Consolidation of gyttja in a rewetted fen peatland: Potential implications for restoration

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SUMMARY

Water availability is a major concern when restoring degraded vacuum harvested peatlands. The seasonal expression of water arising from the compression of underlying organic deposits may provide a source of water. A bog near Rimouski, Québec (Canada) was harvested using the vacuum extraction method and cut down to underlying sedge peat; restoration procedures were implemented in the autumn of 2009. The residual peat layer is 0.4–1 m thick, and overlies a 1–1.5 m thick gyttja deposit. Gyttja is a coprogenous lake bottom sediment on which peat sometimes forms. Little is known about the hydrophysical properties of gyttja and the implications it may have for peatland restoration. The upper 40 cm of gyttja had average bulk density 0.12 g cm^{-3}, particle density 1.57 g cm^{-3} and porosity 92 %. The organic matter and fibre contents of the gyttja were > 45 %, and both decreased with depth. Oedometer test results showed 9 and 72 % strain at 3.5 and 200 kPa, respectively, demonstrating the potential for water release upon compression, which in the field is caused by water table lowering. However, during the year of measurement (2011) the changes in effective stress caused by water table lowering were < 1 kPa, corresponding to a water table decline of < 10 cm. Under these conditions the volumetric moisture content of the top 30 cm of gyttja decreased by only 0.4 % and we observed 0.5 cm of gyttja settlement; this represented 0.4 % and 1.7 % strain, respectively. On the basis of these strains, we conclude that the release of water due to the consolidation of gyttja in 2011 had little impact on rewetting of the overlying peat. However, it may be important under drier conditions with a larger seasonal water deficit, and may have been important prior to restoration when larger water table fluctuations were observed.

KEY WORDS: compression, hydrology, organic soil, restoration

INTRODUCTION

The term 'gyttja' was presented by von Post (1862) and re-introduced by Hansen (1959) as a combination of organic and inorganic materials precipitated from a water column *via* biochemical processes. Gyttja is a coprogenous deposit with gel-like consistency that sometimes infills aquatic systems. These aquatic systems can also be terrestrialised through the development of a covering peat layer (Campbell *et al.* 1997, Dempster *et al.* 2006, Łachacz *et al.* 2009, Rydin & Jeglum 2006). Numerous studies have reported the presence of gyttja soils in peatlands (Hulme & Durno 1980, Warner *et al.* 1990, Kuhry *et al.* 1993, Campbell *et al.* 1997, Maukilau 1997, Branfireun & Roulet 1998, Smerdon *et al.* 2005, Dempster *et al.* 2006,). Few studies have evaluated the hydrophysical properties and composition of gyttja, and its hydrological role in natural and disturbed systems is essentially unknown. Our interest in the hydrophysical role of gyttja stemmed from a need to optimise restoration of a peatland harvested for horticultural peat.

Döll & Schneider (1995) reported the hydraulic conductivity of gyttja evaluated by constant head permeameter tests and reported values ranging from ~ 0.04 to 0.09 cm d^{-1}. In a Southern Ontario kettle peatland, Campbell *et al.* (1997) determined that gyttja was low in carbonates and that its organic content ranged from about 40 to 80 % by mass based on loss on ignition testing, and generally decreased with depth; basal gyttja typically contained the lowest amount of organic matter. Łachacz *et al.* (2009) showed a range in organic matter content of 0.2 to 87.5 % and also showed that it declined with depth; the calcium carbonate content was generally low, yet reached up to 67.5 % of dry weight. Zurek-Pysz (1992) reported a gyttja consisting of nearly 80 % calcium carbonate by mass and only 16.5 % organic matter. It is evident that the organic matter content and composition of minerals in gyttja is highly variable, which can result in a large range of mechanical (*e.g.* compression) and hydrological properties. Compression in organic soils can occur naturally in response to seasonal water table variation and represent an important water storage change mechanism (Price & Schlozhauer 1999) that results in a high and stable water table relative to the surface (Whittington & Price 2006). Compression also occurs in response to machinery during peat extraction or forest harvesting (O'Mahoney *et al.* 2000).

Drainage can also cause partially reversible and non-reversible changes to the peat structure, reducing the storativity of the peat and water transport within it (Price 1997, 2003). In peatlands there are three primary components to subsidence: shrinkage, which occurs above the water table; oxidation, which predominately happens above the water table; and compression, taking place below the water table (Schothorst 1977). Only shrinkage and compression are partially reversible. Schothorst (1977) determined that compression of peat layers below the water table represented 35 % of total subsidence due to long-term deep drainage. Compression and shrinkage account for more than 95 % of the seasonal soil volume changes where peat-harvesting activity has taken place (Kennedy & Price 2005); over the long term oxidation may be more important (Schothorst 1977).

Compression of peat below the water table is a mechanical process caused by the changes in effective stress (σ_e) induced by seasonal water table fluctuations. The total stress at a point in the system, caused by the weight of the soil (solids, water and air) overlying that point, is expressed as

$$\sigma_T = \rho_T g h \,, \qquad [1]$$

where σ_T is total stress (Pa), g is gravitational acceleration (9.81 m s^{-2}), ρ_T is the total density of the overlying material (kg m^{-3}) of height h (m). σ_T is countered by buoyant forces in the soil matrix that are created by soil-water pressure (ψ) (Terzaghi 1943), resulting in an effective stress (σ_e) of

$$\sigma_e = \sigma_T - \psi \qquad [2]$$

Drainage lowers the water table (ψ decreases), increasing the effective stress on the system, and thus the rate and magnitude of subsidence (Hobbs 1986). Effective stress varies largely due to seasonal changes in the position of the water table. In drained peatlands water table drawdown of up to 60 cm is common and the associated change in effective stress (σ_e) can be up to 6 kPa (Price 2003). Changes in peat volume due to compression (and shrinkage) can be immediate and synchronous with water-level changes (Lang 2002, Price & Schlotzhauer 1999). We do not know how gyttja layers respond to water table fluctuations. Terzaghi (1943) states that a time lag may be evident in volume change if a soil exhibits both high compressibility and low permeability (as does gyttja) because changes in the saturated moisture content do not occur rapidly.

In previous studies the compressibility of gyttja has been assessed from a structural engineering, rather than an environmental, point of view. Hence, Zurek-Pysz (1992) examined the compressibility of gyttja but the lowest pressure tested (12.5 kPa) was greater than the pressures typically generated by seasonal water table changes in peatlands, although possible for artificial drainage. At 12.5 and 200 kPa the strain experienced was ~5 % and 35 %, respectively, for detrital calcareous gyttja. The proportion of mineral and organic matter content influence the mechanical characteristics of gyttja soils (Becker *et al.* 2004), the latter being more susceptible to strain (Dingman 1994).

