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Abstract

Northern peatlands are a vital component of the global carbon cycle, containing large stores of soil organic carbon and acting as a long-term carbon sink. Moss productivity is an important factor in determining whether these wetlands will retain this function under future climatic conditions. Research on unsaturated water flow in peatlands, which controls moss productivity during periods of evaporative stress, has focused on relatively deep bog systems. However, shallower peatlands and marginal connective wetlands can be essential components of many landscape mosaics. In order to better understand factors influencing moss productivity, water balance simulations using Hydrus 1-D were run for different soil profile depths, compositions and antecedent moisture conditions. Our results demonstrate a bimodal distribution of peatland realizations; either primarily conserving water by limiting evapotranspiration or, maximizing moss productivity. For sustained periods of evaporative stress, both deep water storage and a shallow initial water table delay the onset of high vegetative stress, thus maximizing moss productivity. A total depth of sand and peat of 0.8 m is identified as the threshold above which increasing peat depth has no effect on changing vegetative stress response. In contrast, wetlands with shallow peat deposits (less than 0.5 m thick) are least able to buffer prolonged periods of evaporation due to limited labile water storage, and will thus quickly experience vegetative stress and so limit evaporation and conserve water. With a predicted increase in the frequency and size of rain events in continental North America the moss productivity of shallow wetland systems may increase, but also greater moisture availability will increase the likelihood they remain as wetlands in a changing climate.

1. Introduction

Northern peatlands are a large net sink for atmospheric carbon, storing ~220-550 Pg C (Turunen *et al.*, 2002; Yu, 2011), and are thus a vital component of the global carbon cycle (see Gorham, 1991; Frolking and Roulet, 2007). Although they cover just 3% of the global land surface, they account for 20 to 30% of the total soil carbon pool (Gorham, 1991; Smith *et al.*, 2004). Northern peatlands are potentially vulnerable to climate change (Waddington *et al.*, 1998), particularly given that their hydrology, biogeochemistry, and ecology are tightly coupled to climate (Thormann *et al.*, 1997; Holden, 2005; Bridgham *et al.*, 2008; Wu, 2009). A warmer, drier climate may result in positive feedbacks (Blodau *et al.*, 2004; Ise *et al.*, 2008) turning northern peatlands into carbon sources and thus exacerbating global warming (Wu and Roulet, 2014).

In the absence of natural or anthropogenic disturbance, carbon sequestration in peatlands is largely the result of long-term productivity exceeding decay; thus, factors that control moss productivity are one component in determining whether peatlands are sources or sinks for atmospheric carbon. The maintenance of high soil-water pressures/low tension within the near-surface by a steady supply of water is vital to prevent desiccation of the growing moss and retardation of productivity and carbon sequestration (McNeil and Waddington, 2003; Strack and Price, 2009; Dimitrov *et al.*, 2011). Therefore factors controlling water tension in peat at the top of a profile (i.e. near-surface tension) will control: removal from deeper soil stores, water use efficiency, and the level of productivity in peat forming mosses (Thompson and Waddington, 2008; Kettridge and Waddington, 2014).

Much of the research on northern peatland ecohydrology has focused on deep peatlands, in which drops in water table elevation never exceed the depth of peat and pressure gradients draw water up from deeper in the peat profile (Tsuboya *et al.*, 2001). There is currently a lack of research on shallower organic soils within which the unsaturated zone regularly intersects the confining layer; either of bedrock or mineral soil, beneath the peat. In boreal and sub-arctic peatlands of North America, the complex surficial geology created by multiple glaciations leads to a mosaic of wetland ecosystems (Hartshorn *et al.*, 2003; Reeve and Gracz, 2008) often interconnected and bordered by shallow, marginal organic soils. The exact landscape function of shallow or marginal wetlands (hereinafter included in the spectrum of peatlands on the landscape) will be dictated by their topographical position. Two examples are shallow wetlands on flat relief, and those on sloping relief or in shallow gullies. Where shallow wetlands sit in a depression or at the margins of larger wetland systems, they may be more likely to build peat. However, where they are on sloping terrain they may behave as responsive, topographically steered shallow wetlands, which during wet periods may act to hydrologically connect other landscape areas. Thin organic layers have been described in a margin swamp setting in the boreal plain (Ferone and Devito, 2004; Thompson *et al.*, 2015). Topographically steered shallow wetlands have been referred to as "discharge slope wetlands" (Reeve and Gracz, 2008) and "ephemeral draws" (Devito *et al.*, 2005; Macrae *et al.*, 2006) depending on their landscape position and observed function; their role in landscape connectivity has been documented in a range of hydro-climatic settings (O'Geen *et al.*, 2003; Cable Rains *et al.*, 2006; Klaus *et al.*, 2015). However, the degree to which shallow wetlands act as long-term water sources or water sinks, and whether they act to accumulate carbon, is largely unknown. These thin organic areas may be less resistant to periods of water stress due to the limited capacity to internally buffer water loss (Schouwenaars and Gosen, 2007) and the potentially higher rates of decomposition owing to shorter residence times of water and carbon (Beer and Blodau, 2007). However, such periods of high water stress are countered by periods of saturation and rapid inundation during rainfall events that may prevent encroachment of forestland species, maintain wetland conditions (Rodriguez-Iturbe *et al.*, 2007) and maximize their resilience.

Landscape ecohydrological functioning of peatlands is partly controlled by water transport within peat; however, our understanding of water transport in unsaturated peat remains partial, due to difficulties in accurately measuring their hydraulic properties and unsaturated water flow (Price *et al.*, 2008). Field observations show significant spatial variability in horizontal and vertical hydraulic conductivity over several orders of magnitude (e.g. Boelter, 1965; Beckwith *et al.*, 2003; Kennedy and Price, 2005; Hogan *et al.*, 2006; Baird *et al.*, 2008; Lewis *et al.*, 2012; Branham and Strack, 2014; Baird *et al.*, 2016). In recent years, knowledge of the controls on vadose zone hydrology in *Sphagnum* mosses has been developed through numerical modelling (e.g. Kennedy and Price, 2004; Schouwenaars and Gosen, 2007; Price and Whittington, 2010; McCarter and Price, 2014; Kettridge *et al.*, 2015). It has been shown that water fluxes in peat mosses can be simulated in one-dimension using only liquid flow (Kellner and Halldin, 2002), provided boundary conditions are defined appropriately (Price *et al.*, 2009) and pressure gradients are small (Grover and Baldock, 2013). The latest generation of flow models account for spatial variability in peat properties (e.g. Baird *et al.*, 2012;

