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Peat deformation and biogenic gas bubbles control seasonal variations in peat hydraulic conductivity

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Abstract:

The hydraulic conductivity (K) of peat beneath the water table varies over short (annual) periods. Biogenic gas bubbles block pores and reduce K, and seasonal changes in the water table position cause peat deformation, altering peat pore size distribution. Although it has been hypothesized that both processes reduce K during warm dry summer conditions, temporal variations in K under field conditions have been explained previously by peat volume changes (strain) alone. We determine the effect of both controls on K by monitoring changes in gas content ($\Delta\gamma$), strain and K within a poor fen. Over the growing season, K decreased by an order of magnitude. In the near-surface peat (0.3–0.7 m), this reduction is more strongly correlated with $\Delta\gamma$, providing the first field-based evidence that biogenic gas bubbles reduce K. In the deeper peat (0.7–1.3 m), K is correlated principally with strain. However, causality is uncertain because of multicollinearity between strain and $\Delta\gamma$. To mitigate for multicollinearity, we took advantage of a peatland drainage experiment where the water table was artificially dropped at the beginning of the growing season, reducing correlations between strain and $\Delta\gamma$. $\Delta\gamma$ remained the primary cause of K variations just beneath the water table at a depth of 0.5–0.7 m, although further down through the peat profile (0.7–1.2 m) changes in K were controlled by strain. We suggest that the larger pore structure of the poorly decomposed peat just below the water table is impacted less by volume changes than that of the more decomposed peat at depth. However, within this poorly decomposed peat, K is reduced by the high gas contents that result from higher rates of methane production.

KEY WORDS peat; hydraulic conductivity; deformation; methane; gas bubbles

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INTRODUCTION

Peatlands are an essential water and carbon resource, storing ~10% of the global surface freshwater (Holden, 2005) and accounting for approximately one third of the terrestrial soil carbon pool (Gorham, 1991). The rate and pattern of water flow through a peatland regulate its internal ecohydrological (Baird *et al.*, 2011) and biogeochemical functioning (Morris and Waddington, 2011) and the export of water and carbon to the atmosphere and the wider catchment (Bubier, 1995: Dinsmore *et al.*, 2011). A processes-based understanding of the hydrological form and function of peatlands is, therefore, essential to determine the response of these critical ecosystems to changing climatic conditions and to develop informed, relevant, management strategies.

Water flow through a peatland is controlled by the hydraulic conductivity (K). Peat K varies strongly (10^{-2} to 10^{-8} m s^{-1}; Fraser *et al.*, 2001) over a range of spatial scales and depends on the porosity and pore size distribution of the peat and the tortuosity and connectivity of the pore network (Rezanezhad *et al.*, 2009; Quinton *et al.*, 2008). Peat K generally decreases as the peat becomes more decomposed (Boelter, 1965), often following a log-linear relationship with depth (Morris and Waddington, 2011), although more complicated relationships, or lack of relationship, are widely observed (Clymo, 2004; Chason and Siegel, 1986). K is lower within the margin (lagg) region of raised bogs than the central dome (Lapen *et al.*, 2005; Baird *et al.*, 2008) and is generally lower within hummock microforms compared with adjacent lawns and hollows (Whittington and Price, 2006). Peat K also varies over short (annual) periods associated with the buildup of biogenic gas bubbles (Beckwith and Baird, 2001), changes in peat volume (Price, 2003) and pore-water chemistry (Ours *et al.*, 1997; Hoag and Price, 1997). Such temporal variations in peat K provide the focus of this article. We first provide a brief overview of the controls of biogenic gas bubbles, peat compression and pore-water chemistry on peat K.

Biogenic gas bubbles

Within peatlands, the zone beneath the water table is rarely water saturated (Kellner *et al.*, 2004). Biogenic gas bubbles are produced by the decomposition of organic matter under anaerobic conditions. This entrapped gas content varies spatially and depends on the rate of peat decomposition (Kellner *et al.*, 2006), the ability of the peat to entrain biogenic gas bubbles (Kettridge and Binley 2011; Comas *et al.*, 2005) and the export of dissolved organic

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carbon through diffusive fluxes (Thomas *et al.*, 1996) and water movement (Strack *et al.*, 2005). Rates of anaerobic methane production are highest just below the peat surface but below the water table, where the poorly decomposed peat and plant root exudates, provide a rich supply of labile carbon (Joabsson *et al.*, 1999). However, in some peat profiles, high gas contents have been observed at depth, associated with the entrapment of biogenic gas bubbles by woody peat layers (Comas *et al.*, 2005). The entrapped gas content varies seasonally. During the winter, gas contents are low because of the low rates of decomposition and high solubility of the cold pore water (Strack *et al.*, 2005). The entrapped gas content then increases under warmer summer temperatures as the rate of decomposition increases, often reaching a fuzzy threshold gas content (Kellner *et al.*, 2006) above which entrapped gas is lost to the atmosphere via episodic ebullition (Coulthard *et al.*, 2009).

Laboratory studies have shown that the entrapped biogenic gas bubbles block pores and reduce peat *K*. Beckwith and Baird (2001) and Baird and Waldron (2003) incubated near-surface *Sphagnum* peat samples under constant temperature conditions and monitored changes in the entrapped biogenic gas content and *K*. They observed strong linear, or two-part linear, correlations between *K* and the monitored entrapped gas content, with *K* at the beginning of the experiments being five to eight times higher than that observed at the end of the 70-day incubation period (Beckwith and Baird, 2001). However, variations in *K* resulting from the entrapment of biogenic gas bubbles have not presently been observed under field conditions.

