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Evidence that piezometers vent gas from peat soils and implications for pore-water pressure and hydraulic conductivity measurements

J. M. Waddington,[1]*
S. J. Ketcheson,[1]
E. Kellner,[1,2] M. Strack[3] and
A. J. Baird[4]

[1] *School of Geography and Earth Sciences, McMaster University, Hamilton, ON, Canada*
[2] *Midvatten AB, Borlange, Sweden*
[3] *Department of Geography, University of Calgary, Calgary, AB, Canada*
[4] *School of Geography, University of Leeds, Leeds, UK*

*Correspondence to:
J. M. Waddington, School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario, L8S 4K1, Canada.
E-mail: jmw@mcmaster.ca

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Abstract

Entrapped gas bubbles in peat can alter the buoyancy, storativity, void ratio and expansion/contraction properties of the peat. Moreover, when gas bubbles block water-conducting pores they can significantly reduce saturated hydraulic conductivity and create zones of over-pressuring, perhaps leading to an alteration in the magnitude and direction of groundwater flow and solute transport. Some previous researches have demonstrated that these zones of over-pressuring are not observed by the measurements of pore-water pressures using open-pipe piezometers in peat; rather, they are only observed with pressure transducers sealed in the peat. In has been hypothesized that open-pipe piezometers vent entrapped CH_4 to the atmosphere and thereby do not permit the natural development of zones of entrapped gas. Here we present findings of the study to investigate whether piezometers vent subsurface CH_4 to the atmosphere and whether the presence of piezometers alters the subsurface concentration of dissolved CH_4. We measured the flux of methane venting from the piezometers and also determined changes in pore-water CH_4 concentration at a rich fen in southern Ontario and a poor fen in southern Quebec, in the summer of 2004. Seasonally averaged CH_4 flux from piezometers was 1450 and 37·8-mg CH_4 m^{-2} d^{-1} at the southern Ontario site and Quebec site, respectively. The flux at the Ontario site was two orders of magnitude greater than the diffusive flux at the site. CH_4 pore-water concentrations were significantly lower in open piezometers than in water taken from sealed samplers at both the Ontario and Quebec sites. The flux of CH_4 from piezometers decreased throughout the season suggesting that CH_4 venting through the piezometer exceeded the rate of methanogenesis in the peat. Consequently we conclude that piezometers may alter the gas dynamics of some peatlands. We suggest that less-invasive techniques (e.g. buried pressure transducers, tracer experiments) are needed for the accurate measurement of pore-water pressures and hydraulic conductivity in peatlands with a large entrapped gas component. Furthermore, we argue that caution must be made in interpreting results from previous peatland hydrology studies that use these traditional methods. Copyright © 2009 John Wiley & Sons, Ltd.

Key Words piezometer; peat; peatland; methane; pore-water; over-pressuring

Introduction

Piezometers are commonly used to measure pore-water pressures and hydraulic conductivity of mineral and organic soils (Freeze and Cherry, 1979). Simple stand-pipe piezometers, consisting of a pipe sealed at the bottom with a zone immediately above the base of slotted openings (the 'intake'), usually but not always covered with a mesh or screen, and inserted into the soil, are relatively cheap to purchase or construct. However, recent studies (e.g. Kellner *et al.*, 2004) suggest that this traditional and convenient method to measure pore-water pressures and hydraulic conductivity may be inadequate in peat soils due to the presence of gas bubbles (mainly methane–CH_4).

Entrapped gas bubbles within peat can affect hydrological behaviour by altering peat buoyancy, (Fechner-Levy and Hemond, 1996), storativity (Kellner *et al.*, 2005), saturated hydraulic conductivity (Baird and Waldron, 2003), void ratio and the expansion/contraction properties (Price, 2003;