There have been several studies of rewetting drained peatlands where gyttja is present (Kieckbusch *et al.* 2006, Tiemeyer *et al.* 2006, Kieckbusch & Schrautzer 2007); however, characteristics of the gyttja layer were not assessed and it was just considered to be impermeable. Its role on restoration was not assessed. There are several potential mechanisms by which seasonal peat and gyttja compression may enhance site wetness, which is typically desirable for peatland restoration (Price *et al.* 2003). Compression associated with subsidence of the overlying peat can lower the surface sufficiently to maintain a shallow depth to water table (Whittington & Price 2006), and water expressed from the consolidating material (*e.g.* gyttja) which otherwise may have been unavailable to plants can become available (Hillel 1998). Recolonisation by plants is closely linked to water availability; the longer a harvested site is left abandoned, the more hostile are its hydrological conditions, inhibiting moss growth (Kennedy & Price 2005). To our knowledge, there is no literature reporting on the behaviour of a gyttja layer and its implications for restoration. To do this it is important to better understand the general characteristics of gyttja, and especially how it functions under load, since it is unclear whether it deforms sufficiently in response to seasonal variations of the water table to express water to the overlying peat. The objectives of this research were to assess the hydrophysical and mechanical properties of gyttja, its behaviour under peat harvesting and restoration activities, and its hydrological connection with the overlying peat. Given the dearth of information on gyttja, we examined its behaviour under higher loads than typically occur under hydrologically induced stresses, which may be of value to engineering design.

STUDY SITE

The Bic-Saint-Fabien (BSF) peatland (~ 20 ha) lies approximately 25 km west of Rimouski, Québec (48° 19′ N, 68° 50′ W). For 1981–2010, average annual temperature is 4.4 °C and average annual precipitation is 958.5 mm, with approximately 30 % of the precipitation falling as snow (Environment Canada 2015). The local geology is dominated by sedimentary and metamorphic schists (Dionne 2005, Fortin & Belzile 1996). In 1946 BSF was exploited for horticultural peat *via* the block-cut method; the surface was reprofiled when vacuum harvesting began in the early 1970s. By the time these operations ceased in 2000, the area extracted totalled ~ 11 ha and harvesting activity had cut down to fen (sedge) peat. The extracted peat surface had a saddle-like topography with little residual peat (~ 0.4 m overlying gyttja) in the interior region, which was lower-lying than the elevated peripheral regions where there was upwards of 1 m of residual peat (i.e. the centre of the peatland was depressed). The surface altitude differences have resulted in a wetness gradient across the site with the lower interior region being wetter than most surrounding peripheral regions. The residual peat overlies a layer of gyttja soil, which ranges in thickness from about 1 m to 1.5 m.

Since the residual peat in BSF was minerotrophic sedge peat, this site was restored as a fen. Site restoration began in autumn 2009 and involved blocking active drainage ditches, contouring the cutover section to reduce local surface and hydraulic gradients, constructing peat ridges (bunds) to retain runoff, the application of plant material from a donor site, and a straw mulch treatment (Quinty & Rochefort 2003) which reduces evapotranspiration, minimises diurnal temperature fluctuations, and reduces the erosion of peat by wind (Price *et al.* 1998).

METHODS

Fieldwork

Field data were collected from June 21 to August 10, 2011 (day of year 172–222), which represent post-rewetting conditions. Volumetric moisture content (θ_v) in the peat and gyttja were determined at an interior and a peripheral site (with 40 and 75 cm of residual peat, respectively). Time domain reflectometry (TDR) probes (Campbell Scientific Inc., Utah, TDR100) were installed 5 and 20 cm below the peat surface and 5 and 0–30 cm below the peat base (*i.e.* in the gyttja). The 0–30 cm probe was installed vertically to determine the average soil moisture content of the profile, and all others horizontally. The probes were installed by excavating a small pit to allow access to the peat/gyttja interface, and then the pit was backfilled. θ_v was determined based on the calibration of Kellner & Lundin (2001). This calibration is for peat, thus the absolute value may deviate from that in gyttja, although changes in moisture content are likely to be accurate.

Elevation sensor rods (see Price 2003) were installed at the interior site to measure the seasonal change in thickness of the gyttja layer. Rods were inserted at the peat-gyttja interface and 20 cm below the interface in gyttja. The reader is directed to Price (2003) for a full methods description but, briefly, wooden dowels are fitted with drywall toggle bolts and pushed down inside a tube to the required depths. The tube is removed and the toggle bolts spring open, fixing them in position. The wooden doweling is graduated above the surface and compared to a stable datum (sight wire) to determine movement. Rebar (metal rod) anchored into the clay substrate was used as a datum to monitor the total peat and gyttja layer movement. Precision of measurement is 1 mm although accuracy, based on visual reading from a distance, is more likely to be ± 2 mm.

A meteorological station was installed at the interior site. This included a tipping bucket raingauge (Texas Electronics, Inc. model TR-525M). A manual raingauge with orifice diameter 10.4 cm was installed nearby, 85 cm above the ground surface, to check the tipping bucket data.

Horizontal saturated hydraulic conductivity (K_{sat}) was determined using bail tests following the method of Hvorslev (1951), based on measurements in polyvinylchloride (PVC) pipes from 2008 to 2011. Pipes were bailed several times before the start of the test to develop the piezometer. The inside diameter, outside diameter and length of the slotted intakes were 2.5, 3.3 and 15 cm, respectively; the screen was covered with nylon mesh. Pipes were installed 0.75 and 1.5 m below the ground surface into the gyttja layer at both sites, by pushing the tube carefully into manually drilled pilot holes. Note that the 0.75 m deep piezometer in the peripheral region was at the peat-gyttja interface, installed mostly in gyttja. In total, eight hydraulic conductivity tests were performed on each piezometer at both sites between June 2008 and June 2011. Wells constructed from PVC pipes (perforated along their entire lengths) were installed at the interior and peripheral locations, extending ~1 m below the peat surface to measure the position of the water table. The response times of wells were not tested.

Laboratory

Samples of gyttja were collected in 2011 at the interior location on BSF and brought back to the laboratory to determine bulk density (ρ_b), particle density (ρ_p), porosity (ϕ), organic matter, fibre content, vertical saturated hydraulic conductivity (K_{sat}) and compressibility. Gyttja samples were acquired by digging a small pit to the peat base and extracted using a piston corer constructed from 50 cm long sections of thin-walled 4.5 cm diameter PVC tubing. A larger syringe sampler (PVC pipe i.d. 7.5 cm) was used to collect samples for compressibility tests, as they required a larger diameter. Gyttja was more difficult to extract with the larger diameter sampler so only the upper ~ 25 cm of the gyttja layer could be acquired. A rubber bung fixed to a steel rod fitted snugly inside the pipe acted as the plunger. The inside of the PVC pipe was mildly lubricated with a silicone based lubricant to maintain a seal while allowing the plunger to glide as the tube was pushed into the gyttja; the steel rod and plunger being held at a steady position thus creating the level of suction required to extract gyttja samples.