Changes in peat volume

Peat is a compressible medium (Price, 2003). The rises and fall of the water table over the seasons alter the effective stress (σ_e) through the profile and induce a change in the peat volume (strain). The effective stress is given as

$$\sigma_e = \rho g h - \psi, \tag{1}$$

where g is the gravitational acceleration, ψ is the pore-water pressure, and ρ and h are the density and thickness, respectively, of the peat deposits above a given position within the profile. A drop in the water table increases the weight of the overlying water and peat supported by the soil below. Within primary compression (Price, 2003), water is expelled as the pores collapse under this increased weight. At an effective stress less than the peat preconsolidation pressure, such changes in the peat volume are reversible, and the peat expands with a decrease in the effective stress (Kennedy and Price, 2005). The compression of a volume of peat for a given stress is given by its stress–strain relationship and is dependent upon the peat structure (Price *et al.*, 2005) and its location within the peatland microtopography (Waddington *et al.*, 2010).

Compression modifies the peat pore size distribution, preferentially collapsing larger hydrological active pores within the peat matrix (Chow *et al.*, 1992) and reducing *K* (Price, 2003, Whittington and Price, 2006); we do not consider larger macropore structures within the peatland, such as pipes (Holden *et al.*, 2009), that may respond differently to a given stress. The reduction in peat *K* for a given drop in the water table position varies between undisturbed and cutover peatlands (Price, 2003) and between different microhabitats (Whittington and Price, 2006). Reductions in peat *K* over two orders of magnitude have been observed within cutover peatlands within a single growing season associated with a decline in the water table position of 0.3 m (Price, 2003). In comparison, observed reductions in *K* within undisturbed peatlands are smaller. However, a two-order-of-magnitude reduction in peat *K* has been suggested by longer term modifications to the water table position within a previously undisturbed peatland (Whittington and Price, 2006).

Pore-water chemistry

Peat *K* also varies with changes in pore-water chemistry. A change in the pore-water chemistry causes humic acids on the surface of peat fibres to coagulate and to increase in density. This increases the diameter of the active pore network in a process defined by Ours *et al.* (1997) as *pore dilation*. The coagulation of the organic acids is reversible, and the establishment of the original pore-water chemistry returns the peat *K* to its original value (Ours *et al.*, 1997). Flocculation was shown by Comas and Slater (2004) to depend strongly on the peat pore-water electrical conductivity (σ). Between 0.01 and 1.0 S m^{-1}

$$K \alpha \sigma^n, \tag{2}$$

where n ranged from 0.25 to 0.3. However, variations in peat *K* resulting from flocculation are likely to be small within natural, uncontaminated, peatland environments (Kettridge and Binley, 2010), where variations in the pore-water electrical conductivity are likely limited. We therefore focus our subsequent analysis on the combined effects of biogenic gas bubbles and peat deformation.

Research aim

The interpretation of short-term variations in *K* has previously focused on the effects of either peat deformation or gas entrapment in isolation. Although laboratory investigations characterizing the effect of entrapped gas on peat *K* (Beckwith and Baird, 2001; Baird and Waldron 2003) were not influenced by deformation, field-based monitoring used to quantify the effects of peat deformation combined both the effects of gas entrapment and peat deformation. Temporal variations in *K* monitored by Price (2003) demonstrate a clear relationship between water table position and *K*. However, during the period of water table decline, the volumetric moisture contents at a depth of 1.0 m reduced from 0.96 to 0.86 and from 0.85 to 0.80 at the study sites. This is comparable with an increase in the entrapped gas content of the magnitude observed by Beckwith and Baird (2001) and Baird and Waldron (2003).

We aimed to characterize the individual effect of compression and entrapped gas on *K* within an undisturbed peatland under field conditions and to determine how these controls on the seasonal variation in K alter with depth, with changing peat physical properties. We combine statistical approaches and field-based manipulation experiments to differentiate between these two interrelated controls on peat K.

METHODS

The study was conducted within a three-hectare undisturbed region of a harvested poor fen within Quebec, Canada (46.67°N 71.17°W). Measurements were collected at two locations within the study site, defined here as control (C) and experimental (E), where the peat thickness was 1.2 and 1.0 m, respectively. Instrumentation was located in areas within the C and E locations which had previously been shown not to be impacted by the adjacent harvested peatland (Findlay, 2004; Whittington and Price, 2006). Surface vegetation at both locations was dominated by *Sphagnum papillosum*, *Sphagnum magellanicum*, *Sphagnum majus*, and a vascular vegetation of *Rhynchospora alba* and *Carex* spp. (cf. Kellner *et al*., 2004).