Rosenberry *et al.*, 2003). Specifically, entrapped gas bubbles are capable of blocking water-conducting pores leading to a decrease in 'saturated' hydraulic conductivity (Baird and Waldron, 2003). Such pore blocking can lead to the isolation of zones within the peat that become 'over-pressured' as further bubbles form within them (Rosenberry *et al.*, 2003; Kellner *et al.*, 2004). It has been suggested that these zones can alter hydrological flowpaths and flow rates at larger scales (10^0-10^1 m). However, Kellner *et al.* (2005) only detected these over-pressuring zones using sealed (i.e. non-vented) pressure transducers. Measurements from adjacent stand-pipe piezometers did not show this over-pressuring phenomenon, leading the authors to hypothesize that piezometers provide a pathway for the release of gas bubbles to the atmosphere. Like vascular plants in peatlands that can vent CH_4 to the atmosphere (e.g. Ström *et al.*, 2003; Chanton, 2005), piezometers may provide a release pathway for gas either by providing a conduit for gas release so that gas cannot accumulate in peat around the piezometer's intake or by puncturing the (during installation) existing zones of over-pressuring and thereby releasing the entrapped gas. Indeed, some studies (e.g. Romanowicz *et al.*, 1995; Tokida *et al.*, 2005) suggest that entrapped gas can easily escape to the atmosphere by a mechanical disturbance, such as that caused by piezometer installation in peat.

We are unaware of any studies that have attempted to examine if piezometers alter gas dynamics in peat. On the basis of the previous research we hypothesize that stand-pipe piezometers, commonly used in measurements of physical properties such as hydraulic head and hydraulic conductivity, provide a conduit for the release of CH_4 to the atmosphere and reduce pore-water CH_4 concentrations in the vicinity of the piezometer. If piezometers were found to have these impacts, it would suggest that the measurements of hydraulic head and hydraulic conductivity with such piezometers might not provide data on the natural state of the system and that estimation of these parameters may require an alternative approach.

Methodology

Research design and study areas

To determine if stand-pipe piezometers provide a conduit for the release of CH_4 to the atmosphere and reduce pore-water CH_4 concentrations in their vicinity, we measured (i) CH_4 flux from piezometers installed at two research sites, (ii) the dissolved CH_4 concentrations of water in the piezometers, which is normally taken to be in equilibrium with pore water around the intake (provided the piezometer has been recently bailed), and (iii) the dissolved CH_4 concentration in water obtained from adjacent sealed pore-water samplers. We deliberately did not have paired, sealed and open (piezometer) samplers but instead had replicate open samplers in one area and replicate sealed samplers in another area (~2–4 m apart) in order to avoid artificially lowering the concentration at a sealed sampler because it was adjacent to an open one.

This study was undertaken at two peatlands: (i) a poor fen near St Charles-de-Bellechasse (SCB), Québec, Canada (46°40′N 71°10′W), and (ii) a rich fen within the Fletcher Creek Ecological (FCE) Preserve in Puslinch Township, Ontario, Canada (43°24′N 80°07′W). The SCB peatland has peat between 1·0 and 1·5 m in thickness that is underlain by clay mineral soil. SCB data were collected at a floating mat and a flat lawn site both dominated by *Sphagnum papillosum, S. magellanicum,* and *S. majus* and sparse sedge cover including *Carex* spp. and *Rhynchospora alba*. The peat at the FCE site has an average thickness of 75 cm and is underlain by a fine silt and clay layer. Data at the FCE peatland were collected at sites with two different surface covers, marl-dominated and flat lawn with the sedge *Carex aquatilis*.

Sealed pore-water samplers and stand-pipe piezometers at depths of 40 and 60 cm were installed within 2–4 m of each other at three locations in each of the floating mat and *Sphagnum* lawn sites at the SCB peatland. At the FCE peatland, the instruments were installed at depths of 20, 40, and 60 cm within 2–4 m of each other at two locations in the marl flat and at one location in the sedge site. Data were collected from May 31 to August 11 2004 at SCB and from June 29 to October 29 2004 at FCE.

Piezometer CH_4 flux

Measurements of piezometer CH_4 flux were made approximately once every week using gas-sampling devices fitted to the stand-pipe piezometers. The gas-sampling piezometers were made of 2·5-cm inner diameter (i.d.) polyvinyl chloride (PVC) pipe with 20-cm long slotted intake with threaded housings attached to the top of the pipe in order to attach a 1–2-l bottle securely. These bottles were fitted with tubing for gas sampling and were sealed to prevent leaks. Gas samples were obtained by connecting the bottle to the top of each of the gas-sampling piezometers for a period of 4 h. Headspace gas was sampled through the tubing connected to the bottle using a syringe with a gas-tight three-way valve and was returned to the laboratory and analysed for CH_4 concentration within 48 h.

