannot prove adaptation. To validate the empirical approach to testing the hypothesis, the comparison of communities with varied enrichment history under common assay conditions is needed. The effect of repeated exposure with a period of recovery would help to determine if the response is long-lasting while reciprocal treatments of substrates would help to separate the effect of source-water from that of community history. The paired production and respiration measurements would relate these biological comparisons to the metrics chosen. Independent sampling of the source water would serve as biological replication while several bottles from the same sample would be technical replicates.

5.2 Oxygen Implications and Environmental Management

In summary, the key insight here is that efficiency and oxygen demand address different questions. The variable BGE refers to carbon allocation from the processing activity, while the variable Q refers to an oxygen demand conditional on the rate and RQ of the processing. A high Q may not preclude active processing but implies oxygen availability. On the other hand, a low Q may imply constraints on processing and accumulation of unprocessed carbon. Interpretation is paired here and the model does not suggest a desirable sign of either of them. To apply the method to the receiving waters, an independent oxygen budget needs to be created which would include oxygen exchange with the atmosphere, photosynthesis, mixing, inflow, sediment-oxygen exchange, and nonbacterial oxygen consumption. Only after creating such oxygen budget, the resulting oxygen demand may be related to oxygen concentration or its deficiency in hours. Currently, Q may be subtracted from a dissolved oxygen level only with a specified period of time and updated processes in this interval.

5.3 Limits of the Model and Routes for Rejection

Some assumptions have been purposely made restrictive. These include a reduction in the yield, an uncalibrated inhibition range, and constant bacteria biomass. Nutrient release, substrate quality, light, and interactions in a community may cause variations from these functional relationships. In a study where there is no decrease or an increase in BGE with enrichment, the equation will not be valid under such conditions. If a monotonic increase in the processing rate takes place in a sufficiently wide controlled gradient, then this reduces the validity of the chosen inhibition term. There should be comparisons of mechanistic alternatives using independent data and identifiable parameters and not just by fitting alone. Sensitivity to inhibition does not cover all the uncertainties because capacity, saturation, allocation, and respiratory quotient are also uncertain.

VI. Conclusion

This paper proposes an evidence-informed analytical model for understanding bacterial reaction to organic enrichment in freshwater systems affected by pollution. There are two variables that differentiate carbon allocation from oxygen usage: bacterial growth efficiency and the potential oxygen demand in aerobic mode. As per synthetic available-carbon concentration levels varying from 2 to 40 mg C L^{-1}, assumed growth efficiency varies from 42.86% to 22.50%. Base oxygen demand goes up from 2.53 to 6.42 mg O_2 L^{-1} d^{-1} at 2 and 20 mg C L^{-1} correspondingly and goes down to 5.66 mg O_2 L^{-1} d^{-1} in case of 40 mg C L^{-1}, whereas modification of the inhibition factor results in the oxygen demand range of 4.05-6.69 mg O_2 L^{-1} d^{-1}. All above figures are the results of calculated functions and are not the measurements, pollution

levels, or adaptation proof. The findings explain why reduction in oxygen use cannot be used as the basis for recovery determination. The empirical study requires independent measurements of production and respiration rates, carbon compound identification, repeated exposure history, and oxygen balance.

References

[1] Wan, L., Cao, L., Song, C., Cao, X., & Zhou, Y. (2023). Regulation of the nutrient cycle pathway and the microbial loop structure by different types of dissolved organic matter decomposition in lakes. *Environmental Science & Technology*, *57*(1), 297-309. https://doi.org/10.1021/acs.est.2c06912

[2] Cuevas-Lara, D., García-Oliva, F., Sánchez-Carrillo, S., & Alcocer, J. (2024). Organic matter processing by heterotrophic bacterioplankton in a large tropical river: Relating elemental composition and potential carbon mineralization. *Plos one*, *19*(11), e0311750. https://doi.org/10.1371/journal.pone.0311750

[3] Pradeep Ram, A. S., Billard, H., Perriere, F., Voldoire, O., & Colombet, J. (2024). Impact of top-down regulation on the growth efficiency of freshwater bacterioplankton. *Microorganisms*, *12*(10), 2061. https://doi.org/10.3390/microorganisms12102061

[4] Vesamäki, J. S., Rigaud, C., Litmanen, J. J., Nissinen, R., Taube, R., & Taipale, S. J. (2024). Recycled by leaf inhabitants: terrestrial bacteria drive the mineralization of organic matter in lake water. *Ecosphere*, *15*(5), e4871. https://doi.org/10.1002/ecs2.4871

[5] Shang, J., Li, Y., Zhang, W., Ma, X., Niu, L., Wang, L., & Zheng, J. (2024). Hysteretic and asynchronous regime shifts of bacterial and micro-eukaryotic communities driven by nutrient loading. *Water Research*, *261*, 122045. https://doi.org/10.1016/j.watres.2024.122045

[6] Tu, T., Li, L., Li, W., Zhang, S., Zhong, H., Ge, G., ... & Wu, L. (2025). Different patterns of bacterioplankton in response to inorganic and organic phosphorus inputs in freshwater lakes-a microcosmic study. *Water Research*, *268*, 122645. https://doi.org/10.1016/j.watres.2024.122645

[7] Iannucci, F. M., Jones Jr, J. B., Olson, K. L., Muscarella, M. E., & Hotchkiss, E. R. (2024). Temperature and flow control organic carbon metabolism in boreal headwater streams. *Journal of Geophysical Research: Biogeosciences*, *129*(10), e2024JG008281. https://doi.org/10.1029/2024jg008281

[8] Piwosz, K., Villena-Alemany, C., & Mujakić, I. (2022). Photoheterotrophy by aerobic anoxygenic bacteria modulates carbon fluxes in a freshwater lake. *The ISME Journal*, *16*(4), 1046-1054. https://doi.org/10.1038/s41396-021-01142-2

[9] Dory, F., Cavalli, L., Franquet, E., Van Wambeke, F., Misson, B., Mounier, S., ... & Bertrand, C. (2024). Algal-and soil-derived dissolved organic matter shapes bacteria-phytoplankton interactions in a high-altitude lake. *Freshwater Biology*, *69*(4), 509-526. https://doi.org/10.1111/fwb.14225

[10] DeVilbiss, S. E., Badgley, B. D., Hotchkiss, E. R., & Steele, M. K. (2024). Subsidy-stress responses of ecosystem functions along experimental freshwater salinity gradients. *Biogeochemistry*, *167*(5), 743-757. https://doi.org/10.1007/s10533-024-01131-5

[11] Coulson, L. E., Weigelhofer, G., Gill, S., Hein, T., Griebler, C., & Schelker, J. (2022). Small rain events during drought alter sediment dissolved organic carbon leaching and respiration in intermittent stream sediments. *Biogeochemistry*, *159*(2), 159-178. https://doi.org/10.1007/s10533-022-00919-7

[12] Jane, S. F., Hansen, G. J., Kraemer, B. M., Leavitt, P. R., Mincer, J. L., North, R. L., ... & Rose, K. C. (2021). Widespread deoxygenation of temperate lakes. *Nature*, *594*(7861), 66-70. https://doi.org/10.1038/s41586-021-03550-y