Variations in peat deformation, entrapped gas content, and peat K were monitored at both sites from early May to late September 2002. Peat deformation was monitored using elevation sensor rods (Price, 2003) installed at depths of 0.05, 0.1, 0.2, 0.3, 0.5, and 0.7 m at both the control and the experimental sites and at the additional depths of 1.0 and 1.3 m within the control site and at a depth of 1.2 m within the experimental site. Peat volume changes were calculated between each elevation rod and were equal to the difference in elevation between two rods at time t, divided by the elevation difference at the time of installation on day of year (DOY) 142, t_0. This ratio between peat volumes at time t and t_0 is hereafter referred to as strain. Measurements representing the average strain within each layer between adjacent elevation rods are reported here in terms of the depth of the elevation rods above and below the layer. For example, layer 0.3–0.5 m represents the zone between elevation rods installed at a depth of 0.3 and 0.5 m from the peat surface at time t_0. The elevation rods were monitored on average once every 2 days over the length of the growing season until DOY 266. The effective stress at depth $z = \sum \Delta z_u + \sum \Delta z_s$ (σ_z) is (Waddington *et al*., 2010)

$$\begin{aligned}\sigma_z = \textstyle\sum_{u=1}^{m} \left[\rho_p(1-\eta_u) + \rho_w\theta_u\right] g\Delta z_u \\ + \textstyle\sum_{s=1}^{n} \Big[\left(\rho_p - \rho_p\right)(1-\eta_s) \\ + \left(\rho_g - \rho_w\right)\gamma_s\Big] g\Delta z_s\end{aligned} \tag{3}$$

where ρ_p, ρ_w, and ρ_g are the densities of peat, water, and gas, respectively, η is porosity and γ is gas volume. Volumetric moisture contents (θ_v) were measured within the peat layers delimited by the elevation rods, at depths of 0.25, 0.4, 0.6, 0.85 and 1.0 m below the peat surface within the control and experimental sites using Campbell Scientific CS615 moisture probes. The volumetric moisture content of each probe was given by (Birchak *et al*., 1974):

$$\theta_v = \frac{\varepsilon^{\vartheta} - (1-\eta)\varepsilon_m^{\vartheta} - \eta\varepsilon_a^{\vartheta}}{\varepsilon_w(T)^{\vartheta} - \eta\varepsilon_a^{\vartheta}}, \tag{4}$$

where ε is the dielectric permittivity and the subscripts m, a, and w denote measured, peat, air and water respectively. T is temperature, η is porosity, and ϑ is a dimensionless constant equal to 0.35 (Kellner and Lundin, 2001). Moisture probes were calibrated under laboratory conditions. Errors in the absolute moisture contents were ±0.05. Uncertainty in the change in peat moisture contents was ±0.01 and provides the focus of this article. The change in the volumetric gas content beneath the water table, $\Delta\gamma$, is calculated from the moisture content measurements, and given as

$$\Delta\gamma = (\eta_t - \eta_0) - (\theta_t - \theta_0), \tag{5}$$

where η_t, the porosity at time t, is given by

$$\eta_t = 1 - \frac{(1-\eta_0)}{L/L_0}, \tag{6}$$

L denotes the layer thickness, and subscripts t and 0 denote the measurement time and the time of installation, respectively. Two piezometers were installed within each peat layer in the control site, and two piezometers were installed within each peat layer within the experimental site at a depth of 0.25, 0.4, 0.6, 0.85 and 1.0 m, adjacent to the elevation sensor rods. Piezometers were constructed from PVC tubes with a radius of 1.27 cm, with slotted intakes 5 cm long at a depth of 0.25 m, 10 cm long at a depth of 0.4 m and 20 cm long at a depth of 0.6, 0.85 and 1.0 m. Slug and bail tests were performed on the piezometer every 2 weeks over the growing season. Water levels within the piezometers were measured using a combination of manual measurements using a water depth probe and logging pressure sensors. The value of K is calculated as outlined by Hvorslev (1951)

$$K = -\frac{A}{Ft}\ln\left(\frac{h}{h_0}\right), \tag{7}$$

where A is the inside cross-sectional area of the piezometer standpipe, F is the shape factor of the piezometer intake, h_0 is the initial head difference, and h is the head difference at time t since the slug withdrawal. Although the approach assumes an uncompressible medium, it does provide reliable estimates of K when exchanges between storage within the porous medium and the piezometer are nearly complete (Surridge *et al*., 2005). We assume this to be when $h/h_0 = 0.05$.

In the experimental site, the water table dropped below the elevation at which the 0.25 m moisture content probe and piezometers were installed. However, the deformation of the peat below the probes meant that they also dropped with the lowering of the water table position (*cf.* Kellner *et al*., 2006). As a result, the moisture content probe installed initially at a depth of 0.25 m below the peat surface remained permanently below the water table. Although the 0.25 m piezometers also dropped with a lowering of the water table, the intakes were partly within the unsaturated zone after drainage. Measurements were not conducted within these piezometers once unsaturated conditions had occurred.

Within the control site, the water table position remained permanently above all piezometers and moisture content probes during the study period.

On DOY 160, a small hand dug ditch ($l = 30$ m, $w = 0.5$ m, $d = 0.5$ m) connecting a small open water pool in experimental site and the local harvested peatland drainage network was created. To minimize impact to the peatland, no machinery was used in creating this ditch, and most of the ditch was constructed by accessing the peatland from a previously constructed boardwalk. The ditch reduced the water table in the experimental site from an initial depth of ~0.05 to ~0.35 m by DOY 165. The water table position within the control site was not impacted by this drainage (Whittington and Price, 2006). Instrumentation was located ~10 m from the ditch but within 2 m of the lowered water table in the pool.

