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Effect of entrapped gas on peatland surface level fluctuations

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Abstract:

Peat is a highly compressible medium and changes in peat surface level in response to shifts in water storage and entrapped gas volume have been reported previously. Since both peat compressibility and capacity to entrap gas are related to peat structure, we hypothesize that the relationship between water table and surface level may vary across a peatland. The objective of this study is to investigate the relationships between peat surface level positions, water table positions and subsurface gas pools at local topographic low-lying areas within a poor fen, which differ in peat properties and vegetation cover. Three sites were investigated, two with highly movable surfaces (FA and FB) and one which was more stable (NF). Deviations from the water table position–surface level position relationship (residuals) appear to be related to changes in atmospheric pressure. However, this relationship varied between FA and NF. The differences in these relationships were supported by distinct patterns of gas dynamics between these sites. Ebullition tended to occur only during periods of falling atmospheric pressure at FA, whereas it occurred much more frequently at NF without atmospheric pressure being the primary control. Evidence of ebullition based on changes in volumetric water content below the water table were supported by ebullition measured by surface gas traps and by shifts in pore water pressure deviation. These different responses of surface level fluctuations to changes in atmospheric pressure between sampling locations are likely related to variations in peat properties between the sites. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS ebullition; methane; peatland; peat volume change; water table fluctuations

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INTRODUCTION

Peatlands may experience large seasonal and short-term surface level fluctuations in response to shifts in water table positions owing to the floating nature of some peat systems (Hogg and Wein, 1988; Fechner-Levy and Hemond, 1996) and the high compressibility of peat soils (Roulet, 1991; Price and Schlotzhauer, 1999; Kellner and Halldin, 2002; Price, 2003). These surface level changes are caused by shifts in effective stress acting on the peat matrix related to variations in water table position (Price and Schlotzhauer, 1999; Price, 2003) and entrapped gas content (Hogg and Wein, 1988; Fechner-Levy and Hemond, 1996; Glaser *et al*., 2004). The position of the surface level relative to the water table is an important control on peatland hydrology (Quinton and Roulet, 1998) and biogeochemistry (e.g. Roulet *et al*., 1992), and thus factors affecting the surface level position need to be understood to improve our understanding of peatland ecohydrology. The goal of this research is to examine the relationship between peatland surface level positions, water table positions and gas dynamics.

Shifts in water table position lead to peatland surface level variations by altering pore water pressure. The effective stress acting on the peat matrix at a point is the balance between the total stress due to the overlying mass of peat and water and the pore water pressure (Price, 2003). As the water table declines, pore water

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pressure is reduced and more of the total stress is borne by the peat matrix, resulting in subsidence. Rising water tables can reverse this effect as long as the strain is less than the preconsolidation pressure (Terzaghi, 1943). The amount of subsidence resulting from a shift in water table varies spatially, potentially in relation to differences in peat properties. Kellner and Lundin (2001) observed greater compression in laboratory tests on peat samples from hollows than from ridges and suggest that this may be related to different degrees of humification at the two sites. In addition to responding to water table fluctuations, peatland surface level positions may also be significantly influenced by changes in entrapped gas volume (Hogg and Wein, 1988; Fechner-Levy and Hemond, 1996; Glaser *et al.*, 2004). The seasonal production of CH_4 within peat soils has been observed to increase entrapped gas content within the peat and result in the lifting of the peat surface at floating sites throughout the growing season (Hogg and Wein, 1988; Smolders *et al.*, 2002). The build-up and release of entrapped gas has also been implicated for causing surface level fluctuations in a variety of peat systems over several time scales (Fechner-Levy and Hemond, 1996; Price, 2003; Glaser *et al.*, 2004; Strack *et al.*, 2005). Fechner-Levy and Hemond (1996) observed that the deviation in surface level positions in a floating bog around estimated surface level–water table relationships was related to atmospheric pressure. They concluded that this relationship was caused by the effects of pressure on the volume of an entrapped gas reservoir via the ideal gas law and Henry's law. Thus, when atmospheric pressure dropped, the gas would exsolve and gas volume expand; the upward buoyant force would increase and the surface level rise. In a raised bog, Glaser *et al.* (2004) observed surface level oscillations of 20 cm within several hours, which they attributed to ebullition events. During these rapid surface level oscillations, the surface rose slightly, fell substantially within a few hours and then rebounded in the following hours. The authors suggest that the initial rise was the result of building gas pressure, which after reaching a threshold of peat matrix strength was released resulting in the rapid surface level drop. As water moved into the zone to replace the lost gas, the surface level returned to near its original position. At this site, overpressuring was measured at sealed piezometers at 2-m depth. The observed surface level oscillations were coincident with depressuring events providing further evidence for the involvement in entrapped gas dynamics in fluctuations of peat surface level. Similarly, Price (2003) observed that surface level fluctuations in a natural bog did not consistently correspond to changes in water table positions, and it was suggested this was due to entrapped methane gas.