Šimůnek *et al.*, 2016); however, there are often insufficient field data to parameterize such models (Cunliffe *et al.*, 2013). Furthermore, there is a lack of understanding of both the controls on spatial variability in hydraulic parameters (Holden and Burt, 2003; Holden and Burt, 2003; Belyea and Baird, 2006; Baird *et al.*, 2008; Lewis *et al.*, 2012) and the effects of variability in hydraulic parameters on the balance between water conservation and moss productivity in bogs (Kettridge *et al.*, 2015). There are currently sufficiently detailed measurements of peat properties to generate representative values (Dimitrov *et al.*, 2010), but given the uncertainty in the effects of parameter variability on peat hydrology (Kettridge *et al.*, 2015) it is questionable whether summary values could adequately characterize the range of natural behaviors. Hence, there is a role for numerical modelling in constraining the range of expected responses and behaviors in peat to periods of water stress, given the known range of variability in hydraulic parameters.

The application of numerical modelling investigations as a tool to understand vadose zone hydrology in peatlands is in a relative infancy. A number of models have simulated water flow in unsaturated peat by applying the Richards equation, mass conservation principles, hydraulic conductivity functions and water retention curves (Dimitrov *et al.*, 2010). Examples include: HYDRUS 1-D (Simunek *et al.*, 1998; Price *et al.*, 2008; Kettridge *et al.*, 2015; Šimůnek *et al.*, 2016), FLOCOPS (Kennedy and Price, 2004), MODFLOW (Bradley, 1996; Harbaugh and McDonald, 1996), Visual MODFLOW (McKenzie *et al.*, 2002) and *ecosys* (Dimitrov *et al.*, 2010). HYDRUS 1-D (Simunek *et al.*, 1998; Šimůnek *et al.*, 2016) has been shown to produce good agreement to measured, fluctuating water contents for simple boundary conditions (Price *et al.*, 2008; McCarter and Price, 2014). The code has also been used in a more heuristic framework to elucidate some of the controls on near-surface water tensions, such as microtopographical position (Moore and Waddington, 2015) and the dominant hydraulic properties of peat (McCarter and Price, 2014; Kettridge *et al.*, 2015). Kettridge *et al* (2015) used a Monte-Carlo modelling framework with HYDRUS 1-D and determined that saturated hydraulic conductivity (K_s) and the empirical van Genuchten water retention parameter α (representing the inverse of air entry pressure) are first order controls on near-surface water tensions. There remains a key knowledge gap, however, in how the natural range of variability in peat hydraulic properties interacts with peat depth, surficial geology and thus internal storage to control the conditions under which northern peatlands will primarily conserve water or be ecologically productive.

In this study, we aim to use a numerical model to characterize the range of behaviors among different areas within the mosaic landscape of northern peatlands in response to periods of evaporative stress. Therefore, the objectives of this study are to: i) elucidate the functional form of water conservation and moss productivity with depth; ii) investigate how antecedent conditions affect the ability of peat to remain productive under periods of evaporative stress in order to understand how resistant such systems may be to future dry periods; iii) investigate whether denser, decomposed peat responds differently to water stress than less dense peat; and iv) ascertain how water tensions and water-table depths respond to atmospheric inputs over a simulated growing season in a western boreal peatland.

2. Methods

2.1 Modelling Investigation Design

A factorial design was used to explore the effects of varying substrate texture, peat thickness and initial water table depth on near-surface tension. Soil profiles were represented by three materials (clay, sand and peat) layered sequentially from the base of the profile to the evaporating surface. A sand layer was included between the peat and the confining clay layer to reflect the common surficial geology in boreal peatlands resulting from peat formation upon glacial till deposits. The thickness of these layers and the initial water table depth in the simulations were varied systematically (Table I) by setting an equilibrium pressure head from the base of the soil profile to generate a range of model scenarios. HYDRUS 1-D was run for each scenario using 5000 Monte Carlo realizations of varying peat hydraulic characteristics generated from the distributions in Table II. Each realization was run with a simulated diurnal variation in evaporation totaling of 4 mm day^{-1} for 50 days (total 200mm) which is representative of the study region. The bottom clay layer was considered a low hydraulic conductivity boundary layer; we fixed this layer at a thickness of 0.50 m. Thus, there are three degrees of freedom in the experimental set up: thickness of peat, thickness of sand and starting water table depth. Throughout the rest of the paper we use the term *profile* to represent the arrangement of the combined material layers in the simulated soil column, the term *scenario* to describe a combination of a soil profile and a water table, and the term *realization* to describe a single model run.

[Table I Here]

To accomplish Objective 1, a series of profiles were created with different depths of peat (0.00 m to 0.50 m; Table Ia) overlying sand (0.50 m) and clay (0.50 m). Additionally, two other series of profiles were created with varying sand depths; the first set had a fixed depth of peat of 0.05 m (Table Ib), the second had a fixed peat depth of 0.50 m (Table Ic), each with sand depths of 0.00 m, 0.05 m, 0.10 m and 0.30 m. By comparing within these profiles, we were able to determine if the ratio of peat:sand depth for shallow organic layers is important in controlling the onset of high surface-layer water tensions, as well as determining if very shallow layers show different behaviors to deeper layers. To accomplish Objective 2, we used the series of soil profiles from Objective 1 with different depths of peat (0.01 m to 0.50 m; Table Ia) overlying sand (0.50 m) and clay (0.50 m). To these profiles, a series of starting water table depths were applied to represent different antecedent dryness levels (0.01 m, 0.05 m, 0.25 m, and 0.05 m below the base of the peat layer). To address Objective 3, we repeated all model runs from Objectives 1 and 2 using a second distribution of peat hydraulic properties based on field data of only well decomposed and/or dense peat.

Objective 4 is to determine how the balance between evapotranspiration (ET) and rainfall during a simulated annual growing season affects cumulative vegetative stress over time. To address Objective 4, eight scenarios were selected from those used in Objectives 1 and 2 to simulate entire growing seasons (Table III). Three scenarios were selected to give a range of profile depths (deep, shallow and intermediate) for a shallow starting water table. Two additional scenarios were selected for the intermediate soil depth with a deeper starting water table and a different peat:sand depth ratio respectively. Finally, three scenarios with shallow soil profiles were selected, again to represent the range of depths (deep, intermediate, shallow) used in the shorter model runs. Rainfall input was from an Environment and Climate Change Canada meteorological station at Slave Lake, located within the Boreal Plain of Alberta, Canada (55°17'35.000" N, 114°46'38.000" W). Simulations were run for 150 days, representing rainfall from 23rd April to 31st August 2013, this represents a period of time from the approximate start of the growing season at the study site.