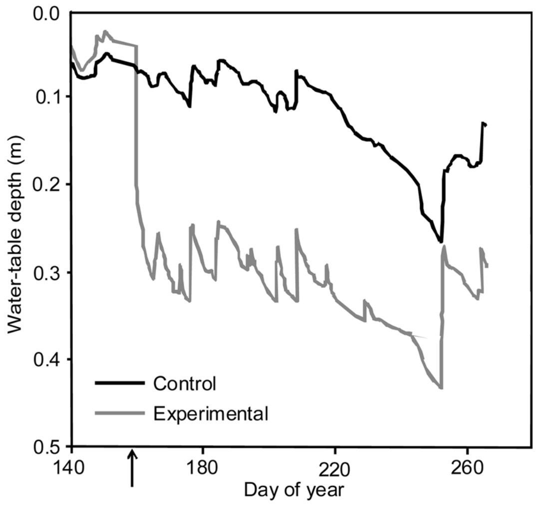

Figure 1. Water table depth over the experiment period at site C (black) and site E (grey). Drainage of the experimental site occurred on DOY 160. The time of drainage is indicated by an arrow

RESULTS

At the beginning of the study period, the water tables at sites C and E are comparable, ranging between a depth of 0.05 and 0.10 m (Figure 1). At site C, the water table position remains relatively constant until DOY 217. It then declines steadily during drier conditions, reaching a maximum depth of 0.32 m on DOY 252. The strain at site C follows a similar pattern to the water table position, remaining relatively constant prior to the period of water table decline, ranging between 0.95 and 1.3 (Figure 2A), before decreasing steadily to between 0.83 and 0.95 on DOY 252. In comparison, at site E, the water table drops to 0.25 m over 24 h on DOY 161 due to artificial drainage from the site. The strain in each peat layer between elevation rods decreases

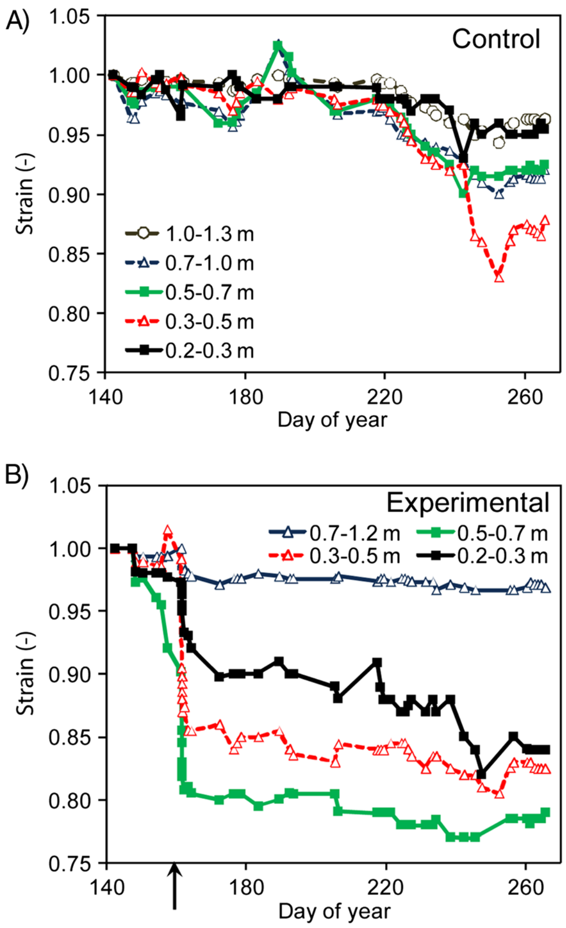

Figure 2. Strain in peat layers at site (A) C and (B) E over the experiment period. Arrow in panel B indicates time of drainage

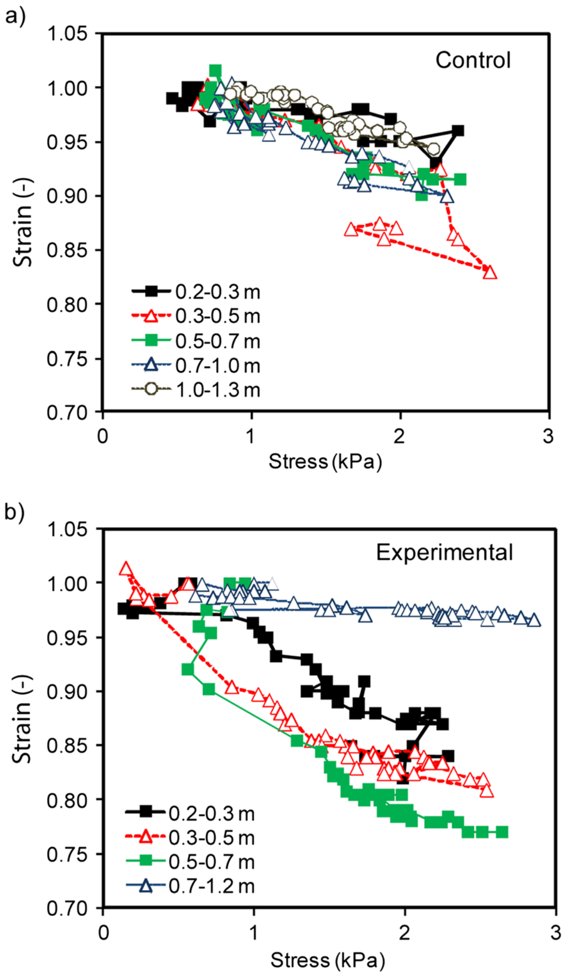

Figure 3. Stress–Strain relationships at sites (A) C and (B) E

during this period (Figure 2B). This decrease is most substantial within layer between a depth of 0.50 and 0.70 m, reducing to a minimum of 0.8. After the period of artificial drainage, the water table depth remains relatively constant at site E until DOY 217 when the water table declines steadily to a maximum depth of 0.44 on DOY 252 (Figure 1; similar to site C). The strain continues to decline steadily within all layers during this period. This decline in strain postdrainage is greatest between a depth of 0.20 and 0.30 m, decreasing from 0.89 to 0.84.