Although entrapped gas has been observed in a variety of soil types (Faybishenko, 1995), seasonal fluctuations in its volume in peatlands have been linked to the production of CH_4 (Hogg and Wein, 1988; Fechner-Levy and Hemond, 1996). Methane production requires highly reduced conditions and a carbon source, and thus CH_4 production in the saturated, organic soil in peatlands is common. The rate of CH_4 production is related to water table position (e.g. Moore and Dalva, 1993) and temperature (e.g. Dunfield *et al.*, 1993) indicating that more CH_4 should be produced in areas where water tables are near the surface and late in the growing season when peat temperatures are warm. As CH_4 is produced over the growing season, gas may remain entrapped within the peat owing to the presence of a confining layer. This layer may consist of a zone of peat with pores that are too small for entrapped gas bubbles to pass through. As bubbles enter these pores, they become entrapped and block the passage of even smaller bubbles (Romanowicz *et al.*, 1995). Because peat properties, such as porosity, bulk density and pore size distribution are related to its vegetation composition and degree of decomposition (e.g. Rycroft *et al.*, 1975), the potential for gas to be entrapped may vary between and within peatlands. In fact, Glaser *et al.* (2004) suggest that woody layers in bog peat are more likely to trap gas, leading to the creation of a zone of overpressure, than sedge peat. Similarly, Kellner *et al.* (2004) observed different magnitudes of overpressuring at two locations within a poor fen.

Therefore, surface level fluctuations will likely vary spatially both owing to differences in peat compressibility and in the ability of peat to entrap gas bubbles. This variation in surface level position has implications for near surface hydrology and biogeochemistry. For example, Lafleur (1990) found more consistent evapotranspiration rates at peatlands with floating surfaces, while Price and Schlotzhauer (1999) suggest that subsidence at harvested peatlands maintains the water table closer to the surface than in a rigid soil. In addition, if gas-holding capacity varies spatially it will contribute to spatiotemporal variability in CH_4 emissions and subsurface hydrology, which should be included in our description and modeling of peatland ecosystems. Therefore, the objectives of this study were, (1) to determine if the relationship between surface level position, water table position and gas dynamics varied between a location dominated by *Sphagnum* moss with little vascular vegetation and another location with a dense root mat and surface cover of liverworts and (2) to explain these differences by comparing subsurface gas contents and the timing and magnitude of CH_4 ebullition events between sites.

METHODS

The study was carried out between 3 June (day 155) and 17 August 2004 (day 230) at a poor fen in central Québec (46°40′N 71°10′W). All measurements were undertaken at three local topographic low-lying zones (hollows/pools). Two of these had highly movable surfaces and were classified as floating (FA and FB) with seasonal peat uplift visually apparent at FB (Figure 1). These sites had vegetation covers dominated by liverworts (*Gymnocolea inflata*, *Cladopodiella fluitans*) and sedges (*Rhynchospora alba*). The third site, classified as non-floating, (NF) had a more stable surface dominated by *Sphagnum* moss. To determine bulk density, peat cores 30 cm in length and greater than 20 cm in diameter were carefully hand cut from FA and NF. The peat was transported to the laboratory in a container that was the same size as the peat sample packed in water to prevent volume changes. The saturated peat cores were cut into replicate samples of known volume for each 5–7 cm depth layer of the peat core. These sub-samples were dried at 85 °C until constant weight was achieved.

Surface level and water level were determined with pulleys on potentiometers connected to a data logger (CR10X, Campbell Scientific, Utah, USA) measuring every minute and averaging every 20 min. For water level measurements, a float in a stilling well was attached to one end of the pulley, and for surface level

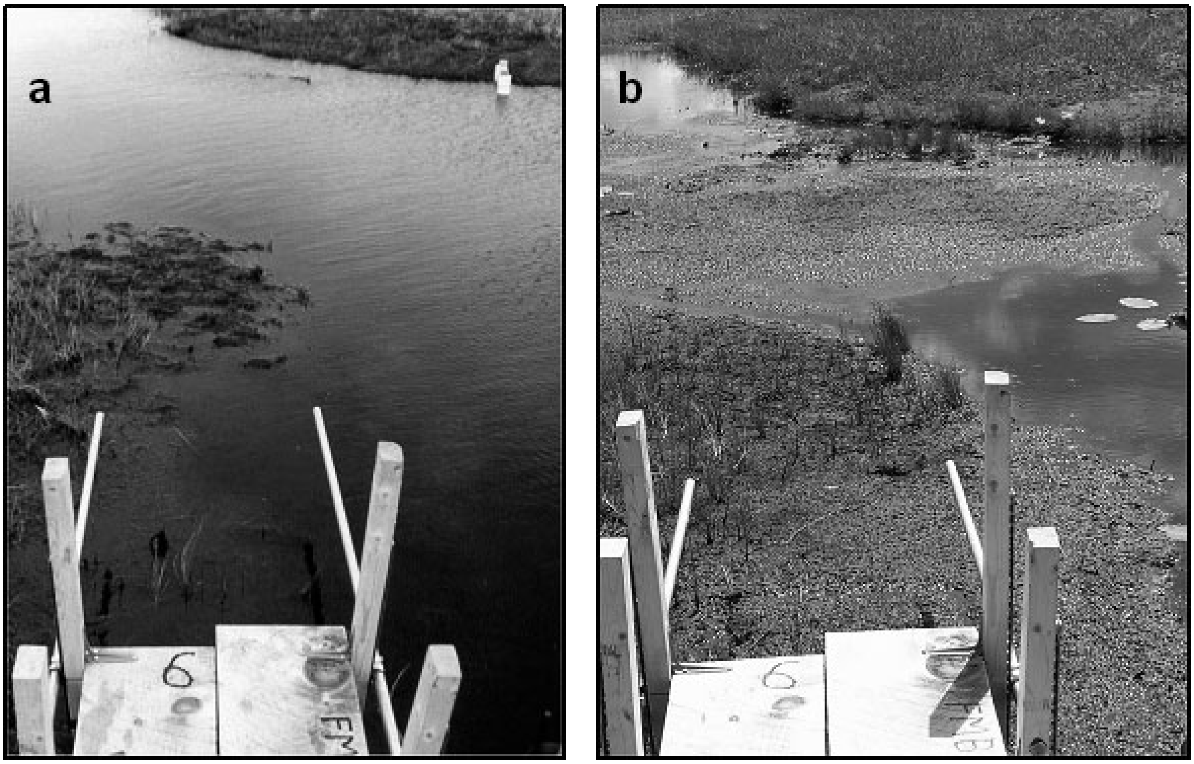

Figure 1. Seasonal peat uplift at FB. Photos were taken on 24 May (a) and 9 July (b) with the water level being 6 cm higher in (b)