Pore-water CH_4

Pore-water CH_4 concentration was sampled approximately once every week using the gas-sampling piezometers and sealed pore-water samplers immediately following piezometer CH_4 flux measurements. The sealed pore-water samplers consisted of a 15 cm length of 2·5 cm i.d. PVC pipe with a 10–12-cm screen length, sealed at both ends with stoppers. The stopper at one end contained a central hole through which a sampling tube had been fitted. Each pore-water sampler was inserted vertically into the peat to the appropriate depth, with the sampling tube extending from the top end of the sampler to the peatland surface to allow water collection. At the surface, the sampling tube was sealed with a three-way valve and the entire sampler was filled with water and the valve closed between sampling. To collect a pore-water sample, a syringe was connected to the valve and at least 60 ml of water was extracted to flush the sampling tube. Then a 20–30-ml sample of pore water was collected. Pore-water samples were collected from the open stand-pipe piezometers, immediately following bailing, by inserting a sampling tube to the depth of the screened section (intake), connecting a syringe and collecting 20–30 ml of water. Samples were returned to the laboratory and analysed for CH_4 concentration within 48 h.

CH_4 concentration

Pore-water CH_4 concentration was determined using headspace analysis (Ioffe and Vitenberg, 1982)—after equilibration with nitrogen—using a Varian 3800 gas chromatograph (GC) equipped with flame ionization detector at 250 °C and Porapak N column at 50 °C with helium as the carrier gas and a flow rate of 30 ml min^{-1}. Gas samples were also analysed for CH_4 concentration using the Varian GC.

Statistical analysis

Since the SCB and FCE sites were very different in terms of vegetation, chemistry and hydrology and because they were sampled during slightly different times of the year, data from each site were analysed independently. At both sites the pore-water concentration data were non-normally distributed. Thus, analysis of variance was performed using general linear models (GLMs) following a Box-Cox power transformation to a normal distribution. To assess whether sealed and open piezometers differed in pore-water CH_4 concentration at individual within-site sampling locations and on particular sampling dates, non-transformed data was assessed using the non-parametric Mann-Whitney test. In all the cases an α value of 0·05 was used.

Results

Pore-water CH_4 concentrations

Analysis of variance revealed that pore-water concentrations at both the FCE and SCB sites were significantly affected by sealing, date, depth and within-site sampling location (Table I). At both sites sealed samplers had significantly higher pore-water CH_4 concentrations than open samplers. At the SCB peatland, the average of pore-water CH_4 concentrations for the open and sealed samples was 1·2 and 1·9 mg l^{-1}, respectively, while the FCE peatland site illustrated a greater difference (1·9 and 3·5 mg l^{-1}). At SCB, pore-water CH_4 concentration was significantly higher at floating mats than at *Sphagnum* lawns and significantly higher at 60 cm than 40 cm depth. At FCE, pore-water CH_4 concentration was significantly higher at marl areas compared to short sedge areas and was significantly higher at 20 cm than at 40 cm which was significantly higher than 60-cm depth.

Since we were primarily interested in whether pore-water concentrations varied significantly between open stand-pipe piezometers and sealed pore-water samplers, we further investigated differences between these types of samplers at each within-site sampling location by grouping all dates and depths and on each date by grouping all within-site sampling locations and depths. When specific within-site sampling locations were considered, all the sites showed the same trend of sealed pore-water samplers having higher CH_4 concentrations than open samplers. However, this difference was only significant (Mann-Whitney, $p < 0.05$) at the floating mat site at SCB and at the marl site at FCE (Figure 1). When different dates were investigated, at SCB concentrations at sealed samplers were significantly higher than open samplers only on the last three sampling dates. At FCE, sealed sampler CH_4 concentrations were significantly higher than open sampler concentrations on four of eight sampling dates, but unlike SCB these were scattered throughout the sampling period and not grouped towards later dates.

Table I. Results of analysis of variance for pore-water CH_4 concentration[a]

Site	Factor	*df*	*F*	*p*
SCB	Sealing (open, sealed)	1	25·83	<0·001
	Within-site location (floating, *Sphagnum* lawn)	1	57·57	<0·001
	Date	6	27·04	<0·001
	Depth (40, 60 cm)	1	16·01	<0·001
FCE	Sealing (open, sealed)	1	28·17	<0·001
	Within-site location (marl, *Carex* lawn)	1	8·28	0·005
	Date	8	2·17	0·034
	Depth (20, 40, 60 cm)	2	19·74	<0·001

[a] Data were analysed separately for SCB and FCE. Results are based on transformed data using a Box-Cox power transformation to a normal distribution.