The stress–strain relationships at site C are generally linear and show strong uniformity through the peat profile to a depth of 1.3 m (Figure 3A), although deviation from linearity is observed at a depth of 0.3–0.5 m. The peat profile is more compressible at site E, with a more negative relationship between stress and strain (~50% increases in gradient in the 0.50–0.70 m peat layer; Figure 3B). However, the stress–strain relationship is more variable at site E, with a significantly lower rate within the deepest peat layer.

Generally, $\Delta\gamma$ increases at all measurement locations over the study period, from DOY 140 to 260 (Figure 4). The magnitude of the increase in $\Delta\gamma$ varies between sites C and E and between measurements depths. Increases in $\Delta\gamma$ are highest within site C, reaching 0.08 at a depth of 0.40 m on DOY 250. $\Delta\gamma$ declines through the peat profile, reaching maximum values of 0.038, 0.023 and 0.015 at depths of 0.60, 0.85 and 1.0 m, respectively. At site E, $\Delta\gamma$ follows a similar general increase over the study period, reaching a maximum 0.07 at a depth of 0.25. Through the

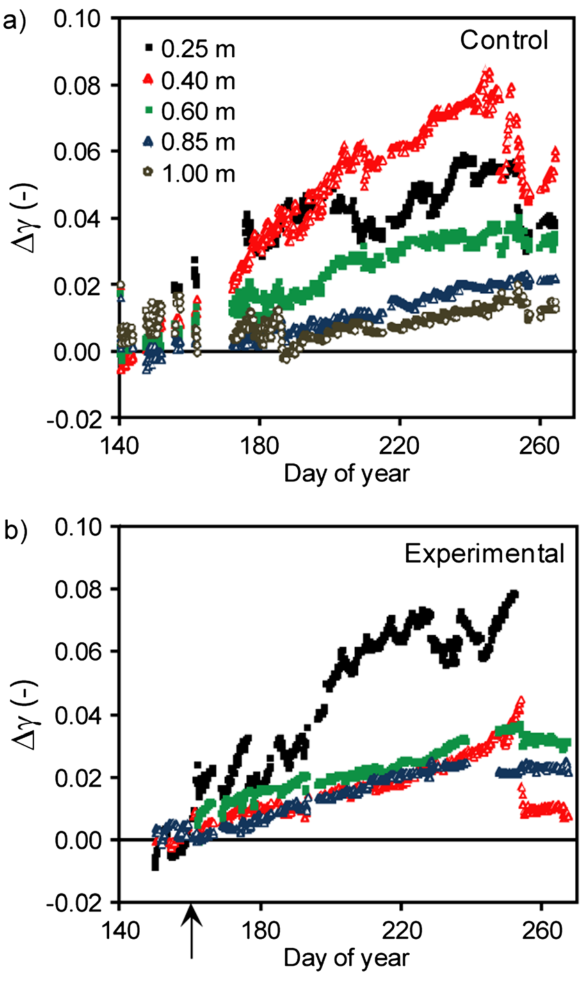

Figure 4. Change in entrapped gas content, $\Delta\gamma$, at (A) C and (B) E, adapted from Kellner *et al.* (2006). Arrow indicates time of drainage

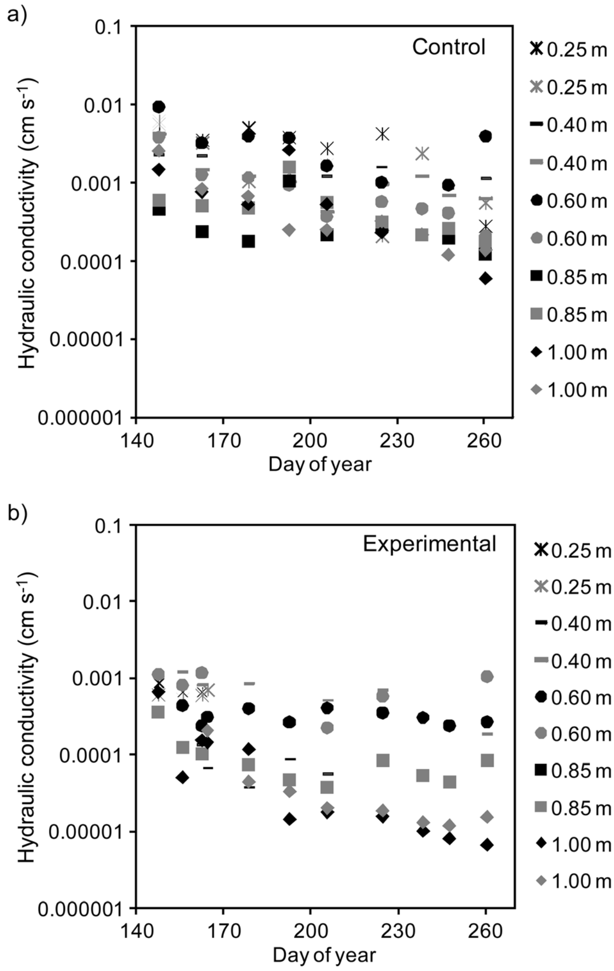

Figure 5. Hydraulic conductivity at (A) C and (B) E. Different piezometers are indicated by grey and black symbols. Different piezometer depths indicated by different symbol shapes