[Table II here]

[Table III here]

2.2 Model Simulations

The responses of profiles to atmospheric inputs were simulated using HYDRUS 1-D using Richard's equation (Simunek *et al.*, 1998). Water retention is characterized by the Van Genuchten (1980) model:

$$\theta(h) = \begin{Bmatrix} \theta_r + \dfrac{\theta_s - \theta_r}{(1 + (a|h|)^n)^m \theta_s} \end{Bmatrix} \qquad h < 0 \; h \geq 0$$

and: (1)

$$m = 1 - \frac{1}{n} \qquad n > 1$$

where $\theta(h)$ is soil water retention as a function of pressure head h, θ_r and θ_s are the residual and saturated water content for the media, respectively, α is an empirical parameter related to the inverse of air entry pressure (m^{-1}), and n is an empirical parameter for the pore size distribution. Unsaturated hydraulic conductivity ($K(h)$) is a function of saturated hydraulic conductivity (K_s) and pressure head:

$$K(h) = K_s S_e^L \left(1 - \left(1 - S_e^{1/m}\right)^m\right)^2 \quad h < 0$$

$$K(h) = K_s, \;\; when\, h \geq 0 \qquad (2)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

where S_e is the effective saturation and L is a dimensionless pore tortuosity parameter (Simunek *et al.*, 1998).

2.3 Monte Carlo Routine

As the hydrological parameters of peat vary widely both within and between microforms, we applied a Monte Carlo routine to parameterize our peat profiles across a wide range of measured peat hydrological values. The HYDRUS 1-D Monte Carlo code was conceptualized by Beven and Binley (1992) and adapted by Kettridge et al (2015) to incorporate L, allowing input parameters of Ks, α, n and L for each realization.

2.4 Water Transport Parameters

Distributions of *L* were taken from Kettridge et al (2015), based on data in McCarter and Price (2014) from the Riviere-du-Loup (47.9° N, 69.4° W) and Saint-Charles-de-Bellechasse (47.6° N, 71.6° W) peatlands. McCarter and Price (2014) provide a detailed characterization of *L* based on 24 measurements across a range of peat types (*S.fuscum, S.rubellum* and *S.magellanicum*) and depths (0-0.3 m). *L* was derived by fitting the van Genuchten model (Equations 1 and 2) to the measured water retention and hydraulic conductivity using the Retention Curve Program of Unsaturated Soils (RETC) (Van Genuchten *et al.*, 1991). Values of *L* are normally distributed with a mean and standard deviations of -1.41 ± 0.92.

Kettridge et al (2015) characterized distribution of K_s across 13 studies with peat depths ranging from 0.05 to 5.30 m, finding a log normal distribution of values, with a log mean value of -5.86 ± 1.2 m s^{-1} (n=63).

2.5 Water Retention Parameters

A probability distribution for *α* and *n* was obtained using a combination of field measures from Thompson and Waddington (2013) and Lukenbach *et al*. (2015), for ombrotrophic peatlands in Alberta, Canada. Details on sites and data collection methods are available in Thompson and Waddington (2013) and Lukenbach *et al*. (2015), respectively. The data characterize the wide range in values of peat hydraulic properties. Notably, Lukenbach *et al*. (2015) includes samples from dense, marginal peat with high levels of decomposition and high bulk densities. These peat samples are categorized as a sub-set of hydrological measures for well decomposed and/or dense peat. The sub-set in turn allows us to explore the effects of the degree of peat decomposition on water retention in peatlands (Objective 3).

Water retention curves derived from laboratory data were fitted with the Van Genuchten model using RETC to determine *α* and *n* at 0.05m increments through the peat profiles. Water content at saturation (θs, Ψ=0 cm) was estimated as being equal to porosity which was derived from bulk density measurements, assuming a peat particle density of 1.47g cm^{-3} (Redding and Devito, 2006).

Values of α were log-normally distributed with average log (α) values of 0.603 ±1.776 m^{-1} (±standard deviation); for the well decomposed samples average log (α) values were -0.434 ±1.301 m^{-1} (Table II). Hydraulic parameters for sand (Table II) were derived from values for

Northern Alberta in Huang et al. (2011) and parameters for clay (Table II) were derived from Perreault et al., (2013) for heavy clay soils in Quebec, Canada.

Although the model simulations are not set up to simulate a specific type of peatland, the source of the hydraulic parameter data and the design of the model scenarios means the results should be seen as representing *Sphagnum* dominated bogs or poor fens with a layer of peat up to 0.5 m thick overlaying glacial deposits.

2.6 Statistical Analysis

As near-surface water tensions are unlikely to follow a normal distribution across a range of hydraulic property values, we calculated the probability of near-surface tension exceeding the key threshold of -100 mb, which represents the onset of physiological stress in the growing mosses (Price and Whitehead, 2001; Thompson and Waddington, 2013). The -100 mb threshold was established by Price and Whitehead (2001) in deep, cut-over peat systems in Quebec; we use this threshold in the absence of specific data of Sphagnum growth in thin peat systems in the sub-humid Boreal plain, but future field investigations could explore this threshold in other environments. Results were then plotted as both probability of exceedance of -100 mb (P_{100}), and probability density of tension against time.

For the growing season simulations, the mean total dynamic stress was calculated by applying the moisture stress approach (Moore and Waddington, 2015). Static vegetation water stress (ξ) represents the relative degree of *Sphagnum* stress based on surface moisture content (Porporato *et al.*, 2002):

$$\xi(t) = \left[\frac{s^{*}-s(t)}{s^{*}-s_{w}}\right]^{q} \qquad (3)$$

where s is surface moisture content and s^* and s_w are moisture stress thresholds, and q represents potential nonlinear effects of soil moisture deficit. We set s^* to ψ = -100 mb as representing the tension below which *Sphagnum* productivity declines and s_w to ψ = -400 mb as representing the tension at which *Sphagnum* chlorophyllous cells lose turgor and recovery from desiccation is minimal. To account for the rate at which stress evolves, the length of time spent in a stressed state and the cumulative effect of multiple periods of stress, mean total dynamic stress, was calculated (Porporato *et al.*, 2002):

$$\text{if} \qquad \overline{\xi'}\,\overline{t_{s*}} < k t_{seas};\ \zeta = \left(\frac{\overline{\xi'}\,\overline{t_{s*}}}{k t_{seas}}\right)^{(\overline{n_{s*}})^{-0.5}} \qquad (4)$$

else $\quad \zeta = 1$

where k is an indicator of *Sphagnum's* ability to recover from stress (set to 0.46), t_{seas} is the length of the growing season/simulation, ξ' is the relative magnitude of stress, t_{s*} is the duration of time below $s*$ and n_{s*} is the number of periods of stress.