CH_4 fluxes through piezometers

Seasonal average (± standard deviation) piezometer CH_4

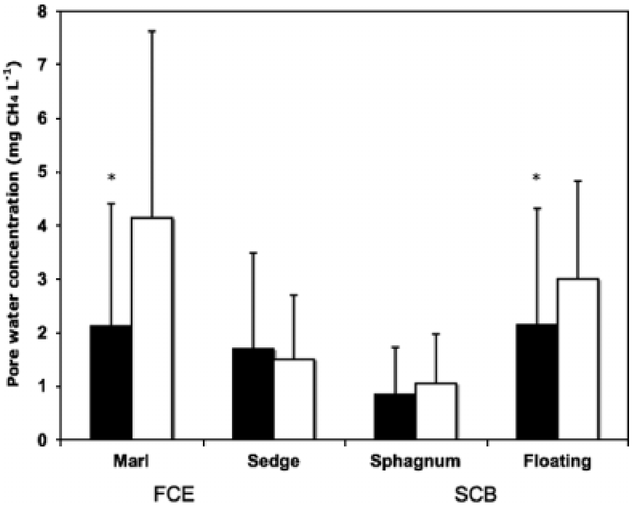

Figure 1. Average seasonal pore-water CH_4 concentrations at open piezometers (black bars) and sealed samplers (white bars) at the FCE and SCB peatlands. Asterisks indicate significantly ($p < 0.05$) lower pore-water concentrations at open piezometers

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fluxes were greater at FCE (1845 ± 312 to 3234 ± 1036 mg CH_4 m^{-2} d^{-1}) than SCB (11 ± 4 to 39 ± 17 mg CH_4 m^{-2} d^{-1}) (Figure 2). FCE fluxes were greatest at the 20-cm sampling depth, and decreased with depth (marl: 40 cm = 995 ± 388 mg CH_4 m^{-2} d^{-1}; 60 cm = 204 ± 53 mg CH_4 m^{-2} d^{-1}). CH_4 fluxes through the piezometers demonstrated variability throughout the sampling season at both the FCE and SCB peatlands, usually illustrating a trend of decreasing fluxes as the sampling season progressed.

Average (± standard deviation) growing season CH_4 flux measured with static chambers near the sampling sites used in this study were 200 ± 113 and 535 ± 833 mg CH_4 m^{-2} d^{-1} at SCB at floating mat and *Sphagnum* lawn sites, respectively (see also Strack and Waddington, 2008), and CH_4 flux ranged from 123 to 247-mg CH_4 m^{-2} d^{-1} at FCE sites (Waddington, unpublished data).

Several of the sampling sites demonstrated decreasing CH_4 piezometer flux through the season and an increasing difference between sealed and open pore-water CH_4 concentrations (Figure 3).

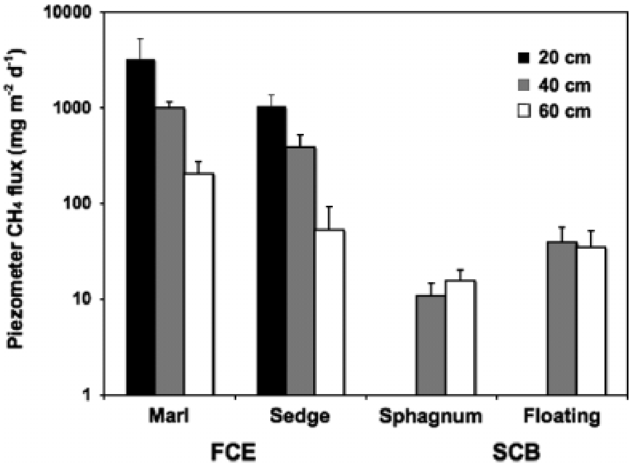

Figure 2. Average CH_4 flux through the gas-sampling piezometers at the FCE and SCB peatlands

Discussion

When all depths, sampling locations and dates were grouped, pore-water concentrations were significantly higher in sealed compared to open samplers. The pore-water CH_4 concentrations in sealed samplers were generally significantly greater than in open piezometers at the FCE peatland but less so at the SCB peatland. Moreover, while fluxes of CH_4 from piezometers at the SCB site were lower than diffusive fluxes measured using the chamber method (see Strack and Waddington, 2008), fluxes of CH_4 from shallow piezometers at the FCE peatland were an order of magnitude greater than diffusive fluxes, thus supporting our hypothesis that piezometers are venting CH_4 to the atmosphere and altering *in situ* gas dynamics. Piezometers likely provide a conduit for CH_4 bubbles, thus releasing CH_4 gas that would normally remain dissolved or in free phase in the peat. We also can see clear indications that the venting effect increases with increasing gas content in the soil.