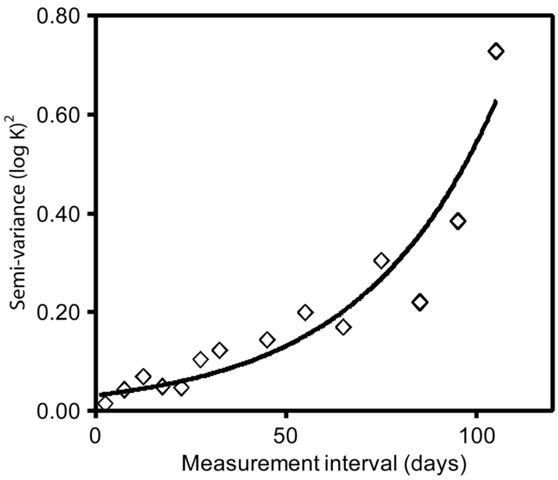

Figure 6. Semivariance between successive measurements of log K within piezometers. Semivariance is calculated within 5-day periods up to a measurement interval of 30 days after which measurements are grouped into 10-day periods

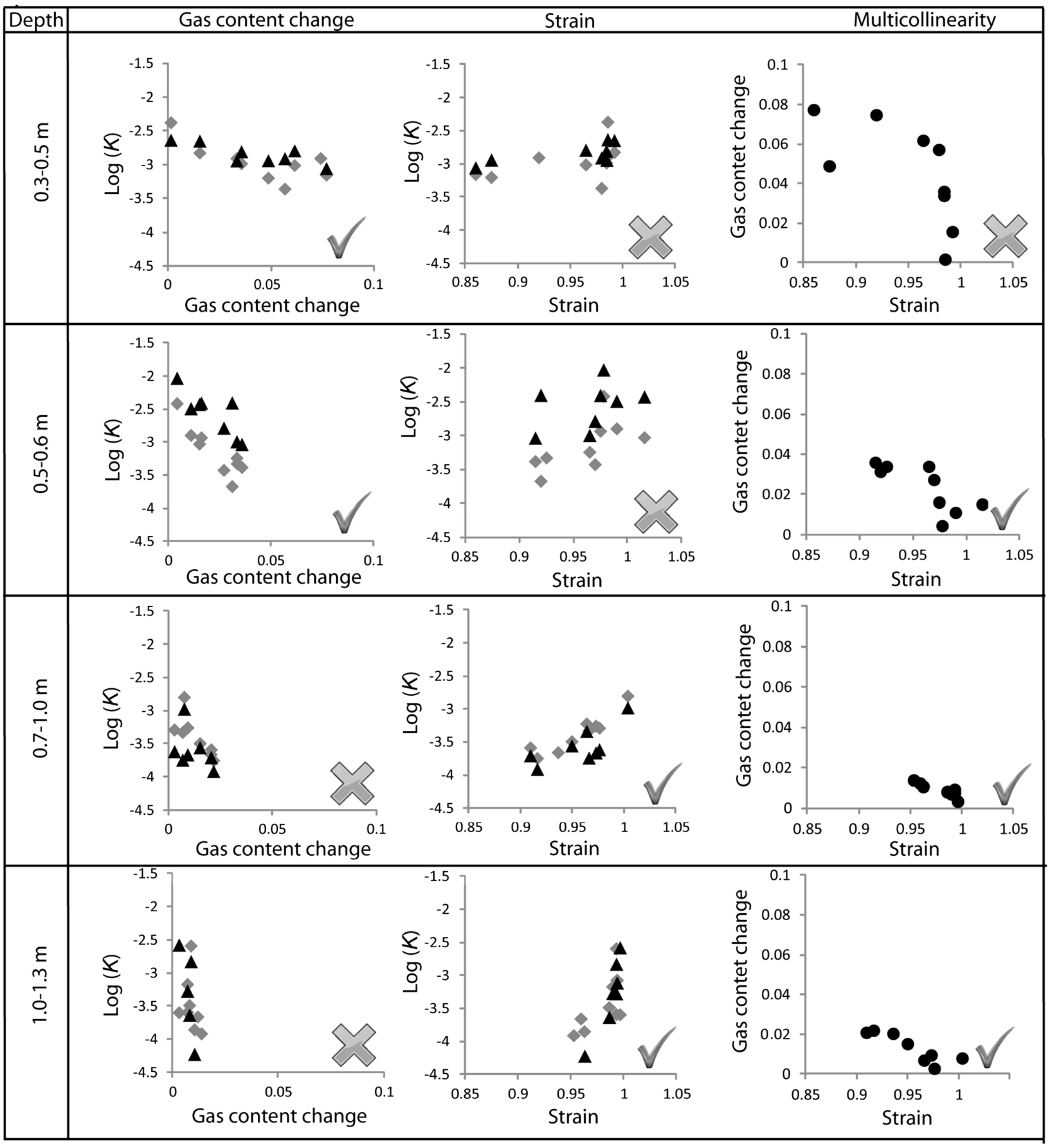

Figure 7. Relationships at site C between log (K) and changes in gas content ($\Delta\gamma$), log (K) and strain and gas content and strain within each layer. Checkmark indicates a significant linear relationship ($p < 0.05$), and a cross indicates an insignificant relationship ($p > 0.05$). Different piezometers are indicated by grey and black symbols

remainder of the peat profile, the increase in $\Delta\gamma$ is relatively consistent, increasing to a maximum of approximately 0.03 on DOY 250.