The 4.5 cm diameter gyttja cores were cut into 5 cm segments at the depths indicated below; depths represent the sample mid-point (e.g. 5 cm depth is 2.5–7.5cm). For the upper 40 cm of the gyttja layer, vertical K_{sat} and ρ_b were determined every 5 cm; ρ_p and ϕ were determined at 10, 20, 30 and 40 cm depths; organic matter content was determined for 5, 15, 25 and 35 cm depths; and fibre content was determined for 5 and 35 cm deep. A mean value for each of the aforementioned properties at each depth was derived from a sample size of three. Vertical K_{sat}, ρ_b, and ϕ were determined by ASTM standard F1815 (ASTM 2011b). Vertical K_{sat} was determined using Darcy's law, by maintaining a constant head at the upper end while collecting the outflow to determine specific discharge. For each sample a geometric mean was obtained from three trials. Samples were oven dried at 80 °C (as opposed to 105 °C, to avoid burning of organic matter) to determine ρ_b. Particle density (ρ_p) was determined by inserting a known mass (~ 6–9 g) of dried, crushed soil in a graduated cylinder, which was then filled with a measured volume of a wetting fluid (kerosene) to determine sample volume. ρ_b and ρ_p were used to calculate ϕ as

$$\phi = 1 - (\rho_b/\rho_p) \qquad [3]$$

Organic matter and fibre content were determined according to ASTM standards D2974 and D1997 (ASTM 2007, 2008). The amount of organic matter in gyttja was measured using loss on ignition (LOI) tests. Oven-dried gyttja samples (several grams each) were placed in a muffle furnace and incinerated at 450 °C for three hours, then reweighed. The mass from each sample lost on ignition represents its organic fraction. To determine fibre content, gyttja was wet-sieved (number 100 sieve, 150 μm) to wash away fine particulates, leaving the larger fibres. The sieve with fibres was submerged in 2 % hydrochloric acid to dissolve carbonates if they were present. After washing again with water the material caught by the sieve was incinerated to separate the mineral content and fibre content.

Compression tests were done with an oedometer based on ASTM standard D2435/D2435M (ASTM 2011a) with minor modifications. Compression tests were performed on gyttja samples from 5, 10 and 20 cm below the peat base, with said depths representing the midpoint of each 19 mm sample (initial sample height). Tests for 5 and 10 cm depths were triplicated and for the 20 cm depth were duplicated. Samples were submerged in water for several days prior to compression in an effort to achieve saturation replicating field conditions. Samples were kept submerged for the duration of the experiment. In addition to the standard loads typically tested (6.25, 12.5, 25, 50, 100 and 200 kPa), a load of 3.5 kPa was added to better capture the rate and magnitude of compression that gyttja would experience under field conditions. All other loads were tested despite not being in the range of seasonal water table variations, to be consistent with standard procedure. Testing at higher pressures provides insight on stress levels that may have been reached through initial artificial drainage and to better characterise the mechanical role of gyttja for other practitioners. Each load was left for approximately 24 hours. The oedometer tests were one-dimensional as the specimen was constrained laterally to prevent lateral deformation. Total strain (ε) and void ratio (e) were calculated at the end of each 24-hour load increment. Strain was calculated as

$$\varepsilon = \Delta H/H_0 \qquad [4]$$

where ΔH is change in sample height and H_0 is the initial sample height before loading (*i.e.* 19 mm). The height of solids (H_s) and height of voids (H_v) were used to calculate the void ratio as

$$e = H_v/H_s \qquad [5]$$

The height of the void spaces at the end of each load increment was calculated as the difference between the sample height (H) and the height of the solids where

$$H_v = H - H_s \qquad [6]$$

The height of the solids remains the same for all load increments and is given as

$$H_s = M_d/AG_s\rho_w \qquad [7]$$

where M_d is the dry gyttja mass, A is the area of the oedometer ring, G_s is the specific gravity of gyttja and ρ_w is the density of water. Compression results were used to create plots of strain *versus* effective stress and void ratio *versus* log-scale effective stress. The former plot was used to estimate how much water could be released from the gyttja layer in the field at different effective stresses.

The void ratio *versus* log-scale effective stress plot was used to estimate the preconsolidation stress (P_c). P_c is the maximum stress previously experienced by the soil and, thus, provides information on the stress history of the soil. Once the effective stress exceeds the preconsolidation stress, virgin compression (typically at a higher rate) occurs (Hobbs 1986, Hillel 1998). P_c was estimated following the Casagrande (1936) method (Figure 1a). This method involves visually estimating the point on the void ratio *versus* log effective stress curve that has the smallest radius (Figure 1a). A tangent (Line 1) and a horizontal line (Line 2) are drawn at this point, the angle created by these lines is bisected (Line 3), and the straight-line portion of the curve (virgin compression) is extended back (Line 4) to intersect Line 3 at the pressure corresponding to P_c (Figure 1a). The recompression index (C_r) is the stress-strain relationship for the section of the curve with stress that is less than the preconsolidation stress (P_c)

$$C_r = \Delta e/\Delta\log(\sigma_e) \qquad [8]$$

and the virgin compression index (C_c) is the relationship for the section of the curve where the preconsolidation stress has been exceeded.

$$C_c = \Delta e/\Delta\log(\sigma_e) \qquad [9]$$

The slope of the unloading curve (not shown in Figure 1) was used to determine C_r.

Vertical K_{sat} (m min^{-1}) was calculated from compression results for the 3.5, 6.25 and 200 kPa load increments using

$$K_{sat} = C_v m_v \gamma_w \qquad [10]$$

C_v is the coefficient of consolidation (m^2 min^{-1}), γ_w is the specific weight of water (9.81 kN m^{-3} at 20 °C), and m_v is the coefficient of volume compressibility (m^2 kN^{-1}), which is calculated as