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measurements lightly weighted dowels were set on the surface and attached to pulleys. Surface level and water table positions were measured relative to a stable arbitrary datum at each site anchored in the clay layer beneath the peat. These measurements were verified with weekly manual measurements at FA and NF. Owing to the loose, unconsolidated nature of the peat at FB, surface level fluctuations could not be reliably measured and, therefore, the investigation of water table–surface level relationships was carried out only at NF and FA. The relationship between surface level and water level position was assessed for periods of at least 3 days in which both were consistently rising or falling (Fechner-Levy and Hemond, 1996). These criteria were applied to the entire data set and in all cases periods which met the criteria occurred when the water table was falling, with seven analysis periods at FA and four at NF. Relative surface levels were computed as the variation around this relationship (residuals) and compared to atmospheric pressure recorded 30 km from the study site in Québec City (Environment Canada, 2004). Atmospheric pressure from this weather station was well correlated ($R^2 = 0{\cdot}99$) to that measured at the study site during other periods. During each time period assessed, the atmospheric pressure rose and fell and thus any relationship between relative surface level and atmospheric pressure holds under conditions of both rising and falling pressure. Positive residuals indicated that the surface was rising and negative values that it was sinking. Thus, a positive relationship between the relative surface level position and atmospheric pressure suggests that falling atmospheric pressure is related to periods when the surface level is sinking, suggesting a reduction in entrapped gas volume, or ebullition. In contrast, a negative relationship indicates that falling atmospheric pressure leads to rising of the surface and thus a larger gas volume. This observation would be consistent with gas which is not released from the peat and which has a volume varying according to the ideal gas law and Henry's law.

Subsurface gas content at FA, FB and NF was determined by measuring peat water content below the water table using water content probes (CS615, Campbell Scientific, Utah, USA). The probe length was 30 cm and probes were centered at a 50-cm depth. This type of sensor uses time-domain measurement methods that are sensitive to dielectric permittivity, although the method by which dielectric permittivity is determined is different from TDR (time-domain reflectometry) (Seyfried and Murdock, 2001). The probes were calibrated in the laboratory for variations in both water content and temperature (2–25 °C). Changes in water content were corrected for changes in peat volume owing to compression and swelling determined using peat elevation sensors (Price, 2003), and the remainder of the change was assumed to result from changes in entrapped gas volume. In addition, pore water pressure was measured continuously at FA and FB at the same depths using sealed pressure transducers (KPSI 173, Pressure Systems Inc., Virginia, USA). These were installed by creating an insertion cavity to the desired depth with an auger, placing the pressure transducer into the cavity, backfilling with 10 cm peat mud and then sealing it with a 10-cm bentonite layer to avoid the creation of preferential flow paths. Pore water pressure deviation was determined by subtracting changes in atmospheric pressure measured at a nearby (30 km) Environment Canada weather station and changes in water table position. This pore water pressure deviation is similar to excess pressure determined by Kellner *et al.* (2004) and should be an indication of pressure fluctuations resulting from gas dynamics.

Ebullition was measured using inverted funnels with a surface area of $0{\cdot}032\ \text{m}^2$ placed on pool or hollow surfaces. Four funnels were installed at FB, two at FA and one at NF. Funnels were filled with water and sealed, allowing ebullition to be measured as gas displacement of water in the neck of the funnel. Gas was removed after several milliliters had accumulated to ensure that subsequent ebullition could be monitored.

RESULTS

Bulk density

Average bulk density of the upper 25 cm of the peat column was significantly higher at FA than NF (t-test, $p = 0{\cdot}035$) with average values of 0·09 and 0·07 g cm^{-1}, respectively. Furthermore, the depth distribution of bulk density varied between the sites. The surface bulk density was low at NF and increased slightly with depth, while the opposite trend was apparent at FA where bulk density increased towards the surface (Figure 2).

Relationships between water table, surface level and atmospheric pressure

Over short time scales (4 to 6 days), the majority of the variation in surface level (81–99%) could be explained by changes in water table positions at both FA and NF (Table I). At both sites, the water table was below the surface during the study period but was maintained less than 10 cm below the surface by the surface level fluctuations. Shifts in the surface level and water table at both NF and FA are shown in Figure 3. During the early part of the season (before day 205), the slope of the water table–surface level relationship was close to 1·0 at FA, supporting the observation that the surface was very mobile at this location. Deviation from

