Quantifying methane cycling dynamics in Alaskan Arctic lakes

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INTRODUCTION AND STUDY GOALS:

Methane (CH_4) is an important greenhouse gas, and Arctic tundra regions are a key source of CH_4 to the atmosphere. However, little is known about the role of CH_4 in C cycling in the lakes and ponds that cover 20-40% of this ecoregion (Frohn et al., 2005).

Lakes integrate watershed processes by accruing organic matter inputs, and climate change could magnify this effect in the Arctic (Hobbie et al., 1999). Methanotrophy is important in lacustrine food webs, and this role could be amplified in Arctic lakes due to highly oxic water and the simple nature of Arctic trophic structures (Roots, 1989).

I assessed critical components of CH_4 cycling dynamics in Arctic lakes, identifying differences in these processes between shallow and deep lakes, as well as factors regulating CH_4 release from lake sediments. This study will provide a baseline measure of the importance of CH_4 in the carbon (C) budgets of Arctic lakes, against which the impact of future climates can be appraised, and will provide input for process-based climate models.

MATERIALS AND METHODS:

Three shallow (average depth or $\overline{z} \approx 2$ m) and three deep ($\overline{z} \approx 6$ m) lakes in the Arctic Foothills region of Alaska were studied during the thaw seasons of 2010 and 2011. Study lakes were characterized with depth profiles of temperature, O_2, CH_4, chlorophyll *a* (chl *a*), and dissolved organic carbon (DOC).

One clear and two dark benthic chambers (Figure 1) were deployed in each lake to measure exchange of CH_4, dissolved inorganic carbon (DIC), and O_2 at the sediment water interface at $\overline{z}$, with clear chambers controlling for the effects of benthic photosynthesis.

Figure 1: A dark benthic chamber before deployment. Grey cylinder houses a motor that powers an internal 1 rpm stir bar. Samples were collected at the surface via Tygon tubing.

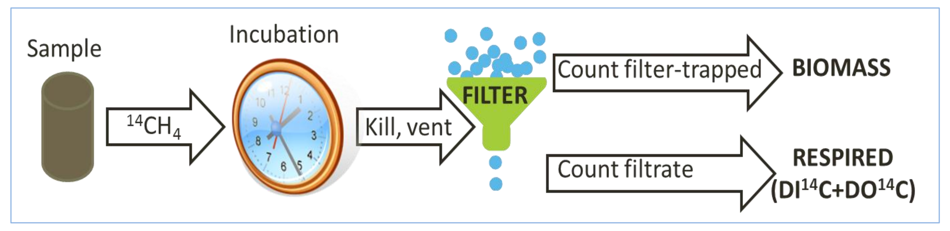

Figure 2: Schematic diagram of $^{14}CH_4$ incubation experiments used to measure CH_4 oxidation activity. Following incubation, samples were killed with NaOH to prevent loss of $DI^{14}C$ in venting.

Methane oxidation was quantified down the water column via $^{14}CH_4$ incubations (Figure 2), and specific (k_{CH4}), volume-based, and whole-lake areal rates of CH_4 oxidation were calculated. Total CH_4 oxidation was subdivided between CH_4 respired and converted to biomass.

Endmember observations of lake surface CH_4 concentration and temperature, along with wind speed data from the Toolik Field Station (TFS) Environmental Data Center (EDC), were used to estimate rates of CH_4 efflux from the study lakes using a simple stagnant film gas transfer model (Broecker and Peng, 1974).

Sediment-water exchange rates were determined by applying a linear fit to benthic chamber dissolved gas concentration data. Due to the small sample size (6 study lakes), nonparametric statistical tests were used for comparisons of means between size classes and chamber types.

RESULTS AND DISCUSSION:

All study lakes stratify thermally in summer, but the shallow lakes mix intermittently in some years. Concentrations of DOC, chl *a*, and CH_4, as well as volume-based CH_4 oxidation rates and k_{CH4}, were extremely low at all depths in the deep lakes, and significantly higher in the shallow lakes (Table 1; Figure 3).

Table 1: Mean and (range) of water column concentrations of chlorophyll a (chl *a*), dissolved organic-C (DOC), and CH_4, and mean and (range) of volume-based and specific (k_{CH4}) rates of CH_4 oxidation in study lakes at the deepest point (z_{max}) of each lake. Deep lake values for all parameters are typically among the lowest reported for lacustrine systems, while shallow lake values are similar to those measured in more productive lakes at lower latitude. Highest bottom water k_{CH4} in the shallow lakes are the largest yet reported.