$$m_v = \varepsilon/\Delta\sigma_e \qquad [11]$$

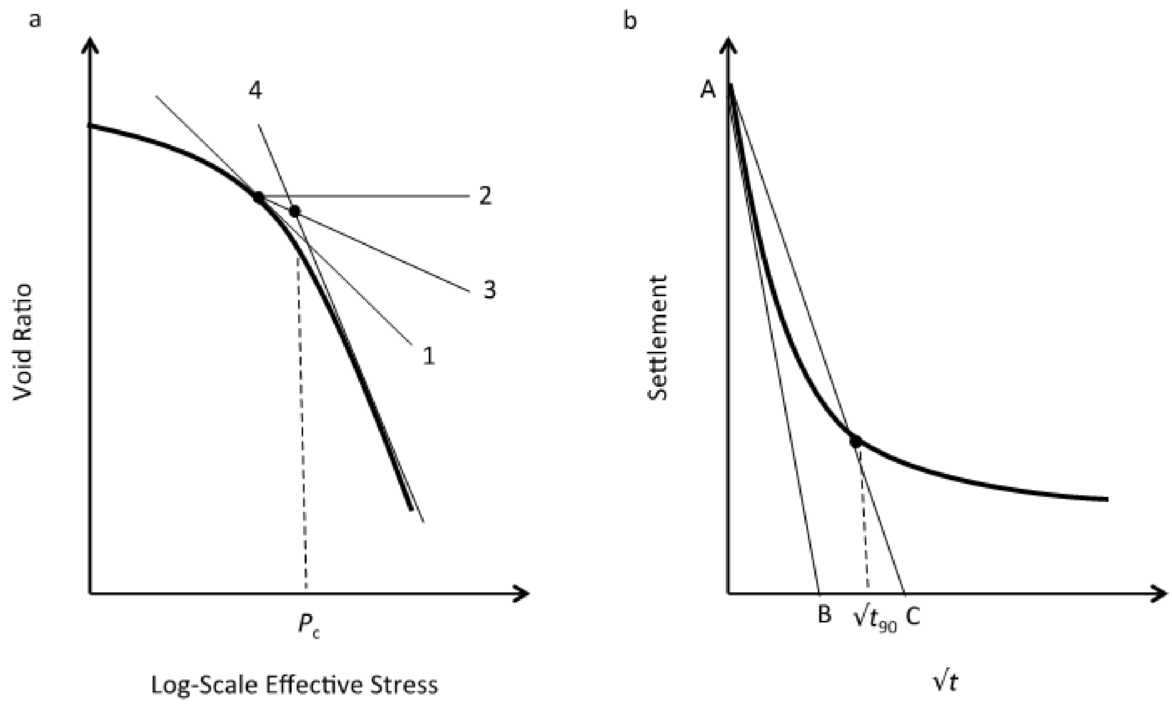


Figure 1. Graphical procedures for estimating (a) preconsolidation pressure following Casagrande (1936), and (b) time of 90 % consolidation following Taylor (1948). See text for details.

for each 24-hour load increment. Since we calculated m_v for each load increment, ε had to be calculated for each load increment taking H_0 (see Equation 4) as the initial sample height at the beginning of that load increment (*i.e.* 19 mm minus settlement from previous loads) [note: 1 kPa is equal to 1 kN m^{-2}]. The square root time fitting method (Taylor 1948) was used to determine C_v using

$$C_v = T_v\, H^2_{dr}/t_{90} \qquad [12]$$

where T_v is a dimensionless time parameter (0.848), H_{dr} for two-way drainage is half the average sample thickness for the load increment, and t_{90} is the time at 90 % consolidation. The t_{90} parameter is estimated from a settlement *versus* square root time curve (see Figure 1b). A straight line (Line AB) is drawn through the initial straight portion of the curve. A second line (Line AC) is drawn from the point on the horizontal axis with abscissa value 1.15 times larger than the value at B. The abscissa of the point where Line AC intersects the curve is t_{90}. We note the potential for ambiguity, but this is a standard curve fitting method and common in the literature (Dananaj & Frankovská 2004, Tai *et al.* 2008).

RESULTS

Between day of year 172 and 222, 2011, BSF received 159 mm of precipitation compared to the 30-year average of 144 mm for the same period. The study season followed a relatively wet spring, with 70 mm of rain falling in the 20 days prior to the start of the study period (day of year 152–171). Four rain events during the study season each delivered more than 10 mm of precipitation. Values recorded by the tipping bucket raingauge were within ± 9 % of those indicated by the manual gauge.

The 40 cm thick peat layer at the interior site was much wetter than the more elevated peripheral site with 75 cm thick peat. The θ_v of the peat was higher and less variable at the interior site (Figure 2) than at the peripheral site. Variability in θ_v declined with depth below the ground surface at both sites (Figure 2). The water table was typically at or just above the ground surface at the interior location, and lower and more variable at the peripheral site, having average seasonal values (± standard deviations) of 1.7 (± 3.1) and -15.1 (± 6.7) cm, respectively. Seasonal water-table ranges were ~13 and 30 cm at the interior and peripheral sites, respectively (Figure 2). The θ_v

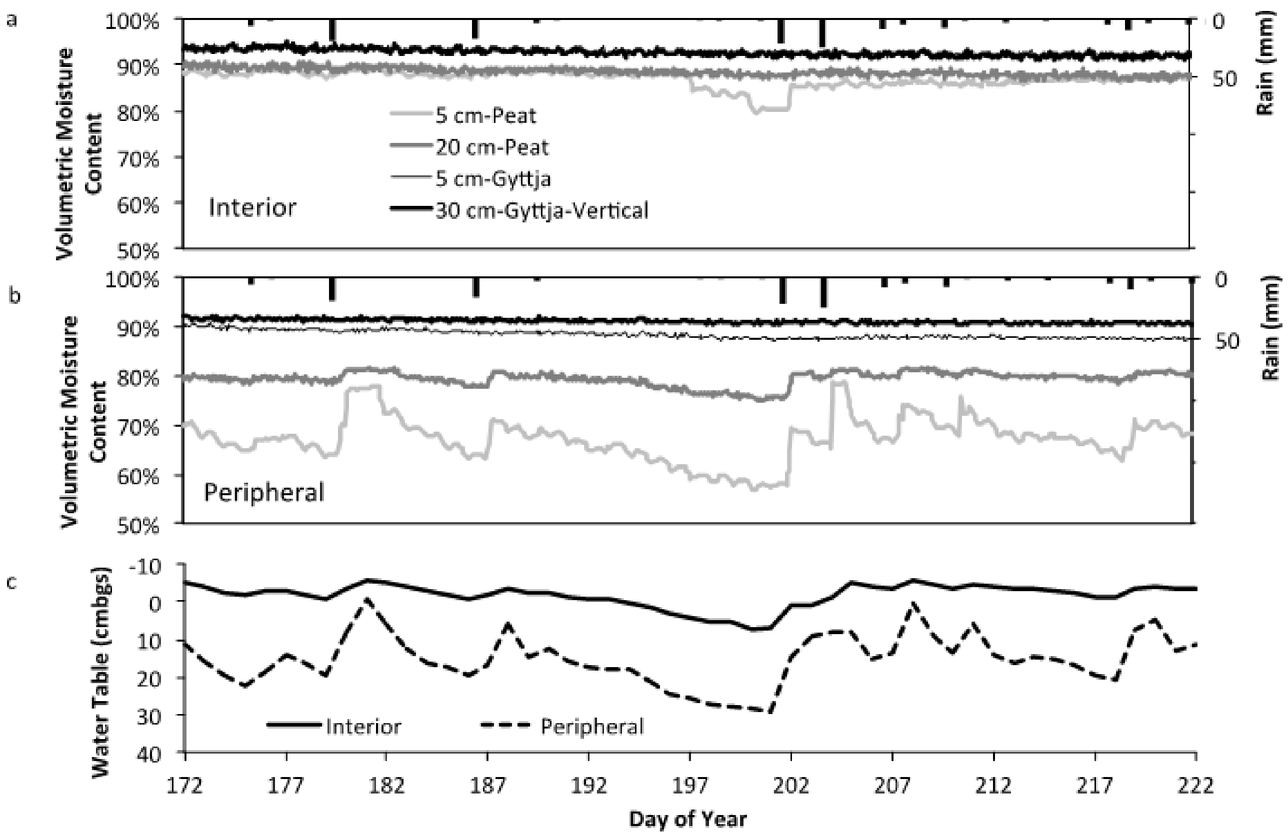


Figure 2. Volumetric moisture content and water table for interior and peripheral regions.

of the gyttja layer at both locations exhibited negligible short-term variation, as it was below the water table and remained saturated for the duration of the study season (Figure 2). However, a gentle, statistically significant ($p < 0.05$) seasonal decrease in θ_v occurred. This trend was more apparent in the drier peripheral region of the site, which experienced a greater water table decline (Figure 2). At the peripheral region the seasonal decrease in moisture content for the 5 and 0–30 cm gyttja probes was 2.6 and 1.0 %, respectively; at the interior site it was 1.8 and 1.5 %, respectively.