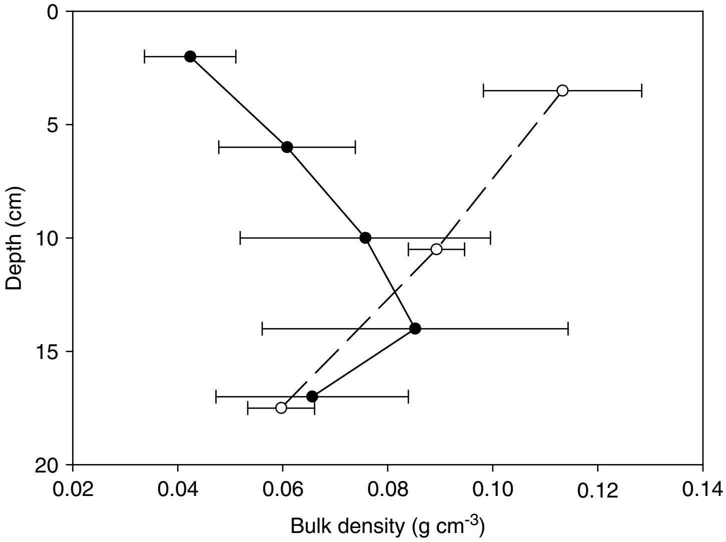

Figure 2. Bulk density profiles in the upper 20 cm of the peat column at FA (open) and NF (closed). Peat cores 20 cm in length were subdivided into 5–7 cm sections for bulk density determination and values are plotted at the midpoint of the section

Table I. Slope and R^2 of water table–surface level relationships and direction of relative surface level–atmospheric pressure relationships at FA and NF. Significant ($p < 0.05$) relative surface level–atmospheric pressure relationships are marked (*)

Site	Period (days of year)	Water table–surface level relationship		Relative surface level–atmospheric pressure relationship
		Slope	R^2	
FA	155–159	0·87	0·98	+
	160–166	0·87	0·99	+*
	185–190	0·73	0·81	−
	193–197	1·01	0·85	+
	200–205	0·94	0·95	+*
	209–213	0·52	0·94	+*
	215–221	0·54	0·82	+
NF	193–197	0·86	0·92	−*
	200–205	0·67	0·98	−*
	209–213	0·72	0·98	−*
	215–221	0·62	0·98	−*

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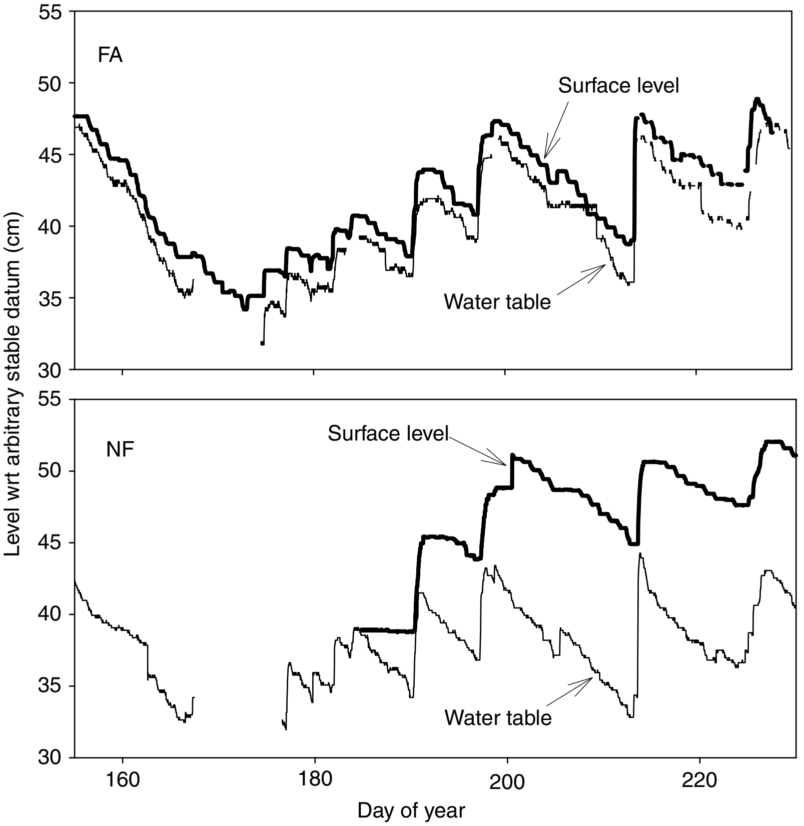

Figure 3. Water table (thin line) and surface level (thick line) relative to an arbitrary stable datum at FA and NF. A different datum was used at each location. Reliable surface level measurements at NF did not begin until day 185

this slope later in the season at FA is likely due to the influence of gas dynamics on surface level position. Despite the apparent floating nature of FA, investigations at this site have not revealed any open water zones within the profile. Instead, we believe that the peat below the upper 30-cm root zone is very loose and highly compressible, allowing the surface level to closely follow the water table. At NF, the surface also followed the water table changes closely; however, the slope was between 0·62 and 0·86.

The relative surface level position (measured - estimated surface level) was significantly (linear regression, $p < 0.05$) related to atmospheric pressure during seven of the 11 time periods assessed. At FA, relative surface level was positively related to atmospheric pressure for all significant periods, while at NF there was a consistently negative relationship between atmospheric pressure and relative surface level (Table I).

Subsurface gas dynamics

At all locations, entrapped gas volume increased gradually throughout the season; however, the pattern of entrapped gas accumulation was spatially variable. At FA, gas volume increased by 2% gradually over the growing season with short-term fluctuations of generally only 0·3–0·5% (Figure 4). In contrast, entrapped gas volume at a 50-cm depth at FB and NF increased by 2–4% and exhibited much greater variability over short time scales often changing by ~2% over the period of a day (Figure 4). We infer that these rapid fluctuations in gas contents of 1–3% result from ebullition events. This appears to occur frequently at NF and FB but is only clearly observed near day 199 and day 214 at FA. These ebullition events at FA are also observed at both FB and NF (Figure 4).