Study Lake	z_{max}	Size Class	Chl *a* (µg L^{-1})	DOC (µM)	Volume-based CH_4 oxidation rate (µmol L^{-1} d^{-1})	k_{CH4} (d^{-1})	CH_4 (µM)
GTH 99	**4.1**	Shallow	1.43 (1.12-1.81)	377 (326-393)	0.84 (0.013-4.10)	0.72 (0.016-2.85)	2.14 (0.63-15.5)
GTH 112	**6.0**	-	6.98 (1.78-9.87)	591 (507-632)	7.63 (0.46-43.0)	1.12 (0.355-3.64)	7.96 (0.28-52.6)
GTH 114	**6.7**	-	7.59 (2.98-28.3)	618 (561-665)	4.01 (0.001-21.3)	0.41 (0.001-1.21)	1.24 (0.37-17.9)
GTH 100	**15.7**	Deep	0.91 (0.63-1.67)	374 (336-432)	0.008 (<0.001-0.023)	0.095 (0.001-0.234)	0.18 (0.06-0.32)
NE14	**18.7**	-	0.50 (0.26-0.95)	333 (192-462)	0.005 (<0.001-0.025)	0.025 (0.001-0.139)	0.20 (0.06-0.35)
Toolik	**26.3**	-	1.27 (0.51-2.15)	436 (314-591)	0.009 (<0.001-0.020)	0.061 (0.001-0.137)	0.18 (0.13-0.27)

RESULTS AND DISCUSSION, CONT.:

Whole-lake areal rates of CH_4 oxidation were also significantly greater in shallow lakes, averaging 591 µmol C m^{-2} d^{-1}, compared to 12 µmol C m^{-2} d^{-1} in deep lakes. Methanotrophic biomass production accounted for roughly 30% of those rates, corresponding to 1 to 5% of previously reported phytoplankton biomass production in shallow lakes, but only 0.1% in deep lakes (Miller et al., 1986; Whalen et al., 2006, 2008).

There was a net accumulation of CH_4 in nearly all benthic chambers in all lakes (cf. Figure 4). Overall, oxidation-corrected sediment-water CH_4 fluxes were significantly larger in the dark chambers than in the clear, and both dark and clear corrected CH_4 fluxes were significantly higher in shallow lakes (Table 2). Methane accounted for 20% of sediment catabolism on average in the shallow lakes, significantly higher than the mean of 2% in the deep lakes.

Sediment emission of CH_4 was regulated by dissolved O_2 (Figure 5), as is widely reported for lakes, and therefore indirectly by light, as demonstrated in wetlands by King (1990). Clear chamber CH_4 fluxes reflect typical summer conditions, while dark chamber CH_4 fluxes may be similar to those that occur in the winter; a storage flux of CH_4 may therefore be significant in the annual CH_4 budgets of the study lakes.

Corrected sediment-water CH_4 flux was significantly correlated (R^2=0.40) with C sedimentation rates given in Bretz (2012), which in turn were positively related (R^2=0.60) to water column chl *a* concentrations. The C:N ratios of sedimenting material were similar to those of phytoplankton biomass (Bretz, 2012), and DOC concentrations were decoupled from catchment area (R^2<0.001). Therefore, despite the oligotrophic nature of the study lakes, sediment C mineralization and sediment-water CH_4 exchange appear to be heavily influenced by autochthonous inputs, particularly in shallow lakes.

Table 2: Rates of C sedimentation (mmol m^{-2} d^{-1}; Bretz, 2012), net sediment inorganic C flux (mmol m^{-2} d^{-1}), corrected CH4 flux (mmol m^{-2} d^{-1}), and % of inorganic C flux comprised of CH_4. All were significantly greater in the shallow lakes.

Study Lake	Size Class	Sedimented C	Corrected CH_4 Flux	Inorganic C Flux (CH_4 + CO_2)	CH_4 % of Inorganic C Flux
GTH 99 Dark	**Shallow**	7.3	2.06	8.8	23.3
GTH 99 Clear	-	7.3	0.71	3.2	22.5
GTH 112 Dark	-	7.0	2.96	11.0	26.8
GTH 112 Clear	-	7.0	3.23	9.7	33.5
GTH 114 Dark	-	8.2	0.651	8.7	7.5
GTH 114 Clear	-	8.2	0.24	4.5	5.3
GTH 100 Dark	**Deep**	0.5	0.007	2.8	0.3
GTH 100 Clear	-	0.5	-0.001	1.9	-0.1
NE14 Dark	-	0.4	0.39	7.0	5.6
NE14 Clear	-	0.4	0.002	1.9	0.1
Toolik Dark	-	0.7	0.398	6.6	6.1
Toolik Clear	-	0.7	0.017	3.7	0.5