The elevation sensor rod measuring the deformation of the gyttja layer (interior site) was relatively static, with a 0.7 cm (+ 0.2 to - 0.5 cm) change in elevation during the study season; the seasonal change in thickness was zero (Figure 3). The rod installed 20 cm below the gyttja surface, in gyttja, was less mobile and had a seasonal range in movement of 0.3 cm (+ 0.2 to - 0.1 cm); the seasonal change in thickness measured at this rod was + 0.1 cm. Both rods experienced most movement when the water table recessed mid-season (Figure 3). In contrast, the range of deformation of the total soil column (*i.e.* measured at the ground surface) was 2.9 cm, exhibiting a similar but muted trend to that of the water table (Figure 3). This means that almost all of the soil volume-change occurred in the peat above the gyttja. Strain in the peat reached ~ 6% for the 40 cm thick peat layer, much of it due to shrinkage when it was desaturated on Days 192–202 (Figure 2c).

Physical and hydraulic properties of gyttja

The mean ρ_b, ρ_p, and ϕ for the upper 40 cm of the gyttja layer was 0.12 g cm^{-3}, 1.57 g cm^{-3} and 92 %, respectively (Table 1). A small increase in ρ_p was evident between the upper 10 and 20 cm of the gyttja layer, otherwise there was very little change with depth. Organic matter and fibre content both decreased with depth (Table 1). The organic matter content (as a proportion of the solids) 5 cm below the peat base was 70.6 % and it decreased to 44.8 % at 45 cm below the peat base. Fibre content in the gyttja layer was 56.4 % and 49.8 % at 5 and 35 cm, respectively. It is apparent that the gyttja at BSF contains of a mineral component that increases with depth. The upper 40 of the gyttja layer has little to no calcium carbonate content, as no reaction was evident when specimens were submerged in a 2 % hydrochloric acid solution.

Vertical K_{sat} decreased with depth up to 35 cm, where there was a small increase. At 5 cm below the peat base (Table 1) it was 4.1 cm d^{-1} declining to 0.9 cm d^{-1}, 30 cm below the peat base. It was 1.9 cm d^{-1} at 35 cm but K_{sat} dropped to 0.7 cm d^{-1} at 40 cm below the peat base. Horizontal K_{sat} for gyttja in the field was lower, with a four-year geometric mean of 0.06 cm d^{-1} (or arithmetic mean of 0.10 cm d^{-1}) for the 75 cm and 150 cm deep piezometers at the interior and peripheral sites (Table 2). The geomean for four-season horizontal hydraulic conductivity reported by Malloy & Price (2014) for the 75 and 150 cm piezometers were 0.11 and 0.07 cm day^{-1},

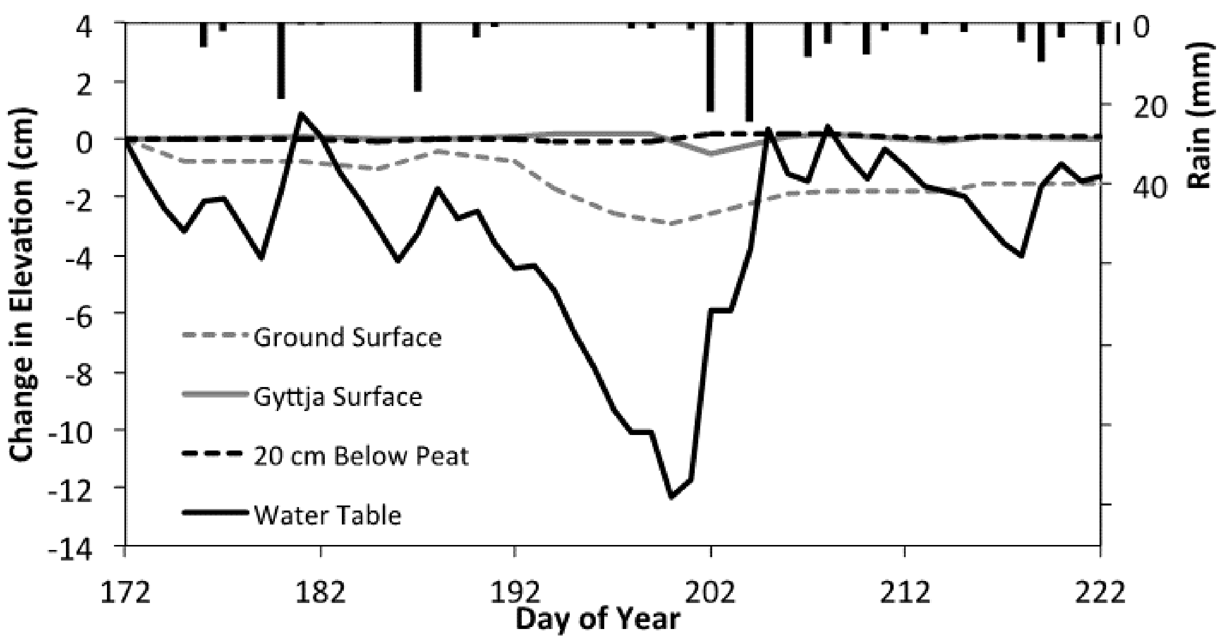


Figure 3. Peat and gyttja subsidence and water table movement at the interior site. The initial (Day 172) water table level was + 5 cm.

Table 1. Gyttja properties (mean of 3 samples) Note: *one set of three gyttja cores was used to determine bulk density, porosity and organic matter content; a separate set of three cores was used to determine fibre content, hydraulic conductivity and particle density. Hydraulic conductivity was calculated as a geometric mean.

Depth (cm)	Bulk Density ρ_b (g cm^{-3})	Particle Density ρ_p (g cm^{-3})	Porosity ϕ (%)	Organic Matter (%)	Fibre Content (%)	*Hydraulic Conductivity K_{sat} (cm day^{-1})
5	0.11			70.6	56.4	4.1
10	0.10	1.48	0.93			3.5
15	0.11			58.3		2.5
20	0.12	1.60	0.93			2.3
25	0.12			50.7		1.3
30	0.14	1.63	0.91			0.9
35	0.11			47.3	49.8	1.9
40	0.12	1.58	0.92			0.7
Average	0.12	1.57	0.92	56.7	53.1	1.8

respectively, based on six testing locations in the harvested peat area. Horizontal K_{sat} for the basal clay layer, measured in the field, was ~ 0.02 cm d^{-1}.