Generally, pore-water CH_4 concentrations in the upper 1 m of peatlands increase throughout the summer (e.g. Rosenberry *et al.*, 2003; Strack *et al.*, 2005) due to an increase in methanogenesis (e.g. Dunfield *et al.*, 1993) as temperatures rise. Increased peat temperatures also reduce CH_4 solubility thereby increasing the volume of entrapped gas bubbles in the peat (e.g. Fechner-Levy and Hemond, 1996). Pore-water CH_4 concentrations in

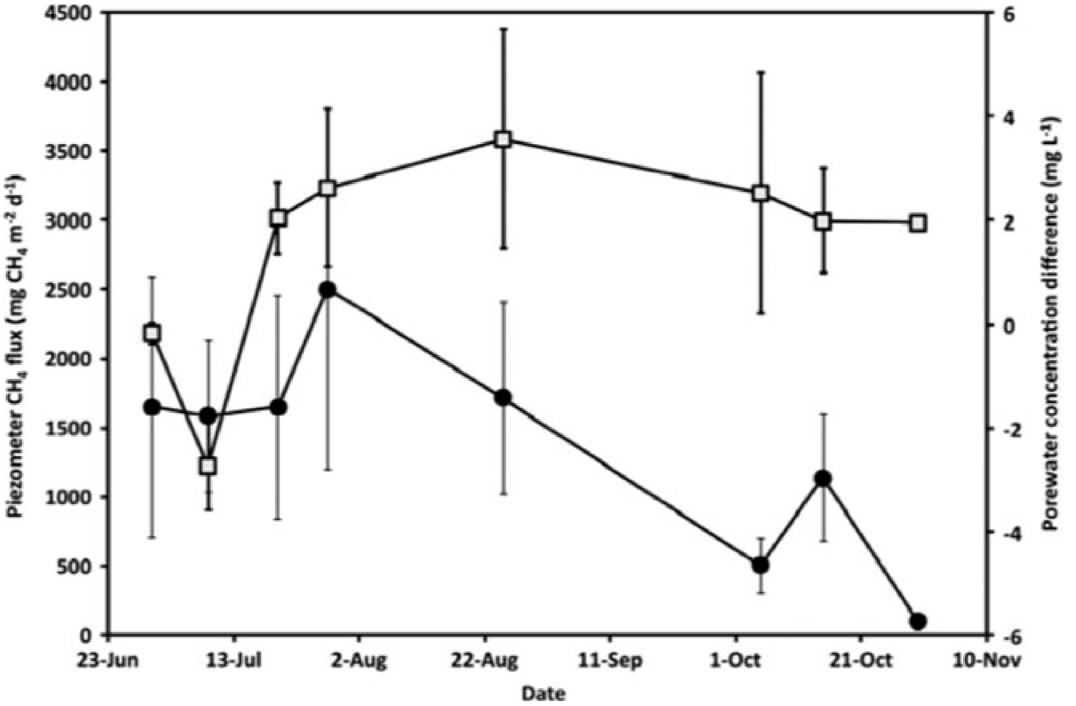

Figure 3. CH_4 flux (filled circles) and difference between sealed and open pore-water CH_4 concentrations (open squares) at the FCE peatland

the open-pipe piezometer samples, however, decreased at some sites as the summer progressed. Therefore, it appears the rate of venting of CH_4 in piezometers exceeds that of peat methanogenesis, thereby reducing subsurface gas content. This explanation is further supported by the observed decrease in CH_4 fluxes through the piezometers throughout the summer season. Normally, CH_4 fluxes from undisturbed peat increase during the summer season, due to the increased production and decreased solubility of CH_4 with increasing temperatures (Strack *et al.*, 2005). However, in the case of the CH_4 flux occurring through the piezometers, a decrease is observed. This is likely a consequence of the mechanical disturbance that is cause by the presence of the piezometer, thus altering the natural state of the peatland. Tokida *et al.* (2005) have found that mechanical disturbances, such as these, can allow gas to easily escape to the atmosphere. Since this trapped CH_4 gas can escape relatively easily through a piezometer after its installation, one would expect the fluxes of CH_4 through the gas-sampling piezometers to decrease throughout the sampling season, because there would be a greater amount of free-phase gas in the soil nearer to the time of installation of the piezometer. Our results are similar to those obtained by King *et al.* (1998) who simulated the physical process of gaseous diffusion through vascular plants by inserting gas-permeable silicone rubber tubing into organic soils. Like us, they found a decrease in pore-water CH_4 concentrations. Consequently, piezometers in peat can be considered analogous to sedges in their effect on CH_4 dynamics (*cf* Waddington *et al.*, 1996; King *et al.*, 1998; Strack *et al.*, 2006).