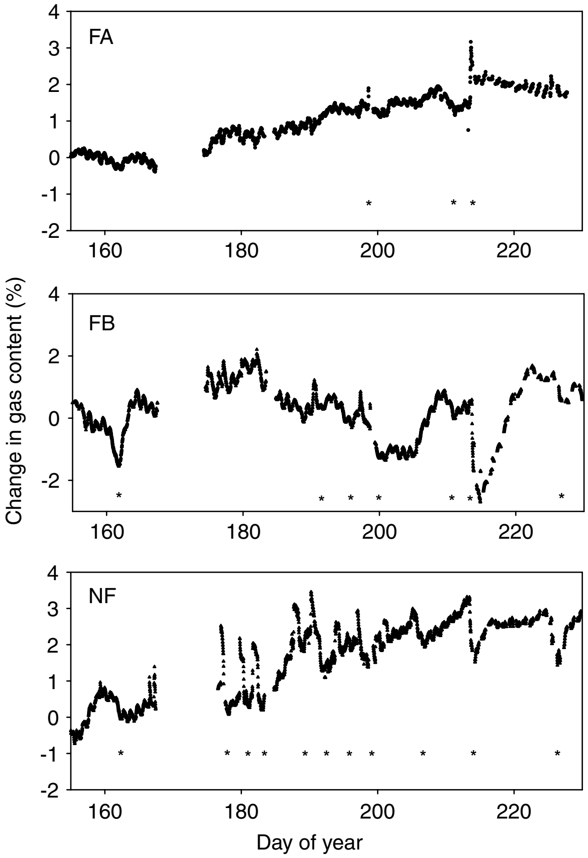

Figure 4. Changes in gas volume at 50-cm depth relative to day 155 at FA, FB and NF. Sudden reductions in gas content may indicate ebullition events and these are marked (*) on each plot

In general, pore water pressure deviation varied as a mirror image of atmospheric pressure variation. This provides evidence for the development of closed zones by pore blockage with biogenic gas which dampens the response of the sensor to atmospheric pressure fluctuations (Kellner *et al.*, 2005). However, it was also observed that some shifts in pore water pressure deviation did not mirror atmospheric pressure changes and these corresponded well to rapid changes in entrapped gas volume. In these cases, periods with higher gas volumes were coincident with periods of enhanced pressure while lower gas volumes appear to correspond to subsurface pressure reduction (Figure 5).

Ebullition occurred at all measurement locations and was more frequent later in the growing season. Since a positive relationship between relative surface level and atmospheric pressure suggests the occurrence of gas release, ebullition data was compared to water table–surface level relationship assessment periods. At FA, several (but not all) periods with significant positive relationships between relative surface level and atmospheric pressure corresponded to ebullition events (Figure 6). Ebullition also occurred at NF; however, it occurred more consistently throughout the season (Figure 4).

DISCUSSION

As reported in other studies, the surface level position in the poor fen was related to the water table position and entrapped gas dynamics. While water table fluctuations were responsible for 81–99% of the surface level

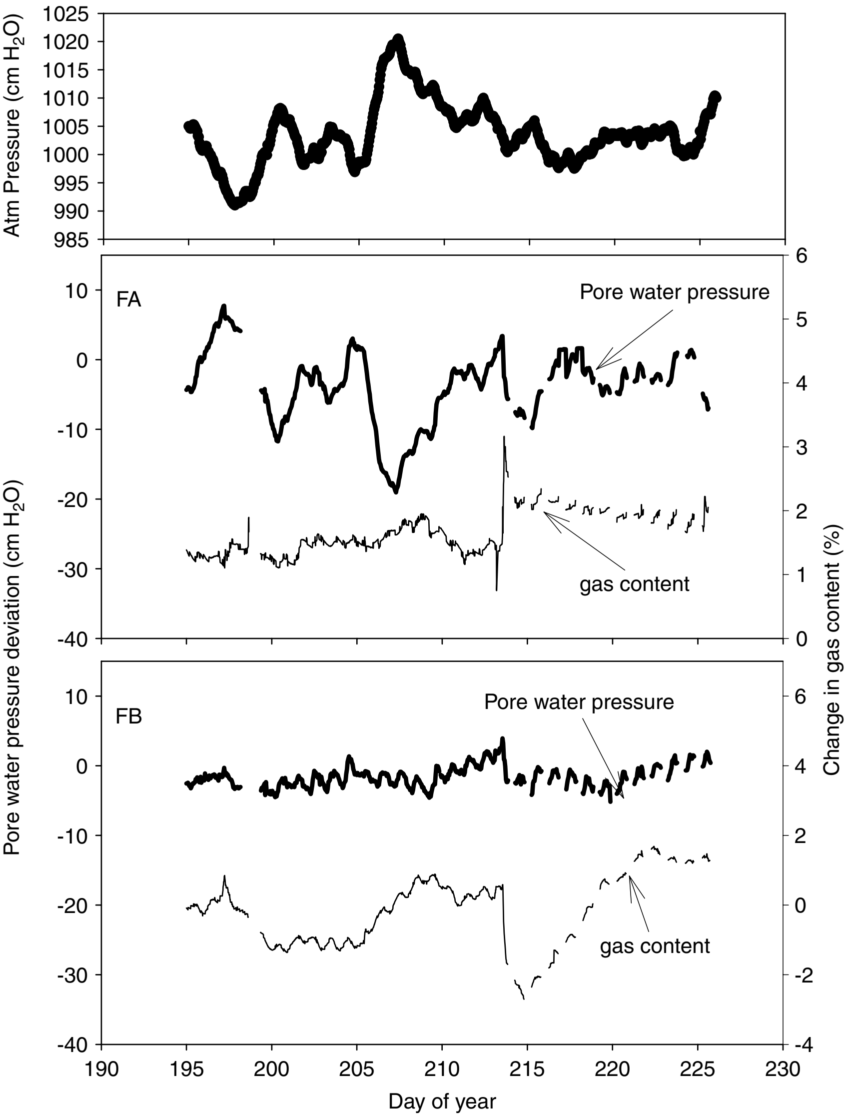

Figure 5. Atmospheric pressure, pore water pressure deviation (thick line, pore water pressure corrected for atmospheric pressure and water table fluctuations) and gas content (thin line) at FA and FB for day 195–225

