Supplementary Material: Lake mixing regime selects methane-oxidation kinetics of the methanotroph assemblage

Dependency of the steady-state methane concentration in the epilimnion on the half-saturation constant

We consider a well-mixed epilimnion that contains a microbial species B in µM C that grows on a single carbon substrate S in µM C according to the Monod growth kinetics. Furthermore, we assume that the substrate is released from the sediment of the lake and that the concentration gradient from the sediment to the epilimnion has reached a steady state. In this case, we have a constant volumetric flux F_S in µM C d^{-1} into the epilimnion.

Without microbial growth, exchange with the atmosphere and substrate consumption, the change of the substrate concentration in the epilimnion is simply

$$\frac{dS}{dt} = F_S \tag{1}$$

According to the Monod kinetics, the growth rate r in d^{-1} of the microbial species is:

$$r = V_{max}\frac{S}{S + K_M} \tag{2}$$

where V_{max} is the maximum growth rate in d^{-1} and K_M the half-saturation constant in µM.

Considering a mortality rate m in d^{-1} and a substrate use efficiency y, the temporal change of the bacterial species is:

$$\frac{dB}{dt} = (y \cdot r - m)B \tag{3}$$

Due to the growth of the bacterial species, the substrate concentration in the well-mixed epilimnion decreases with a rate of $-rB$ and the complete system of differential equations is:

$$\frac{dS}{dt} = F_S - rB \tag{4}$$

$$\frac{dB}{dt} = (y \cdot r - m)B$$

Steady-state consideration 1

A complete steady state is reached if both the concentration of the substrate as well as the biomass of the microbial species remain constant over time:

$$\frac{dS}{dt} = 0 = F_S - rB \tag{5}$$

$$\frac{dB}{dt} = 0 = (y \cdot r - m)B$$

By rearranging the second equation, we get an equation for the equilibrium substrate concentration:

$$S^{eq} = \frac{K_M}{y \cdot V_{max}/m - 1} \tag{6}$$

According to equation 6, the equilibrium substrate concentration is indeed a function of the half-saturation constant K_M. However, the equilibrium concentration is not necessarily equal to the half-saturation constant. Depending on the ratio $y \cdot V_{max}/m$ the equilibrium concentration can be lower or higher than the half-saturation constant.

The equilibrium concentration is smaller than the half-saturation constant for $y \cdot V_{max} > 2m$ and is higher than the half-saturation for $m < y \cdot V_{max} < 2m$. Because the maximum growth rate is likely higher than twice the mortality rate, the equilibrium concentration is smaller than the half-saturation constant.

Estimated equilibrium concentration in the epilimnion of Lake Rotsee: In the epilimnion, we measured an average K_M of 1.8 µM. Based on literature values, we can assume a substrate use efficiency of 0.4 (Leak & Dalton, 1986) and a mortality of 0.022 day^{-1} (Roslev & King, 1995). In the epilimnion, we measured an average maximum methane oxidation rate of about 4 fmole h^{-1} $cell^{-1}$. Assuming a cellular carbon content of 0.42 pmole C $cell^{-1}$ (Oswald et al., 2015; Posch et al., 2001; Romanova & Sazhin, 2010) this converts to a maximum methane oxidation rate of 0.2 day^{-1}.

With this, we would expect an equilibrium methane concentration of:

$$S^{eq} = \frac{1.8\ \mu\text{M}}{0.4 \cdot 0.2\ \text{day}^{-1}/0.022\ \text{day}^{-1} - 1} = 0.7\ \mu\text{M} \tag{7}$$

The highest measured maximum methane oxidation rate was 8.4 fmole h^{-1} $cell^{-1}$, which converts to a methane oxidation rate of 0.48 day^{-1}. This higher rate woul result in an equilibrium concentration of about 0.2 µM.

These estimates should be treated with caution because all the values used for the calculation (in particular mortality and cellular carbon content) are fraught with considerable uncertainty. Nonetheless, it demonstrates that the expected methane concentration is lower than the half-saturation constant K_M.

Steady-state consideration 2

In an alternative approach we assume steady-state for the substrate concentration but not for the biomass:

$$\frac{dS}{dt} = 0 = F_S - rB \tag{8}$$

$$\frac{dB}{dt} = (y \cdot r - m)B$$

By rearranging the first equation, we get an equilibrium substrate concentration of:

$$S^{eq} = \frac{F_S \cdot K_M}{B \cdot V_{max} - F_S} \tag{9}$$

Estimated equilibrium concentration in the epilimnion of Lake Rotsee: In the epilimnion, we measured an average K_M of 1.8 µM. With a cellular carbon content of 0.42 pmole C cell^{-1} (Oswald et al., 2015; Posch et al., 2001; Romanova & Sazhin, 2010) and average cell numbers of 0.1x10^5 – 2.5x10^5 cells mL^{-1}, we estimate average biomass of 4 – 105 µM. In the epilimnion we measured an average maximum methane oxidation rate of about 4 fmole h^{-1} cell^{-1}. Using the above cellular carbon content, this converts to a maximum methane oxidation rate of 0.2 day^{-1}. Based on model work (Zimmermann et al., 2019), the median volumetric flux of methane into the epilimnion is 5 µM day^{-1}.

Inserting these values into equation 9 results in an equilibrium methane concentration of 0.6 – 1.5 µM, depending on the amount of biomass (lower equilibrium concentrations with higher biomass). Again, the expected methane concentration tends to be lower than the half-saturation constant K_M.

References

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