CH_4 fluxes through piezometers often varied between sampling days at the same sites and this is likely due to the high temporal variability of free-phase gaseous CH_4 within the studied peatlands (*cf* Baird and Waldron, 2003; Rosenberry *et al.*, 2003). It has been found that small-scale accumulation and release of gas bubbles may occur several times per day (Strack *et al.*, 2005). Moreover, the FCE peatland had much greater subsurface CH_4 and, thus, higher values of piezometer CH_4 emissions and CH_4 pore-water concentrations. These differences, however, are likely to be solely due to pre-existing differences in the pore-water chemistry and vegetative community of the actual fens themselves and not due to their differences in geographic location. Hence, no relevant spatial variability can be concluded from two sites that differ in their physical and chemical properties.

Our study has focused on sites with relatively thin peat deposits ($\sim$1 m thick) and our results may not be applicable to peatlands with different depths and types of peat. For example, Rosenberry *et al.* (2003) found little difference (a few centimetres) in the hydraulic heads recorded using packed (closed to the atmosphere) and unpacked (open to the atmosphere) piezometers from the same depth and spaced only a meter apart in the Glacial Lake Agassiz peatlands in northern Minnesota. Therefore, we encourage more work on the venting phenomenon in a wider range of peatlands than studied here.

Implications for hydrological measurements in peat soils

Free-phase gas in peatlands can alter storativity (Kellner *et al.*, 2004), decrease saturated hydraulic conductivity (Baird and Waldron, 2003), and alter peatland biogeochemistry (Strack *et al.*, 2005). The venting, and thus removal, of these bubbles from peat soils via piezometers, if it occurs, represents a removal of the identified effects of these trapped gas bubbles and, thus, an undeniable alteration of the natural state of the peatland.

We have demonstrated that stand-pipe piezometers in some peatlands vent CH_4 gas, thereby reducing the *in situ* dissolved, and likely the free phase, gas contents in peat. Consequently, we provide evidence to support the view of Kellner *et al.* (2005) that measurements of hydraulic properties such as hydraulic head and hydraulic conductivity using piezometer-based methods may not reflect the conditions that exist in undisturbed peat. Our results suggest that this error is likely temporally variable because dissolved and entrapped gas concentrations vary seasonally with variations in CH_4 production and solubility due to changes in peat temperature and atmospheric pressure (Waddington *et al.*, in prep). We have also demonstrated that the impact of piezometers on peat gas dynamics likely varies within (in plan and with depth) and among peatlands; in other words one stand-pipe piezometer may give reliable data and another may not. Consequently, we advocate caution when using traditional stand-pipe piezometers in peat soils.

As noted above, some previous studies have not shown the venting effect that we observed. However, we recommend that peatland hydrologists exercise care when interpreting piezometer data and, where possible, consider using less-invasive data-collection techniques. For measuring pore-water pressures, buried pressure transducers in combination with surface elevation sensors may provide more reliable data. Non-vented pressure transducers would be recommended to guard against the possibility of gas diffusing across a pressure transducer's membrane and then upwards through a venting tube. Alternatively, closed pneumatic piezometers may be used. In these, some CH_4 may diffuse into the water or fluid in the piezometer's body, and thence very slowly through the sidewall of the piezometer's body if it is gas-permeable. However, such losses would be minimal. Of course, some disturbance is involved with the placement of such instruments, but no more than is associated with the use of stand-pipe piezometers, and, after installation, there is no risk of the instruments acting as significant CH_4 vents. For hydraulic conductivity measurements we recommend considering use of tracer experiments, although we recognize that these may not be practicable in peats with a low hydraulic conductivity. Regardless of the instrument used, our study demonstrates the need to examine carefully how CH_4 dynamics, especially of the free phase, may be affected by the act of taking measurements.

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