3. Results

The response of surface tensions to evaporative stress showed a wide range of variability within a single profile across individual Monte Carlo realizations. Water retention in a peat profile is highly dependent on peat hydraulic parameters, therefore it is expected that our Monte Carlo approach with five degrees of freedom in parameters should show a wide range of responses.

3.1 Thickness of soil profiles

The probability of the near-surface tension of a given model scenario exceeding -100 mb (P_{100}) is presented within Figure 1a for peat depths from 0.02m to 0.50m with a 0.05m starting water table depth and the two peat hydraulic parameter distributions. Scenarios from the same parameter distribution show little difference in P_{100} over the first 15 days of the simulation, with all scenarios having a high probability (~65%) of initially exceeding -100 mb. Thereafter, all scenarios show a sharp increase in P_{100} before asymptotically approaching 1. The onset of the increase in probability is inversely related to peat depth.

Although P_{100} illustrates the temporal change of profiles experiencing high surface tensions, some variability in response across the range of peat hydraulic properties is masked. The effect of peat depth on P_{100} over time is illustrated in probability density plots for a range of peat depths with the same starting water table depth (Figure 2). There is a tendency towards a bimodal response, particularly during the first 30 days of simulations, where all profiles show a large proportion of realizations reaching -400 mb tension almost immediately, whilst many realizations maintain relatively low tensions (<-100 mb), with relatively few having intermediately high tensions (-100 to -350 mb). Towards the later part of the scenarios, the realizations which had hitherto maintained relatively low tensions show a rapid increase in tension, which corresponds to the "shoulder" in the probability of exceedance plots (Figure 1).

3.2 Marginal Peat

Model runs representing very shallow, marginal wetlands (Figure 1b) show different patterns of behavior compared to deeper profiles (Figure 1a). Whilst in the initial 3-4 days of evaporation, P_{100} is similar to deep profiles (Figure 1a), probabilities of 1 are reached at 10, 15 and 19 days, respectively, for 0.05 m/0 m, 0.05 m/0.05 m and 0.05 m/0.10 m peat/sand profiles. In comparison, for peat that is 0.05 m deep or greater, probabilities of 1 don't occur until after 45 days (Figure 1a). Similarly to what is shown in Figure 1a, shallow marginal wetland scenarios (Figure 1b) show a pattern of greater time periods before $P_{100} = 1$, with an increasing depth of peat/sand.

For shallow layers of peat, Figures 3c and 3d show the importance of an underlying sand layer. For a thin layer of peat (0.05m) over 0.5m of sand, the probability density plot is qualitatively similar to those for deeper peat layers in Figure 3a and Figure 2. However, for the same 0.05m peat layer over a thin 0.1m sand layer, the pattern of probability density is notably different. Although initially around 20% of realizations are able to maintain relatively low tensions, they quickly converge toward maximum tensions so that by day 25 virtually all realizations are at -400 mb tension.

3.3 Material composition of soil profile

Three sets of profiles, each set with the same absolute depths of peat and sand, but different proportions of material are shown in Figure 1c. Although the first 10 days of evaporation are broadly the same for all scenarios, a greater proportion of sand delays the onset of high P_{100}. The largest change in response with profile composition is for the difference between 0.05 m/0.50 m and 0.50 m/0.05 m, where the deep peat profile shows an upward curve in probability after 7 days, whereas the shallow peat on deep sand profile maintains a probability of 0.75 until day 35. In contrast, for the deepest layers of 0.3 m/0.5 m and 0.5 m/0.3 m of peat:sand respectively there is only a small difference in response. The probability density plots in Figure 3a and 3b show the similarity in response for scenarios with 0.8 m of material above the confining clay layer; here, there is very little difference in the pattern or magnitude of tensions over the scenarios with different peat:sand ratios.

3.4 Antecedent depth to water table

The two sets of scenarios with deeper starting water tables are shown in Figures 1d and 1e, which, along with the 0.05 m starting water table depth scenarios in Figure 1a, can be used to compare the effects of antecedent moisture conditions. For the starting water table of 0.25 m (Figure 1d), initial probabilities of high tensions are greater for all scenarios compared to the equivalent peat profiles in Figure 1a. However, all scenarios approach a probability of 1 at approximately the same time as for the shallower water tables of Figure 1a.

Figure 1e shows probabilities for a range of peat depths from 0.05 m to 0.50 m for starting water table 0.05 m below the peat layer, i.e. the scenarios only differ in the depth of unsaturated peat above the water table. These show the onset of -100 mb tensions occurs earlier for scenarios with a deeper starting water table.

3.5 Peat Hydraulic Properties

For all scenarios in Figures 1a, b, d and e, well-decomposed peat scenarios show the same behavior with increasing P_{100} over time and with the sharp increase in P_{100} coinciding. However, probabilities for well-decomposed scenarios are lower than for the full parameter distribution, particularly in the initial 20 days. For the shallow profiles (Figure 1b), well-decomposed peat helps maintain a low P_{100}, especially during the first 10 days for the 0.05 m/0.05 m and 0.05 m/0.10 m profiles.

[Figure 1 around here]

[Figure 2 around here]

[Figure 3 around here]

3.6 Growing season simulations

The growing season simulations (Figure 4) show that for all the peat profiles P_{100} gradually rises during intra-rain periods and then even small rain inputs can re-wet the surface, reducing the probability of -100 mb surface tensions to near zero. However, in the case of small rain inputs, such as that at around day 10, the probability of high tensions quickly increases again afterwards.

For scenarios with 0.5 m of sand below the peat layer and with a starting water table 0.05 m below the surface, P_{100} is very similar throughout the season for all depths of peat (Figure 4a).

The thinnest layer of peat (0.05 m) shows a slightly higher probability of exceeding -100 mb during periods of prolonged evaporative stress, but the deeper profiles of 0.3 m and 0.5 m are virtually identical in probabilities throughout.