At site C, *K* shows a general decline at all depths over the study period—on average by an order of magnitude (from 0.002 to 0.0002 cm s^{-1}; Figure 5A). At site E, *K* is significantly lower than that at site C ($p < 0.001$, averaging 0.0003 cm s^{-1} compared with 0.001 cm s^{-1} at site C) and declines over the study period by, on average, an order of magnitude (Figure 5B). Unlike site C, the range in peat *K* at site E increases with time during this measurement period (Figure 5B).

Although we applied a measurement protocol similar to that outlined by Baird *et al*. (2004) and Surridge *et al*. (2005), a protocol that produced hydraulic conductivity measurements analogous to a separate laboratory-based approach (Surridge *et al*., 2005), determining the accuracy of such measurements, is difficult. However, the precision of our hydraulic conductivity measurements can be approximated from a semivariogram showing the repeatability between increasing measurement intervals (Figure 6). The semivariance between repeat hydraulic conductivity measurements increases with an increasing measurement interval and is approximated by an exponential relationship ($r^2 = 0.87$). The intercept of this regression relationship, the semivariance at a hypothetical measurement interval of zero days, equals 0.032 log(cm s^{-1})^2. Measurement precision is thus substantially higher than the observed order of magnitude variations in *K* during the study period (Figure 5).

DISCUSSION

Measurements show that peat *K* is not constant during the growing season but varies by up to an order of magnitude, corroborating previous measurements (Price, 2003). Multiple regression analysis was performed between the

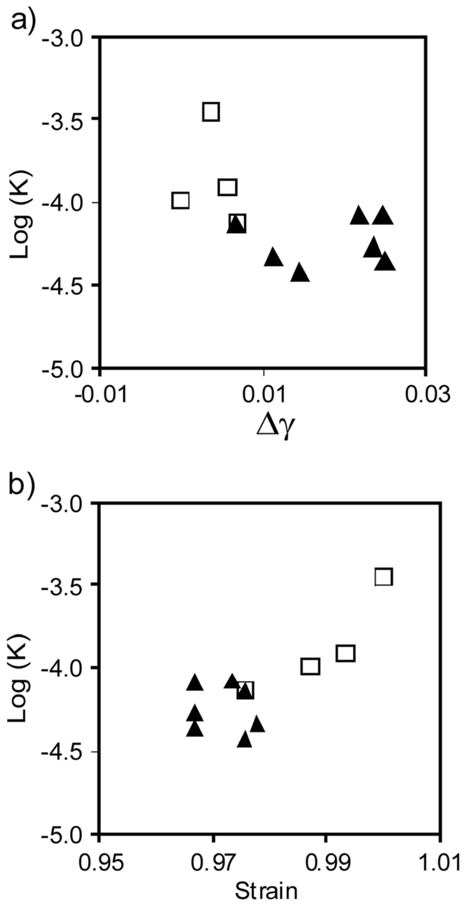

Figure 8. Log (K) *versus* (A) $\Delta\gamma$ and (B) strain at site E within layer 0.7–1.2 m. Measurements before and during the period of drainage are indicated by open squares, whereas measurements during the remaining study period are indicated by solid triangles

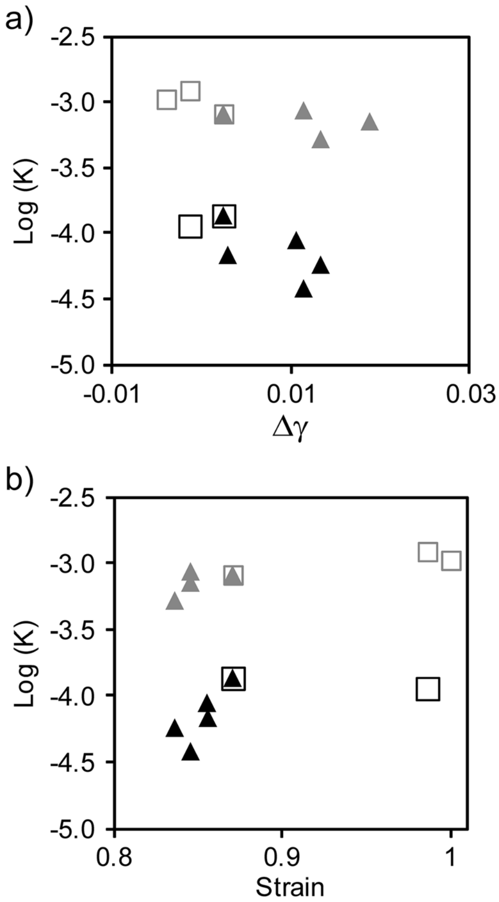

Figure 9. Log (K) *versus* (A) $\Delta\gamma$ and (B) strain at site E within layer 0.3–0.5 m. Different piezometers are indicated by grey and black symbols. Measurements before and during period of drainage are indicated by open squares, and measurements during the remaining study period are indicated by solid triangles