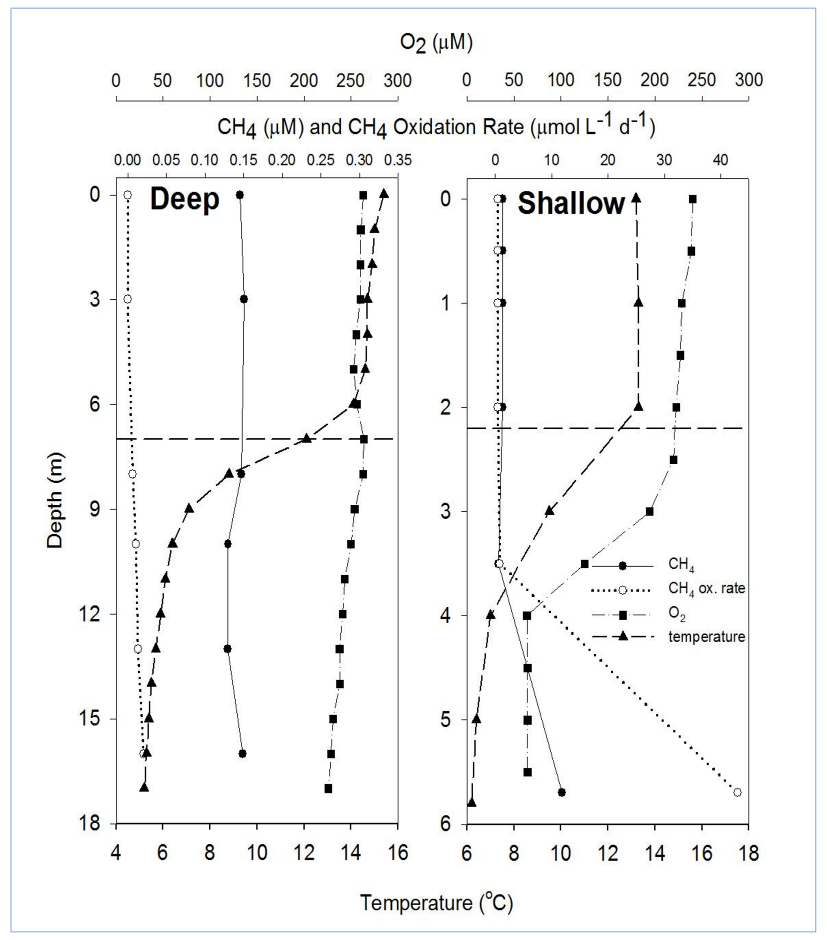

Figure 3: Representative deep (Toolik) and shallow (GTH 112) lake depth profiles of temperature, dissolved O_2 and CH_4, and volume-based CH4 oxidation rates. Profiles of O_2 were orthograde in the deep lakes, but heterograde in the shallow lakes, with shallow lake bottom waters depleted in O_2.

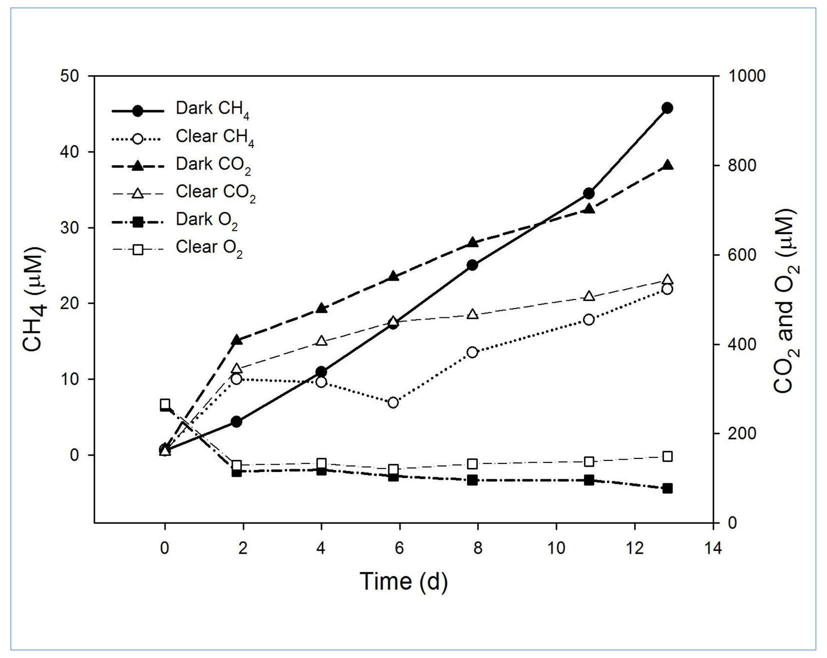

Figure 4: Representative (GTH 114) benthic chamber time series for changes in dissolved CH_4, inorganic C, and O_2 concentrations. The magnitudes of dissolved gas fluxes were typically greater in dark benthic chambers.