[Figure 4 around here]

For different antecedent conditions, simulated by varying the starting water table depth (Figure 4b), P_{100} is initially higher for the deeper water table. However, scenarios are able to adjust through the growing season with rainfall inputs recharging the water storage in the peat, such that by the middle of the growing season there is no difference in P_{100} between the scenarios.

Where the absolute depth of peat and sand is consistent between simulations and the ratio of peat:sand is changed from 3:5 to 5:3, there is virtually no difference in the response of P_{100} during the growing season (Figure 4c).

For the very thin organic layer simulations (Figure 4d) the depth of the sand layer below the thin layer of peat is important in buffering against the probability of high tensions particularly during the spring and late summer months when long term precipitation is much lower. For scenarios with 0.05 m of peat over 0.05 m of sand, P_{100} approaches 1 at two points during the simulated growing season. In comparison, profiles with 0.50 m of sand underlying a 0.05 m peat layer have probabilities of approximately 0.5 at the same points.

The results for mean dynamic stress (MDS) show a wide range of responses for realizations within each scenario; we therefore present these as cumulative probability plots (Figure 5). MDS is a unitless metric with a value from 0-1, where 0 represents vegetation which is not stressed over the growing season, and 1 represents the maximum level of stress. For scenarios which share a common starting water table depth (0.05 m), and thickness of underlying layers (0.5 m sand, 0.5 m clay), there is little difference in the cumulative probability of MDS with different thicknesses of peat (Figure 5a). For the shallowest peat layer (0.05 m), the bimodal distribution of MDS cumulative probability is enhanced, with slightly lower probability of values between ζ=0.25-0.50 compared to the deeper peat profiles (Figure 5a). For scenarios using a distribution of peat hydraulic properties derived from well decomposed peat samples, the cumulative distribution has higher probabilities in the range ζ =0-0.3, indicating a greater resistance to stress.

For different antecedent conditions, simulated by varying the starting water table depth (0.05m and 0.25m), the deeper starting water table has lower probability of low cumulative stress (ζ =0-0.4) and a higher probability of MDS ζ >0.55 (Figure 5b). Therefore, in general terms, a deeper starting water table increases the cumulative growing season stress.

The ratio of peat to sand for the same absolute depth above the confining clay layer shows virtually no effect on the cumulative probability of MDS values (Figure 5c), reflecting the almost identical seasonal probability patterns (Figure 4c).

[Figure 5 around here]

The exception to the bimodal, cumulative probability distribution is for very shallow organic layers (Figure 5d). For shallow scenarios there is a fairly even spread of MDS probabilities. This means that thin peat layers, in contrast to deeper layers, have no combinations of hydraulic properties which allow low stress conditions to be maintained during the growing season.

The mean dynamic stress over the simulated growing season shows virtually no change with both increasing depth of peat over 0.3m (Figure 5a) and to the ratio of peat and sand (Figure 5c). Furthermore, MDS is relatively insensitive to increasing peat depth from 0.05m to 0.3m. All scenarios in Figures 5a, 5b and 5c show a bimodal distribution with between 40-50% of realizations having MDS values of ζ <0.05, relatively few realizations in the range ζ =0.05-0.3 and the remaining realizations with MDS values in the range ζ =0.4-0.7.

4. Discussion

4.1 Controls on evaporative stress

The response of model scenarios to drying differs most substantially between deep systems, with greater than 0.5m of sand and peat combined, and the very shallow marginal wetland systems (Figures 1a and 1b). The optimum simulated profile for maintaining a high probability of moss productivity under prolonged periods of evaporative stress is a thin 0.05 m layer of peat over a 0.50 m layer of sand, whereas a deep 0.50 m layer of peat over 0.50 m of sand shifts to water conservation after a much shorter period of evaporation. This result is similar to the findings of Schouwenaars and Gosen (2007) who found that thin layers of peat over a high hydraulic conductivity layer were able to maintain connectivity with a falling water table, whereas thicker layers were not.

Whilst total depth above the confining layer of clay provides the first order control on the profile response to drying, the 50-day model scenarios demonstrate there are several additional second order controls on the probability of a peat profile experiencing high surface tensions, and thus a shift to water conservation over moss productivity. Under a progressive diurnal evaporation with no water recharge, a peat profile moves through three phases of response, as shown by the conceptual model in Figure 6. Initially (phase I) the profile evaporates freely and the probability of high tensions gradually rises; this phase lasts around 19 days. Phase II, from 19 days to 35 days, represents the exhaustion of water stored in high hydraulic conductivity material (peat and sand), meaning it becomes increasingly difficult for the profile to readily supply water to the surface layer to meet evaporative demand. Finally, after 35 days, the profile will experience high surface tensions irrespective of individual hydraulic properties of the peat layer (phase III) and the probability of high tensions converges on 1.

[Figure 6 around here]

The variation in the pattern of response between deeper profiles is due to different starting water tables, different peat depths and different hydraulic parameter distributions. During the initial evaporation phase (phase I), the dominant controls on the probability of high tension are the antecedent wetness conditions at the onset of evaporation, represented by the depth to water table, and the density of the peat layer. Throughout this initial phase the density of the peat (linked to the degree of decomposition) and the antecedent conditions act as first order controls on the probability of the profile maintaining moss productivity or becoming stressed and conserving water. This results from the higher hydraulic conductivities maintained in denser peat under unsaturated conditions, as a result of its higher water retention (Price and Whittington, 2010). Where a period of evaporative stress does not last longer than the 19 days of phase I, profiles of the same depth with a greater proportion of sand compared to peat behave in a very similar manner. Once the length of the evaporative period continues beyond 19 days and enters phase II, the depth of the material above the confining layer (and the depth of peat within this material) become more important, with profiles with deeper peat layers having a higher probability of evaporation shut down. We attribute this effect to the increasing difficulty of maintaining connectivity with the receding water table through a deep peat layer. Although we model a homogenous peat layer with depth, an increase in vertical connectivity could lead to an increase in decomposition, therefore there may be a positive feedback whereby vertically connected peat has higher rates of decomposition and thus is denser and further prone to maintain lower tensions. As period of evaporation moves into phase III, with no rain input for more than 35 days, the peat properties, profile layers and antecedent conditions cease to exert a meaningful control on near-surface tensions, with all profiles showing a high probability of high tensions. Profiles with hydraulic properties resulting in less efficient water transport generate high surface tension despite the water table remaining within the peat (e.g. Kennedy and Price, 2004). Even in those realizations where the peat surface has been able to maintain connectivity to the receding water table, after 35 days of evaporation the water table has dropped into the clay layer, hampering the ability of the profile to transport water to the evaporating surface (Schouwenaars and Gosen, 2007).