Laboratory consolidation

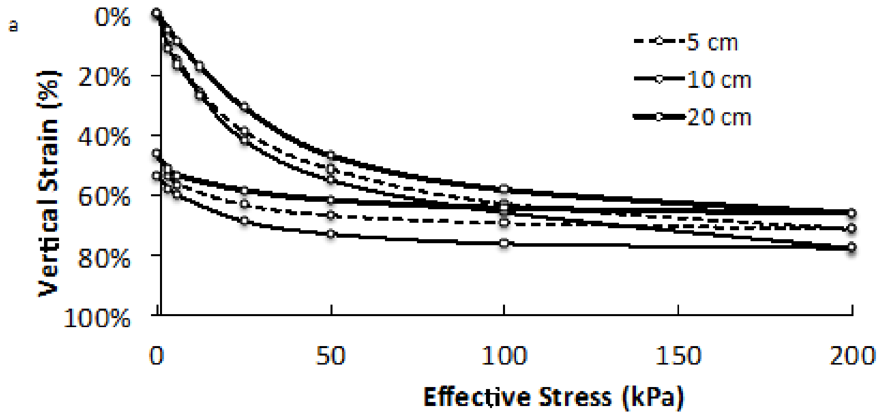
Unlike the in-field vertical compression tests, the laboratory tests showed a considerable amount of consolidation, although under much greater loads than those generated by seasonal changes in water table. Little difference in strain was observed between different depths for the same load, although the deepest samples (from 20 cm below the base of the peat) consistently exhibited less strain for all pressures tested. The mean total strain for all depths was 9, 14, and 72 % at 3.5, 6.25 and 200 kPa, respectively (Figure 4a).

Table 1: Field saturated hydraulic conductivity (4 study season geometric mean from 8 tests).

Location	Depth (cm bgs)	Material	Average (cm day^{-1})
Interior	75	gyttja	0.02
	150	gyttja	0.27
Peripheral	75	peat/gyttja	0.10
	150	gyttja	0.01

Laboratory tests also showed that gyttja compression is only partly reversible (Figure 4). When unloading from 200 kPa, the 10 and 20 cm gyttja swelled by about 3.4 mm, or 25 %, from the maximum compressed state. Unloading results (strain and void ratio) are unavailable for the 5 cm tests at 0 kPa, as the consolidation cell was removed from the oedometer a day early. These data can be reasonably estimated based on measurements for 10 and 20 cm samples (Figure 4a). Similar to strain, little variability in void ratio existed between the three depths tested (Figure 4b). The mean e for 0 (initial), 3.5, 6.25 and 200 kPa was 12.2, 11.0, 10.4 and 2.8, respectively. We estimate from Figure 4b that the average preconsolidation pressure of these gyttja samples was ~ 8 kPa. Therefore, the gyttja at the cutover section of BSF in 2011 was in an overconsolidated state. The average virgin compression and recompression indices for all three depths tested were 6.1 and 1.3, respectively.

The vertical K_{sat} with depth derived from compression tests is displayed in Table 3. The vertical K_{sat} obtained from the initial load tested (3.5 kPa) should theoretically be the most representative of field conditions and, therefore, the most comparable to K_{sat} values determined with the other methods reported herein. At 3.5 kPa the vertical K_{sat} for the 5, 10 and 20 cm tests was 1.1, 1.5, and 0.7 cm d^{-1}, respectively. A decrease in K_{sat} with depth was not evident. As expected, the vertical K_{sat} decreased as the effective stress increased. At 200 kPa the vertical K_{sat} of gyttja declined to 9.3, 6.7 and 6.2 × 10^{-4} cm d^{-1} for the 5, 10 and 20 cm tests, respectively.



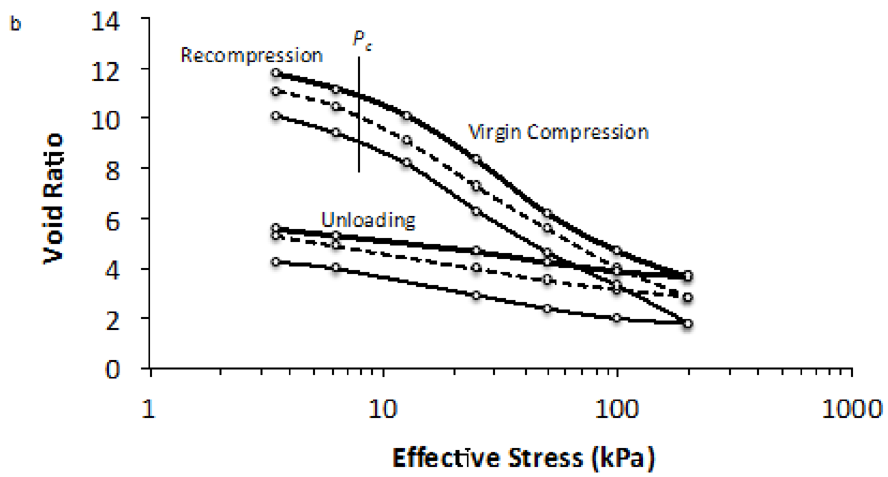


Figure 4. Loading and unloading curves for gyttja showing (a) strain and (b) void ratio, both *versus* log-scale effective stress.

Table 3. Hydraulic conductivity from compressibility tests. Note: 1 kPa is equal to 1 kN m^{-2}.

Load (kPa)	Sample depth (cm)	T_v	H_{dr} (m)	t_{90} (min)	C_v (m^2 min^{-1})	m_v (m^2 kN^{-1})	Y_w (kN m^{-3})	K_{sat} (m min^{-1})	K_{sat} (cm day^{-1})
3.5	5	0.848	9.0E-03	2.5	2.7E-05	3.0E-02	9.8	7.9E-06	1.1E+00
	10	0.848	8.9E-03	2.0	3.3E-05	3.2E-02	9.8	1.1E-05	1.5E+00
	20	0.848	9.3E-03	2.0	3.6E-05	1.4E-02	9.8	5.0E-06	7.2E-01
6.25	5	0.848	8.3E-03	16.0	3.6E-06	1.9E-02	9.8	6.8E-07	9.8E-02
	10	0.848	8.1E-03	9.3	6.0E-06	2.2E-02	9.8	1.3E-06	1.9E-01
	20	0.848	8.8E-03	4.4	1.5E-05	1.5E-02	9.8	2.3E-06	3.3E-01
200	5	0.848	3.1E-03	28.4	2.9E-07	2.3E-03	9.8	6.5E-09	9.3E-04
	10	0.848	2.9E-03	39.4	1.8E-07	2.6E-03	9.8	4.6E-09	6.7E-04
	20	0.848	3.6E-03	46.2	2.4E-07	1.8E-03	9.8	4.3E-09	6.2E-04

DISCUSSION

The post-harvesting topography of the peatland, along with the construction of bunds to retain water, resulted in wetter conditions in the interior part of BSF compared to the peripheral part (Figure 2), and wetter conditions in general than pre-restoration (Malloy & Price 2014). The cause of seasonal differences in ground surface altitude was determined to be, primarily, seasonal soil volume changes in the peat layer. The compression and hydraulic parameters of the overlying peat were not determined for this study, although Price (2003) provides a detailed discussion of peat compressibility. The ability of the peat layer to respond to water table changes by subsidence means that the water table remains closer to the ground surface than it would if the peat was rigid (Whittington & Price 2006); this has ecological implications. It is evident that the gyttja at this site, although compressible, played a lesser role than the peat in adjusting the ground surface altitude. However, we argue that this could change under more extreme seasonal water deficits. Hence, the potential compression, rather than the compression actually measured during this relatively wet season, is considered below.