RESULTS AND DISCUSSION, CONT.:

Both maximum and minimum estimated lake surface CH_4 evasion rates were significantly greater for shallow lakes, with the shallow lake mean maximum estimate, 1.34 mmol m^{-2} d^{-1} similar to fluxes reported for tropical wetlands (e.g. Bartlett et al., 1988).

Overall, differences between the deep and shallow lakes point to the shallow lakes as more productive systems, in which CH_4 plays a larger relative role in C cycling.

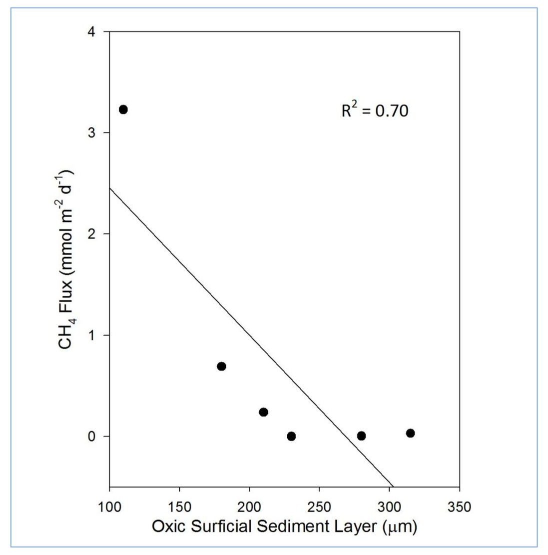

Figure 5: The average extent of the surficial oxic sediment layer was significantly smaller in the shallow lakes (Bretz, 2012), and inversely related to corrected clear chamber CH_4 exchange. Corrected CH_4 flux was greater in dark chambers than clear, likely due to a decrease in oxidized microzone thickness during incubation.

CONCLUSIONS:

My entire data can be combined into a conceptual model of summer CH_4 cycling dynamics in Arctic Foothills lakes, incorporating the sediments as a CH_4 source, with water column oxidation and surface evasion as sinks (Figure 6).

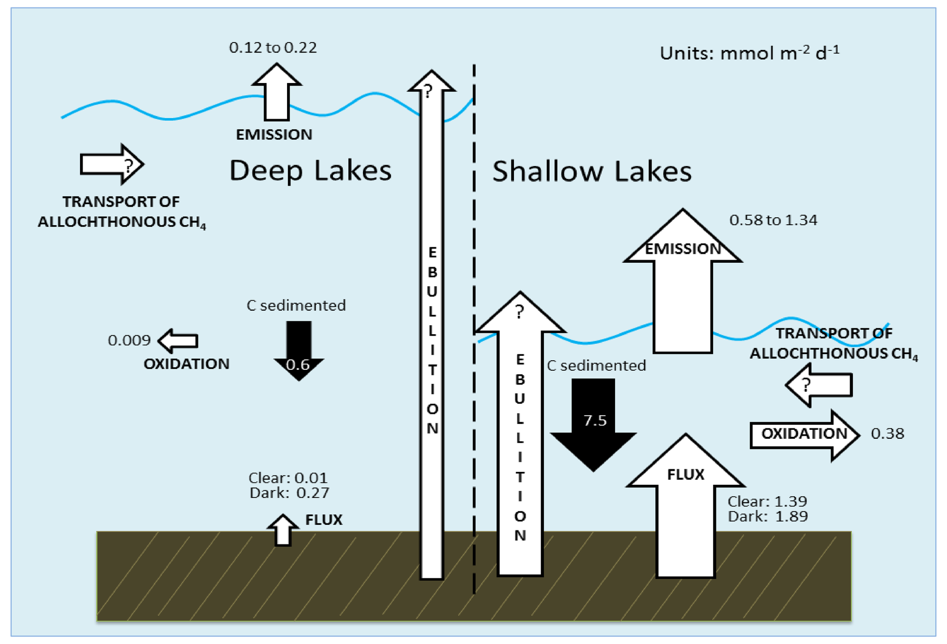

Figure 6: Overall, there is a marked contrast between the scale and form of CH_4 cycling in deep and shallow lakes in the Arctic Foothills region of Alaska.

Expected consequences of a warmer Arctic include enhanced delivery of nutrients and DOC to lacustrine systems (Prowse et al., 2006). My data suggest that projected climate warming in Arctic environments would result in increased diffusive sediment-water CH_4 flux. Climate change-induced effects on the attenuation of this flux by water column CH_4 oxidation are uncertain.

The role of CH_4 as a currency of C and energy in Alaskan Arctic lakes is significant, and seems likely to expand with climate change. However, variables that influence organic matter input and sediment O_2 levels must be considered in attempting to constrain potential climate feedbacks in high latitudes. Based on the data presented here, shallow Arctic lakes should factor prominently in the projections of climate modelers making recommendations to policymakers.

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