It is important to note that for all our 50 day scenarios, P_{100} (the probability of near-surface tensions > -100 mb) is at least 50% after five days of evaporation. A substantial range of peat hydraulic properties therefore result in the scenario shifting to water conservation at the expense of moss productivity under any evaporative stress. Landscape heterogeneity, and in turn landscape function can therefore be enhanced by surficial geology or antecedent wetness, which maintain a bimodal distribution of P_{100} under long periods of evaporative stress, ensuring some parts of the landscape remain productive, whilst others conserve water.

4.1 Growing Season Simulations

Mean dynamic stress (MDS) varied little over a growing season between different depths of peat over 0.5m of sand. For the shallowest peat layer of 0.05 m there is a slightly higher probability of values in the range ζ=0.4-0.5. The main differences in surface tensions with increasing depth of peat in our 50-day evaporation scenarios are between 20-40 days. We would therefore expect that differences in stress over the growing season between different profile depths would only become apparent if there are prolonged rainless periods of 20-40 days. The simulated growing season used in this study only includes two prolonged periods with little or no rain input (first ~20 days and days 90-140), leading to only slight differences in response between shallow and deep peat layers underlain by 0.50 m of sand. Conversely, for the scenarios with a thin layer of peat over a thin layer of sand (Figure 5d) there is limited labile water storage under the growing peat layer and so under typical rainfall distributions the profile will dry out several times during the growing season and experience high surface tensions. Unlike peat layers underlain by 0.50 m of sand, these very thin peat/sand profiles are not able to maintain productivity during periods of water stress under any combinations of peat hydraulic properties.

The cumulative probability plots for MDS shows that almost all scenarios display a bimodal distribution of MDS values with >40% of realizations having very low values $\zeta<0.1$, with another 40% of realizations tending to have high values of $\zeta=0.4-0.7$. The MDS values correspond to the balance between moss productivity and water conservation in peat. With low MDS values corresponding to peat which is able to maintain productivity throughout periods of evaporative stress. Conversely, high MDS values correspond to less productive and primarily water conserving peat. Given that our peat property distributions represent the a wide range of measured peat types across the field sites, our modelling results indicate that irrespective of existing microtopography, depth to water table or species, there is a tendency towards a binary response in levels of moss productivity over a growing season driven by variability in peat hydraulic properties. These differences in productivity levels could initiate differences in peat accumulation rates and the formation of microtopography (Nungesser, 2003), initially through the generation of proto-hummocks and hollows, which would then become self-reinforcing through already documented autogenic feedbacks between depth to water table, species and microtopology (e.g. Belyea and Baird, 2006; Tuittila *et al.*, 2007; Dise, 2009; Morris *et al.*, 2011; Waddington *et al.*, 2015). It has been shown that *Sphagnum* species have different carbon accumulation rates (Nungesser, 2003),which, given our results, may be interpreted as an expression of differences in hydraulic properties between species enabling them to maintain productivity in times of relative water scarcity and evaporative stress.

4.2 Controls on balance between moss productivity and water conservation

Greater depth to water table, for the same soil profile, increases P_{100} for short periods of evaporative stress with no rainfall. However, once this period extends to lengths greater than 20 days, $P_{100\ converges}$ to similar values, regardless of the starting depth to water table. Furthermore, during a growing season, the differences in tensions from starting water table depths are homogenized by recharge from the first few rainfall events (Figure 4b) and thereafter remain fairly similar and low throughout. This intra-seasonal recharge may indicate peatlands have a limited “memory” for antecedent conditions that allow them to recover from dry conditions early in the growing season to maintain productivity later in the season, provided any induced stress does not lead to physiological damage. While profiles with deeper starting water tables recover their initial moisture deficit over the course of the growing season, the greater starting depth to water table leads to a slightly higher initial MDS value compared to a shallower starting water table depth (Figure 3b) and thus slightly less net productivity over a season.

Provided there is a sufficient depth of material to provide labile water storage, the peat and underlying sand fulfil a similar hydrological function. Our results show that the depth of the peat layer has only a small effect on either P_{100}, during the 50-day evaporation experiments, or on MDS over the growing season, provided there is a layer of 0.5m sand underlying the peat layer. The ratio of peat:sand in the profile also has negligible effect on MDS; scenarios with 0.80m of material comprised of 30:50 and 50:30 ratios of peat:sand respectively show almost identical seasonal responses (Figure 5c). Thus, the absolute depth of high hydraulic conductivity material is more important than the total depth of peat, or the proportion of peat within that profile.

The density of peat has a small effect on tensions, with denser peat showing a slightly decreased probability of tensions exceeding – 100mb at any point in the model runs. The greatest differences for denser peat are for the thickest model profiles, during the more prolonged rainfree periods (Figure 4a). Values for MDS reflect this, showing a slightly higher probability (around 5%) for the lowest values of ζ =0-0.2. The key hydraulic property affecting this is inverse entry of air pressure (α), which is both higher, and has a wider range for the full property distribution, compared to dense peat only. Kettridge *et al* (2015) observed that high values of α correspond to low volumetric water contents in the unsaturated zone that limit the supply of water and increase near-surface tensions.

The exception to the bimodal distribution of both tension probabilities and MDS values is the shallowest profiles (Figures 1b and 5d). We conceptualize these shallow systems as representing permanent wetland sites with a relatively shallow depth to confining geology. These include both shallow depression wetlands, as well as shallow, topographically steered systems that may hydrologically connect portions of the catchments with larger peatlands and ponds (Devito *et al.*, 2005; Cable Rains *et al.*, 2006; Klaus *et al.*, 2015). In these profiles there is a fairly even distribution of values between ζ =0-0.7. This suggests that the absence of a deep layer of high hydraulic connectivity and high specific storage makes it impossible for peat hydraulic properties to maintain a high productivity profile throughout a growing season. This contrasts with shallow layers of peat overlaying a deep sand layer where the increased permeability of the underlying layer increases the recharge function of the peat layer (Reeve and Gracz, 2008) and thus better enables the profile to buffer the onset of water stress. The sensitivity of moss productivity in these shallow systems to water input means these features may take a long time to develop deeper profiles. Due to the frequent stress with fluctuating water tables, they may remain locked into a low productivity and high decomposition cycle, which maintains their current ecohydrological function and morphological setting (Rodriguez-Iturbe *et al.*, 2007). Although beyond the scope of this study, a shallower organic layer, and thus greater hydrochemical influence of the sand may have an effect on surface vegetation. Studies have show paludification with sphagnum dominated peat can occur onto sand soils (Hulme, 1994; Payette *et al.*, 2013), although in some cases the greater connection to the sand layer may favour development of alternative stable vegetation states (see Johnstone *et al.*, 2010) and so offer one possible mechanism by which ecohydrological function could change.