variation on short time scales, entrapped gas volume was also important weekly and seasonally. Following day 190, the surface level rose by 8 and 1 cm in response to an increase in gas volume at a 50-cm depth of 0·7 and 0·1% at FA and NF, respectively. Because biogenic gas, particularly CH_4, has a low density, its presence in pore space can enhance peat buoyancy (Hogg and Wein, 1988). Also, the build-up of entrapped gas within pore spaces can create zones of excess pressure (Rosenberry *et al.*, 2003; Kellner *et al.*, 2004), which reduce the total stress borne by the peat matrix, helping to maintain elevated surface levels. This suggests that locations where larger volumes of biogenic gas remain entrapped, due to higher production rates or limited gas release, may experience seasonal peat uplift. In fact, it has been reported that peat buoyancy is related to substrate quality, with conditions favouring CH_4 production linked to increased buoyancy (Smolders *et al.*, 2002). At FA and FB, the peat surface remains elevated into October but is lowered by springtime (May).

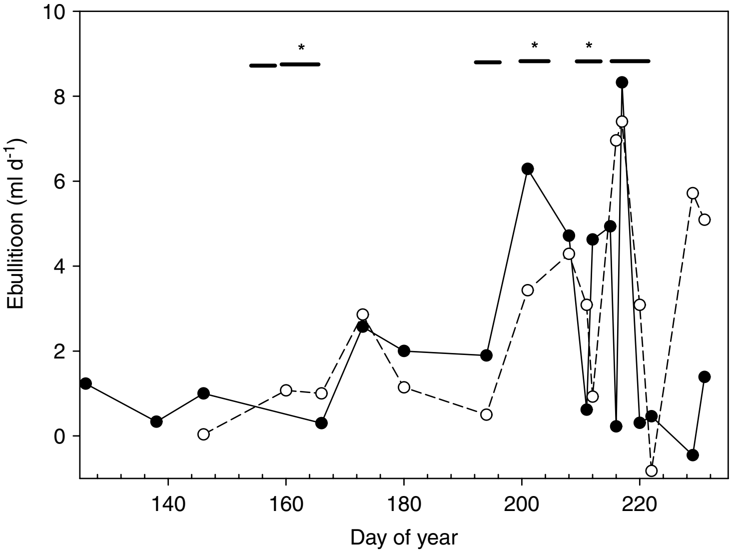

Figure 6. Ebullition as determined from two different surface gas traps at FA (open and closed). Time periods with positive relative surface level–atmospheric pressure relationships are marked with bars and significant surface level–atmospheric pressure ($p < 0{\cdot}05$) relationships are shown (*)

This surface level decline may be related to low CH_4 production rates as temperature falls during the winter period, continued gas release throughout the winter period (Dise, 1992), ebullition of CH_4 as ice melts in the spring, and peat compression by the snowpack.

In this study, we observed that subsurface gas dynamics varied between sampling locations. Previously, subsurface zones of excess pressure have been observed to be spatially limited (Kellner *et al.*, 2004) and potentially related to the presence of physical or biological confining layers which limit entrapped gas release (Romanowicz *et al.*, 1995; Rosenberry *et al.*, 2003). In this study, despite the fact that all measurements were made at local topographic low–lying zones, relationships between relative surface level and atmospheric pressure and patterns of entrapped gas volume suggest that biogenic gas dynamics differ between sites. The positive correlation between relative surface level and atmospheric pressure at FA (Table I) indicates that atmospheric pressure is the main controller of gas release at this location. When atmospheric pressure is high, gas release is impeded leading to larger entrapped gas volumes, increased pore water pressure and a rising relative surface level. When the atmospheric pressure drops, gas release is enhanced, gas volume and subsurface pressure decline and the relative surface level falls. This is supported by the pattern of entrapped gas volume at 50 cm, which shows a gradual increase in gas volume with only a few large variations (Figure 4) corresponding to low-pressure systems. Examining the changes in gas volume on a shorter time scale (Figure 7) reveals a more complicated scenario. At the start of this period (day 200–202), the falling atmospheric pressure corresponds to a sinking surface level. However, the gas content at a 50-cm depth begins to increase. The next drop in atmospheric pressure (∼day 204) is coincident with the surface level rising and a maintenance of gas contents, behaviour consistent with the expansion and exsolution of gas according to the ideal gas law and Henry's law. In contrast, from day 209–213, there is a better correspondence between relative surface level and atmospheric pressure suggesting the occurrence of ebullition. Falling atmospheric pressure on day 213 is coincident with rapid changes in gas volume and pore water pressure deviation (Figures 4 and 5), indicating an accumulation and subsequent release of gas at 50 cm in the peat, possibly because of the mobilization of entrapped gas from other zones. This build-up of pressure prior to an ebullition event has also been described by Glaser *et al.* (2004). We have no evidence that this initial gas accumulation has any impact on relative surface level positions and this disconnect is probably related to small scale variability of

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entrapped gas content. Transient changes in local gas content in the zone near the water content probes may not represent the conditions of the peat column directly below the area where surface level measurements were made. Since there can be opposing effects of temperature, water table and atmospheric pressure on gas volume, direct relationships between these variables are difficult to describe in a field setting.