The rather small change in water-table level at the interior and peripheral sites caused only slight loading of the gyttja. There were no measurements of subsidence at the peripheral location, but at the interior location a small loading (~ 0.8 kPa) when the water table dropped below the peat surface mid-season (day of year 192–202) caused minimal compression of the gyttja layer. From Day 192 until our elevation sensor rod measurement on day of year 202 (the end of the dry period), the change in thickness of the gyttja layer was 0.5 cm (Figure 3). If it is assumed that the volume change occurs primarily in the upper 30 cm of gyttja (explained below), then the strain is ~ 1.7 %.

The small change in gyttja volume was corroborated by a small change in its saturated θ_v (Figure 2) (the water table was always above the gyttja layer). This seasonal decline in θ_v despite continuous saturation suggests a decrease in the volume of pore spaces, consistent with peat compression (Price 2003). Decreases in θ_v below the water table could also be the result of methanogenic gas building up in the soil, although this typically gives an erratic θ_v signal (Kellner *et al.* 2005) that was not observed here. The change in θ_v in the 0–30 cm layer occurred mostly near the top of the layer. For the study season, a greater drop in θ_v was observed for the 5 cm deep probes than for the probes measuring the average moisture content of the upper 30 cm of the layer (Figure 2). The upper region of the gyttja layer also has the highest organic content, greatest fibre proportion, highest hydraulic conductivity and m_v, which make it more susceptible to compression (Tables 1 and 3). At depths below the upper ~ 5–10 cm section of the gyttja layer, the organic content, fibre content, hydraulic conductivity and m_v are all substantially lower, so taken together it is reasonable to assume that relatively little change in θ_v occurred below the 30 cm layer. From the time when the water table dropped 8 cm below the peat surface to the end of the dry period (day of year 192–202), 0.8 kPa loading on the 0–30 cm gyttja layer caused θ_v to decrease by 0.4 % (*i.e.* representing 0.4 % strain); the strain was slightly less than that determined from the elevation sensor rod (1.7 %). The wet conditions and small response prevented the development of a detailed field-based relationship between effective stress and strain. However, this relationship was determined in the laboratory (Figure 4a).

Assuming changes in total stress (σ_T) in the field were relatively minor compared to changes in pore-water pressure (ψ) (see Equations 1 and 2), then the loading (σ_e) that would occur in the field as a result of a water table decline can be seen in Figure 4a. For a change in load (σ_e) between 0 and 1 kPa (representing a 10 cm water table decline), the strain estimated from Figure 4a would be ~ 3 % greater than that determined in the field.

From the field and laboratory consolidation testing (elevation sensor rods, changes in θ_v at the interior site and laboratory consolidation tests), the estimates of strain are 1.7 %, 0.4 % and 3 %, respectively, for ~1 kPa of loading. For this loading we can calculate the amount of water expressed from a 30 cm layer of gyttja as 5.1, 1.2 and 9.0 mm, respectively. These values represent a relatively small proportion of the seasonal water input to the site by rainfall (159 mm). Laboratory compression tests at this loading showed more strain and, therefore, more water release than field methods. It is possible that the excess pore water pressure in the 30 cm gyttja layer caused by the drop in water table did not fully dissipate and reach hydrostatic equilibrium. Therefore, volume change in the field may not have been complete due to the time it takes for water to dissipate from the gyttja layer. This means that the volume change may not have been final and more water could have been released if the water table had remained ~ 8 cm below the ground surface for a longer period of time.

In the year of study, gyttja at BSF was in an overconsolidated state as the range in effective stress in the field was much less than the preconsolidation stress (8 kPa). This means that any soil volume change that the gyttja underwent in the field was at the recompression rate, with less volume change than during virgin compression (C_r = 1.3, C_c = 6.1). The small amount of loading and low rate of volume change during recompression was reflected as a small amount of gyttja volume change in the field. In a dry year with much greater water table recession we expect proportionately higher compression and, therefore, more water could be released. For the same study period (day of year 172–222) before restoration in 2008 and 2009, the range in water table position at the interior well was 34 and 36 cm, respectively, which was much more than observed in 2011 (Malloy & Price 2014). At the peripheral well in 2008 and 2009 the range in water table position was 74 and 57 cm, respectively, compared to < 30 cm in 2011 (Malloy & Price 2014). Consequently, before restoration there was a larger driver for change in gyttja volume (compression), especially at the peripheral well. Figure 5 shows the potential quantity of water that could be released for different effective stresses and thicknesses of gyttja. For example, with a 60 cm water table drop the change in effective stress (~ 6 kPa) could cause strain of ~ 14 % based on oedometer tests. This could potentially result in the expression of 42 mm of water if that change occurred in the upper 30 cm (Figure 5). Therefore, more water could have been released from the gyttja layer before restoration when the range of loading was greater. Although the laboratory and field experiments illustrate the potential for gyttja compression to deliver water to the thin overlying cutover peat in response to seasonal water table lowering, this outcome was not realised during the relatively wet conditions at the site.

Compressibility controls

The mechanical properties of the contrasting gyttja materials are different. There was no evidence of carbonate, which is consistent with the local geology; however, calcium carbonate can comprise a portion of gyttja (Zurek-Pysz 1992, Łachacz *et al.* 2009). Strain of 12.5 kPa for gyttja tested by Zurek-Pysz (1992) was ~ 5 % for gyttja with 25– 30% organic matter content. The average strain for all depths tested here at a similar load (12.5 kPa) was 23 % for gyttja with 45–70 % organic matter (and no calcium carbonate). This suggests that gyttja with high organic matter content is more compressible than gyttja dominated by inorganic materials under the same load. At higher loads (200 kPa), the strain reported by Zurek-Pysz (1992) was ~ 35 % compared to our three-depth average of 72 %, suggesting that organic matter impacts the compressibility of gyttja even under high loads. Our data support the notion that the compressibility of gyttja is related to the organic matter content.

Soil materials under progressive compression show a corresponding reduction in their permeability (Dhowian & Edil 1980, Hobbs 1986, Hillel 1998). This was evident from our compressibility tests, as the permeability of the gyttja decreased by four orders of magnitude under loading from 3.5 to 200 kPa. Consequently, it took longer for the excess pore water pressure to dissipate under higher loads.