During dry periods, deeper peatlands may maintain lateral connectivity, with spatial heterogeneity in the balance between water conservation and moss productivity creating pressure gradients and driving the lateral transfer of water from water conserving areas to productive areas (c.f. Eppinga *et al.*, 2008). In contrast, shallow wetlands are likely to function as largely one-dimensional systems. We suggest shallow margin systems lack sufficient labile sub-surface water storage capacity to drive the productivity of surface mosses, but also insufficient to act as sustained sources of water to adjacent productive areas during prolonged evaporative stress. These shallow systems will be areas of surface saturation, and potentially runoff generation, and will maintain hydraulic gradients from wetlands to uplands.

The hydrology of northern peatlands as a whole is tightly coupled to climate (Thormann *et al.*, 1997; Holden, 2005; Bridgham *et al.*, 2008; Wu, 2009), and climate change is predicted to lead to warmer, drier conditions (Tarnocai, 2009), but also likely to increase in frequency and magnitude of precipitation events across the boreal plain (Mbogga *et al.*, 2009; Wang *et al.*, 2012). As these shallow, marginal systems are locked into a low productivity cycle, and as they have only small carbon stores, they may prove to be a persistent part of the mosaic of landscape types in northern peatlands under climate change, able to conserve water in times of evaporative stress, but wet up quickly during frequent rainfall events and make use of available water during humid periods. With low storage and rapid water table responses resulting in surface saturation and runoff generation, these systems may also be important in maintaining hydrologic connectivity within the wider landscape (Devito *et al.*, 2005; Klaus *et al.*, 2015).

A further consideration is the ability of peat to recover productivity following periods of high stress. In parameterizing the dynamic stress equation, we assume a moderate ability for peat to recover from high stress, but it is possible a very high stress period could lead to pronounced hysteresis in ecological recovery at the onset of rain input, dampening moss productivity for a prolonged period (McNeil and Waddington, 2003). As such, there is a need for field or lab based studies to quantify the ability of different species of moss to recover from periods of high tension and to explore the extent of hysteresis in recovery of surface tensions and ecohydrological functioning of the surface peat layer. There is also an important role for numerical modelling in exploring sensitivity of peat profiles to ecological recovery parameters in the MDS equation.

Wider ecohydrological and hydrogeological studies can help to put these point modelling results into a broader context. However, these initial modelling results provide important insights into the controls on water usage efficiency in shallow and deep peatlands and can aid in further directing and potentially modifying peatland restorations and construction.

5. Conclusions

Understanding how peatlands respond to periods of evaporative stress is important in predicting the ability of a peat profile to retain moisture or to maximize moss productivity. The relative productivity of a peatland is in turn important in its ability to sequester atmospheric carbon dioxide. Results from HYDRUS 1D modelling show that wetland soil profiles are split between those which maximize vegetation productivity and those which primarily conserve water, controlled by peat hydraulic properties. During periods of sustained evaporative stress, the probability of a peat profile experiencing high surface tensions and therefore switching to water conservation at the expense of moss productivity is partly controlled by the depth of the soil profile and the starting water table depth. A deeper profile and a shallower starting water table both prolong the onset of very high surface tensions and thus maximize productivity.

Over a simulated growing season, a soil profile depth of 0.8 m was found to represent a threshold, over which increasing the profile depth, and thus the water storage capacity, had little effect on changing the ecohydrological response. In profiles which were 0.8 m deep, there was also little difference in response for different ratios of peat and sand, indicating that underlying sand fulfils the same hydrological function as deeper peat layers in depression type storage systems with limited lateral flow. Growing season simulations also show that scenarios with a deeper starting water table are able to recover after initial rainfall events and are thereafter indistinguishable from profiles with shallow starting water tables. This intra-seasonal recovery of water table and surface tensions indicates peatlands have a limited 'memory' for antecedent conditions. Very shallow, marginal wetlands are the exception to the general bimodal distribution of water conservation/productivity, with very few realizations resulting in probability of high tensions, or mean dynamic stress. Such shallow systems will only be productive during wet periods, and are likely to be locked into a low productivity cycle with only small carbon stores. Conversely, as they have low storage they will respond rapidly to precipitation events with frequent water table fluctuations and periods of saturation and may remain resilient to dry periods. Thus, these shallow systems may provide important hydrologic connectivity in northern peatland-forestland mosaic landscapes. It will be important to understand their ecohydrological functioning in a landscape context, particularly in light of predicted warmer, drier conditions from climate change, which could place greater pressures on these features at the same time as increasing the importance of their function in the wider landscape.

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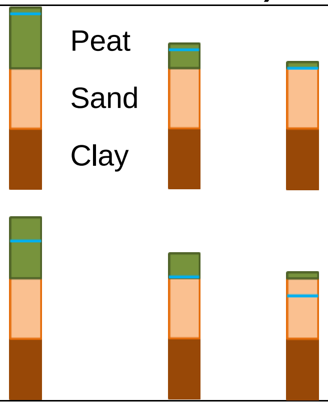
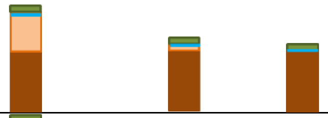
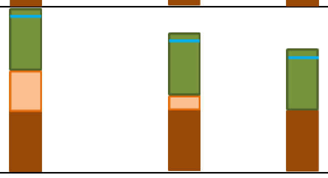
Ref	Layer Thickness (m)			Starting Water Table depth (m)	Illustrations of example soil profiles (blue line is water table)
	Peat	Sand	Clay		
	0.01	0.50	0.50	0.05	
	0.02	0.50	0.50	0.05	
	0.03	0.50	0.50	0.05	
	0.04	0.50	0.50	0.05	
a	0.05	0.50	0.50	0.01, 0.05, 0.10, 0.25	
	0.10	0.50	0.50	0.01, 0.05, 0.15, 0.25	
	0.20	0.50	0.50	0.01, 0.05, 0.25	
	0.30	0.50	0.50	0.01, 0.05, 0.25, 0.35	
	0.40	0.50	0.50	0.01, 0.05, 0.25, 0.45	
	0.50	0.50	0.50	0.01, 0.05, 0.25, 0.55	
	0.05	0	0.50	0.05	
b	0.05	0.05	0.50	0.05	
	0.05	0.10	0.50	0.05	
	0.05	0.30	0.50	0.05	
	0.50	0	0.50	0.05	
	0.50	0.05	0.50	0.05	
c	0.50	0.10	0.50	0.05	
	0.50	0.30	0.50	0.05	

Table I – Factorial experimental design used for ‘50 day’ diurnal evaporation scenarios with no rainfall. This combination of model scenarios allows the first two objectives to be tested: the effects of 1) peat depth/peat:sand ratio, and 2) antecedent conditions.