dependent variable peat *K* and the independent variables $\Delta\gamma$, strain and dummy variable piezometer number. The dummy variable accounts for the differences in *K* between different piezometers, which results from its high spatial variability (Holden and Burt, 2003). Although data analysis was performed using multiple regression relationships, to enable visual comparison, we present the individual correlations between *K* and the variables $\Delta\gamma$ and strain and between $\Delta\gamma$ and strain (Figure 7). At site C, neither $\Delta\gamma$ nor strain is significantly correlated with log (*K*) within layer 0.2–0.3 m ($p > 0.05$; data not shown). This insignificant relationship between log (*K*) and the two primary controls on its temporal variation is uncertain and may result from difficulties in obtaining accurate *K* measurements in the near-surface poorly decomposed peat (Surridge *et al*., 2005), from spatial variability in the entrapped gas content (Strack and Waddington, 2008) and/or from venting of gas through piezometers (Waddington *et al*., 2009). Multiple regression relationships indicate that log (*K*) at site C is significantly correlated ($p < 0.05$) with $\Delta\gamma$ but not strain within layers 0.3–0.5 and 0.5–0.7 m (Figure 7). In comparison, within layers 0.7–1.0 and 1.0–1.3 m, log (*K*) is significantly correlated ($p < 0.05$) with strain but not $\Delta\gamma$. This indicates that variations in entrapped gas content provide the primary control on temporal variations in *K* just below the water table (0.3–0.7 m) and changes in peat relative volume control variations in *K* deeper within the profile (0.7–1.3 m). However, causality is uncertain because of multicollinearity between strain and $\Delta\gamma$; $\Delta\gamma$ and strain are significantly correlated within layers 0.5–0.7, 0.7–1.0 and 1.0–1.3 m ($p < 0.05$; Figure 7). As a result, the significance of the variables $\Delta\gamma$ and gas content within these multiple regressions is uncertain. Within layer 0.3–0.5 m, log (*K*) and strain are not significantly correlated ($p > 0.05$; Figure 7), suggesting that the observed variations in *K* are controlled by the buildup of entrapped biogenic gas bubbles.

The drainage experiment utilized within this study offers the opportunity to separate the multicollinearity in $\Delta\gamma$ and strain under field conditions. By lowering the water table during the initial growing season, the change in peat *K* occurs over a period of low gas content increase. However, multicollinearity between strain and $\Delta\gamma$ is still evident (strain and $\Delta\gamma$ significantly correlated, $p < 0.05$), preventing statistical verification of the controls on the temporal variation in *K* from multiple regression analysis. Although multicollinearity between strain and $\Delta\gamma$ prevents this multiple regression analysis from being applied, such controls can be interpreted by identifying the magnitude of change in log (*K*) during the period of peat deformation and during the subsequent $\Delta\gamma$ increase.

This suggests that biogenic gas bubbles provide the key control on *K* just below the water table and that deformation provides the primary control on changes in *K* in the deeper peat. Within layer 0.7–1.2 m, log (*K*) reduces from -3.44 to −4.12 log (cm s^{-1}) during the period of peat compression (Figure 8). During the subsequent gas content increase, log (*K*) actually increases from -4.12 to −4.07 log (cm s^{-1}). However, within layer 0.3–0.5 m (Figure 9), strain reduced from 1.0 to 0.87 during the drainage of the peatland (three times the reduction observed within layer 0.7–1.2 m). However, log (*K*) reduces by only 0.08 and 0.03 log(cm s^{-1}) during this period. In comparison, log (*K*) declines linearly with increasing $\Delta\gamma$ over the growing season (Figure 9A). Increases in $\Delta\gamma$ at site E were small though (0.018 at a depth of 0.4 m), and the relationship between log (*K*) and $\Delta\gamma$ is not significant. At the intermediate depth of 0.5–0.7 m, between the zone of gas content control on *K* above and $\Delta\gamma$ control on *K* below, there is no definable variation in *K* during the study period. Within the experimental site, the water table dropped below the 0.25 m piezometer and was discounted from the analysis.

The cause of variations in the importance of entrapped gas and deformation on *K* through the peat profile remains uncertain. Differences may be associated with variations in peat physical properties with depth. In more decomposed deeper peat, *K* is likely dominated by a small number of connected macropores that are susceptible to collapse under stress. A reduction in peat volume is associated with the reduction in the volume of these hydrologically active pores and thus has a large influence on seasonal variations in *K*. In comparison, entrapped gas bubbles form throughout the peat (Kettridge and Binley, 2008) and are unlikely to block such active pores due to the small proportion of the peat volume which they comprise. In poorly decomposed peat just below the water table, the water flow occurs through a large interconnected network (Quinton *et al*., 2009). Gas bubbles are more likely to form within this distributed hydraulic network and will block pores and reduce peat *K*. The collapse of individual pores within this distributed network will not substantially influence peat *K* as such a network would provide the loss of only one of many potential pathways through the peat profile.

CONCLUSION

We have demonstrated that peat *K* is not constant over the growing season but instead fluctuates by up to an order of magnitude with changes in the entrapped gas content and with peat deformation. By regulating the changes in water table position, temporal variations in *K* resulting from variations in the entrapped gas content and peat deformation provide a potentially important negative feedback in the hydrological response of peatlands to drought. Under warm dry conditions, the entrapped gas content within the peat will be high, and the peat will compress under the weight of the deep unsaturated zone, reducing *K*. However, this reduction in *K* will decrease water export from the peatland to the wider catchment and may minimize the mitigating effect of these ecosystems on downstream drought conditions. This internal regulation of the peat moisture content will likely increase ecosystem resilience, maximizing the survival of *Sphagnum* species that depend on the transport of moisture to the peat surface through capillary rise (Price *et al*., 2008). In addition, by minimizing reductions in carbon sequestration due to *Sphagnum* stress and reducing the depth of the anaerobic zone that strongly controls the rates of peat decomposition, the loss of carbon from these important stores during such events will be minimized (Strack and Waddington, 2007; Strack *et al*., 2008). In comparison, during cool, wet, winter conditions, the entrapped gas content will be low, and compression will be minimized, maximizing water export from the peatland and maintaining lower water table positions.

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