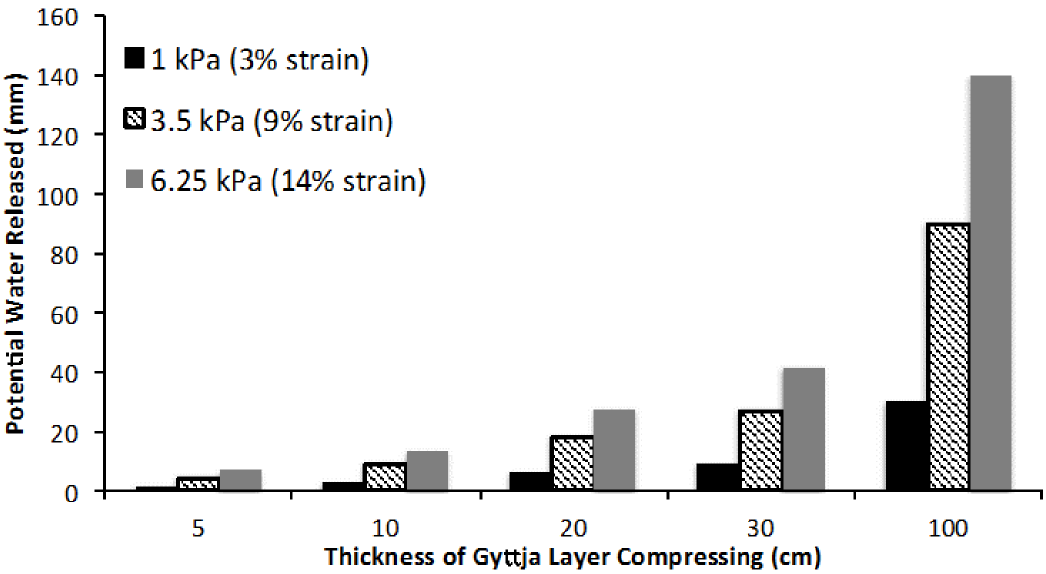


Figure 5. The potential amount of water that could be released from different thicknesses of consolidating gyttja under different loads.

The mean t_{90} for all depths tested for the 3.5, 6.25, and 200 kPa loads were 2.4, 11.1 and 40.2 minutes; the ranges were 3, 21, and 55 minutes, respectively. The ambiguous nature of the method for estimating t_{90} explains the large range in values. Doubling t_{90} halves K_{sat}; therefore, we note that error in estimating t_{90} impacts K_{sat}. We note, however, that our gyttja K_{sat} values determined by consolidation tests (Table 3) and Darcy permeameter tests (Table 1) are quite similar, although consistently higher than those determined by field tests (Table 2). Müller & Larsson (2012) determined the hydraulic conductivity of a gyttja sulphide clay through oedometer tests to be ~ 4 × 10^{-3} cm d^{-1} compared to the ~1 cm d^{-1} reported in this study. The gyttja sulphide clay had an organic matter content of < 10 % and an initial void ratio ~ 3, which is much lower than the value determined for gyttja in this study, explaining the lower hydraulic conductivity. Changes in hydraulic conductivity in the field season (*cf*. Price 2003) would have been small to negligible because of the low range of loading in the wet year. In a drier year, higher loading would cause a sharper decline in hydraulic conductivity, which could delay the release of water. Field hydraulic conductivity values were determined over at least eight tests between the 2008 and 2011 field seasons. Based on variations in dynamic viscosity caused by temperature fluctuations, corresponding variations in saturated hydraulic conductivity are expected (*cf*. Surridge *et al*. 2005); the values expressed here were not adjusted for this. An approximation of the effect of temperature on K_{sat} at the 75 cm piezometers can be made based on soil temperatures at similar depth and times of year (2.5–8 °C measured at the nearby Bois des Bel peatland; unpublished data courtesy of I. Strachan, McGill University). Dynamic viscosity of water for this temperature span ranges ± 15 % (IAPWS 2008), and thus translates into a similar range of uncertainty for K_{sat} if it is not adjusted accordingly. This is much less than the measured spatial variability (Table 2). These field K_{sat} values are probably ~ 50 % lower than if they were adjusted to 20 °C, the approximate room temperature at which the laboratory values were determined. Uncertainty in the field values of K_{sat} is more likely to have arisen from the small sample size (n = 4).

Peat harvesting activity implications

Peat harvesting machinery can produce stress, causing compaction of the substrate (Hillel 1998) depending on the weight of machinery, wheel size, softness of the soil, *etc*. (McKyes 1978). The impact of this at BSF is unknown, but the effect of drainage can be estimated. Artificial drains in peatlands can lower the water table by at least 100 cm (Price 1997), and seasonal water table fluctuations in cutover peatlands can be much enhanced as a result of artificial drainage and peat degradation (Price 1996). If lowering of the water table by 100 cm created a uniform stress of ~10 kPa on the gyttja layer, based on the compression obtained through our oedometer tests, this could result in ~ 20 % strain, assuming that deformation is vertical. For 20 % strain, hypothetically 300 mm of water could be released from a 1.5 m thick layer of gyttja. Although the K_{sat} of gyttja is low, a protracted period of drainage is likely to result in the loss of this water and further virgin consolidation of the gyttja layer (*i.e.* the preconsolidation pressure of gyttja in an undisturbed system is likely to be much less than the ~ 8 kPa reported here). Both factors (water loss and continued virgin consolidation) could potentially make restoration increasingly difficult the longer it is delayed because there would be less potential water release from the underlying substrate, which could aid in rewetting and promote surface level adjustments (Whittington & Price 2006). Therefore, restoration should proceed as soon as possible after mining operations cease. The same arguments can be made for the peat layer.

Future research

In the future it would be beneficial to run oedometer tests on gyttja under lower pressures and with smaller pressure increments (*e.g.* testing at 1, 2, 3 kPa) in line with seasonal water table fluctuations. This was not undertaken during this study due to a limited number of gyttja cores. It would also be instructive to sample gyttja from an undisturbed site, although this would be difficult at undisturbed locations at BSF, where 3.3–3.8 m of peat overlies the gyttja (unpublished 2010 data). Running oedometer tests on gyttja obtained from a natural site would help us better understand the implications of peat harvesting for site hydrology.

CONCLUSIONS

The naturally high water and organic matter contents of gyttja, along with a large void ratio, result in it being a highly compressible material. This means that the subsurface gyttja layer at the Bic-Saint-Fabien peatland has potential to consolidate under stress and supply water to the overlying peat layer, although this was not important in the year of our study. While compression of the gyttja layer was minor, in combination with compression of the overlying peat, this process results in lowering of the surface which brings it closer to the water table. This may be more important for plants than the actual water delivery. The potential for gyttja to compress and supply water in post-harvested peatlands should be greatest after peat production stops and before rewetting begins. The loading during this period is likely to be less than the preconsolidation pressure (recompression), yet still great enough to compress gyttja and release water. Although not studied in detail here, the release of water caused by shrinking and swelling of the gyttja layer after Bic-Saint-Fabien was abandoned might have served as a self-preservation mechanism (*cf*. Whittington and Price, 2006), making Bic-Saint-Fabien easier to rewet. Since we did not find any detailed parameterisation for gyttja in the published literature, the values provided here provide the first insights into its role in the hydrology of harvested and abandoned peatlands.

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