At NF, the negative relationships between relative surface level and atmospheric pressure (Table I) suggest that atmospheric pressure is more important for controlling the volume of entrapped gas at this site based on the ideal gas law and Henry's law than for causing its release via ebullition. This does not preclude the possibility of ebullition at this location, but instead suggests that atmospheric pressure is not the main controller of gas release. Evidence based on both surface gas traps and subsurface gas content (a 50-cm depth) reveals that entrapped gas content is quite variable at this site, supporting a conceptual model in which gas is consistently produced and released with little relationship to atmospheric pressure changes.

It is likely that the spatial variability in gas dynamics is related to differences in vegetation community and peat properties between the sites. The *Sphagnum* cover at NF results in a depth distribution of bulk density typical for peatlands (Clymo, 1984). The low-density surface layer is supported by the physical structure of the living mosses. As this begins to decay at depth, the structure collapses and bulk density increases (Clymo and Hayward, 1982). This relatively open structure near the surface may play a role in enabling the easier release of biogenic gases leading to the consistent ebullition observed at this site. In contrast, at FA the hepatics and sedges form a dense, sealed layer at the surface. In addition, below this layer the peat is more highly decomposed than at NF. This highly decomposed peat and dense surface layer may act as a barrier against the release of gas. Thus, a reduction in atmospheric pressure is required to increase the gradient between subsurface and atmospheric pressure enough to overcome the strength of the peat structure, leading to gas release. While patterns of bulk density provide some information about differences between site properties,

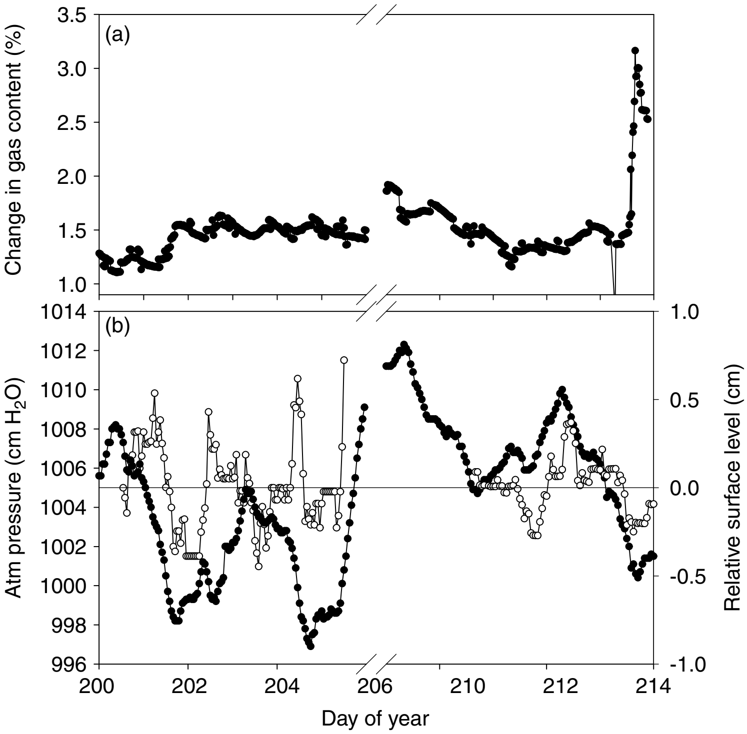

Figure 7. (a) Change in gas content at 50 cm and (b) atmospheric pressure (closed) and relative surface level (open) at FA for day 200–206 and 209–213

a more detailed description of the peat matrix, such as pore size distribution, fibre content and humification will provide a greater insight into the factors controlling spatial variability in gas dynamics and surface level fluctuations.

IMPLICATIONS

Surface level position within peatlands is important hydrologically, ecologically and biogeochemically. Surface moisture constancy is related to the variability in resistance to evapotranspiration (Lafleur, 1990) and the relative position of the water table and surface level is important for the delivery of moisture to the surface (Kellner and Halldin, 2002; Price, 2003). In flooded areas, surface level as controlled by peat buoyancy has been linked to ecological succession (Giller and Wheeler, 1988; Mallik, 1989), and surface moisture conditions are also important for *Sphagnum* survival (Price and Whitehead, 2001; Smolders *et al*., 2002). Similarly, the maintenance of moist surface conditions may enhance methane production and limit decomposition (e.g. Clymo, 1984; Moore and Dalva, 1993), and peat uplift may increase soil temperatures enhancing rates of biogeochemical reactions (Scott *et al*., 1999). In this study, we have shown that peat surface level position is affected by the water table position, atmospheric pressure and gas dynamics and thus in order to better describe peatland hydrology we need to understand these interactions. The results presented suggest that the response of surface level position to atmospheric pressure may vary between hydrologically similar sites (i.e. local topographic low-lying zones) and that this variability can help us investigate spatial differences in gas dynamics possibly related to the distribution of vegetation and peat properties. The linkages between these aspects of peatland hydrology and their variability within and between peatlands require further investigation before gas dynamics within peatlands can be fully described and modelled.

Furthermore, apart from influencing peatland hydrology, entrapped biogenic gas also has many biogeochemical implications. Since this entrapped gas may be largely CH_4, localized concentration gradients can develop and influence diffusive methane fluxes (Rothfuss and Conrad, 1998). The release of this entrapped gas by ebullition may also be important to peatland methane budgets (Glaser *et al*., 2004; Strack *et al*., 2005). Thus, the integration of gas dynamics into our description of peatland hydrology is important for furthering our overall understanding of these ecosystems.

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REFERENCES

Clymo RS. 1984. The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London B* **303**: 606–654.

Clymo RS, Hayward PM. 1982. The ecology of *sphagnum*. In *Bryophyte Ecology*, Smith AJE (ed.). Chapman & Hall: London; 229–289.

Dise NB. 1992. Winter fluxes of methane from Minnesota peatlands. *Biogeochemistry* **17**: 71–83.

Dunfield P, Knowles K, Dumont R, Moore T. 1993. Methane production and consumption in temperate and subarctic peat soils: response to temperature and pH. *Soil Biology and Biochemistry* **25**: 321–326.

Environment Canada. 2004. Jean Lesage International Airport, Quebec. National Climate Data and Information Online. Available: http://www.climate.weatheroffice.ec.gc.ca/climateData/hourlydata_e.html. Accessed January 2005.

Faybishenko BA. 1995. Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: laboratory experiments. *Water Resources Research* **31**: 2421–2435.

Fechner-Levy EJ, Hemond HF. 1996. Trapped methane volume and potential effects on methane ebullition in a northern peatland. *Limnology and Oceanography* **41**: 1375–1383.

DOI: 10.1002/hyp

Giller KE, Wheeler BD. 1988. Acidification and succession in flood-plain mire in the Norfolk Broadland, U.K. *Journal of Ecology* **76**: 849–866.

Glaser PH, Chanton JP, Morin P, Rosenberry DO, Siegel DI, Rudd O, Chasar LI, Reeve AS. 2004. Surface deformations as indicators of deep ebullition fluxes in a large northern peatland. *Global Biogeochemical Cycles* **18**: GB1003, DOI: 10·1029/2003GB002069.

Hogg EH, Wein RW. 1988. Seasonal changes in gas content and buoyancy of floatin Typha mats. *Journal of Ecology* **76**: 1055–1068.

Kellner E, Lundin LC. 2001. Calibration of time domain reflectometry for water content in peat soil. *Nordic Hydrology* **32**: 315–322.

Kellner E, Halldin S. 2002. Water budget and surface-layer water storage in a *sphagnum* bog in central Sweden. *Hydrological Processes* **16**: 87–103, DOI: 10·1002/hyp.286.

Kellner E, Price JS, Waddington JM. 2004. Pressure variations in peat as a result of gas bubble dynamics. *Hydrological Processes* **18**: 2599–2605, DOI: 10·1002/hyp.5650.

Kellner E, Waddington JM, Price JS. 2005. Dynamics of biogenic gas bubbles in peat: hydrological implications. *Water Resources Research* **41**: W08417, DOI: 10·1029/2004WR003732.

Lafleur PM. 1990. Evapotranspiration from sedge-dominated wetland surfaces. *Aquatic Botany* **37**: 341–353.

Mallik AU. 1989. Small-scale succession towards fen on floating mat of a Typha marsh in Atlantic Canada. *Canadian Journal of Botany* **67**: 1309–1316.

Moore TR, Dalva M. 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. *Journal of Soil Science* **44**: 651–664.

Price JS. 2003. Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. *Water Resources Research* **39**: 1241, DOI: 10·1029/2002WR001302.

Price JS, Schlotzhauer SM. 1999. Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland. *Hydrological Processes* **13**: 2591–2601.

Price JS, Whitehead GS. 2001. Developing hydrological thresholds for sphagnum recolonization on an abandoned cutover bog. *Wetlands* **21**: 32–42.

Quinton WL, Roulet NT. 1998. Spring and summer runoff hydrology of a subarctic patterned peatland. *Arctic and Alpine Research* **30**: 285–294.

Romanowicz EA, Siegel DI, Chanton JP, Glaser PH. 1995. Temporal variations in dissolved methane deep in the Lake Agassiz peatlands, Minnesota. *Global Biogeochemical Cycles* **9**: 197–212.

Rosenberry DO, Glaser PH, Siegel DI, Weeks EP. 2003. Use of hydraulic head to estimate volumetric gas content and ebullition flux in northern peatlands. *Water Resources Research* **39**: 1066, DOI: 10·1029/2002WR001377.

Rothfuss F, Conrad R. 1998. Effect of gas bubbles on the diffusive flux of methane in anoxic paddy soil. *Limnology and Oceanography* **43**: 1511–1518.

Roulet NT. 1991. Surface level and water-table fluctuations in a sub-arctic fen. *Arctic and Alpine Research* **23**: 303–310.

Roulet NT, Moore T, Bubier JL, Lafleur P. 1992. Northern fens: methane flux and climatic change. *Tellus, Series B* **44**: 100–105.

Rycroft DW, William DJA, Ingram HAP. 1975. The transmission of water through peat: I. Review. *Journal of Ecology* **63**: 535–556.

Scott KJ, Kelly CA, Rudd JWM. 1999. The importance of floating peat to methane fluxes from flooded peatlands. *Biogeochemistry* **47**: 187–202.

Seyfried MS, Murdock MD. 2001. Response of a new soil water sensor to variable soil, water content, and temperature. *Soil Science Society of America Journal* **65**: 28–34.

Smolders AJP, Tomassen HBM, Lamers LPM, Lomans BP, Roelofs JGM. 2002. Peat bog restoration by floating raft formations: the effects of groundwater and peat quality. *Journal of Applied Ecology* **39**: 391–401.

Strack M, Kellner E, Waddington JM. 2005. Dynamics of biogenic gas bubbles in peat ad their effects on peatland biogeochemistry. *Global Biogeochemical Cycles* **19**: GB1003, DOI: 10·1029/2004GB002330.

Terzaghi K. 1943. *Theoretical Soil Mechanics*. John Wiley: New York.