	θ_s	θ_r	α (m^{-1})	n	K_s (cm hr^{-1})	L
All Peat	0.94 ± 0.05	0.01	0.60 ± 1.78	1.19 ± 0.12	18.31 ± 2.0	-1.41 ± 0.84
Dense Peat	0.91 ± 0.06	0.01	-0.43 ± 1.30	1.17 ± 0.12	18.31 ± 2.0	-1.41 ± 0.84
Sand	0.37	0.002	0.08	2.11	37.15	-0.89
Clay	0.50	0.10	0.02	1.32	0.44	-1.26

Table II – Mean and standard deviation values for hydraulic properties of material layers used to create the Monte Carlo inputs for modelling. Peat layer properties are derived from Thompson and Waddington (2013) and Lukenbach *et al*. (2015), sand properties from (Huang *et al*., 2011) and clay from Perreault *et al*. (2013)

Peat Depth (m)	Sand Depth (m)	Clay Depth (m)	Starting Water Tables (m)
0.50	0.50	0.50	0.05
0.30	0.50	0.50	0.05
0.05	0.50	0.50	0.05
0.30	0.50	0.50	0.25
0.50	0.30	0.50	0.05
0.05	0.10	0.50	0.05
0.05	0.05	0.50	0.05

Table III – Factorial experimental design used for growing season scenarios with rainfall input.

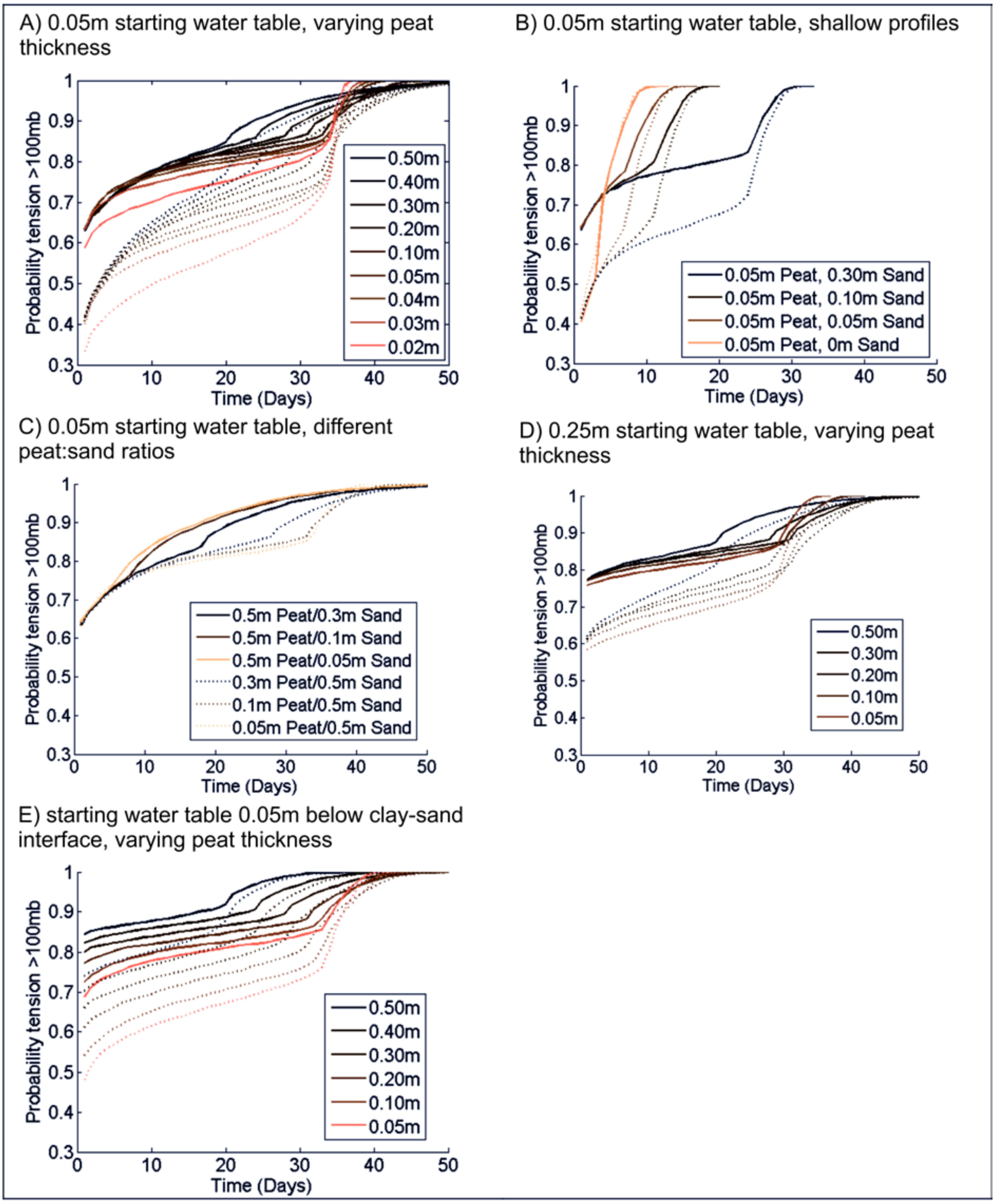


Figure 1 – probability plots of near surface tension for scenarios. A) 0.05 m starting water table and peat depths from 0.02 m to 0.50 m, B) 0.05 m starting water table for shallow profiles, C) variations in peat:sand proportions for profiles of the same depth, D) 0.25 m starting water table and different peat depths, E) water table 0.05 m below peat/sand boundary for different peat depths. For A, B, D and E dotted lines are for parameter distributions based on well decomposed peat only.

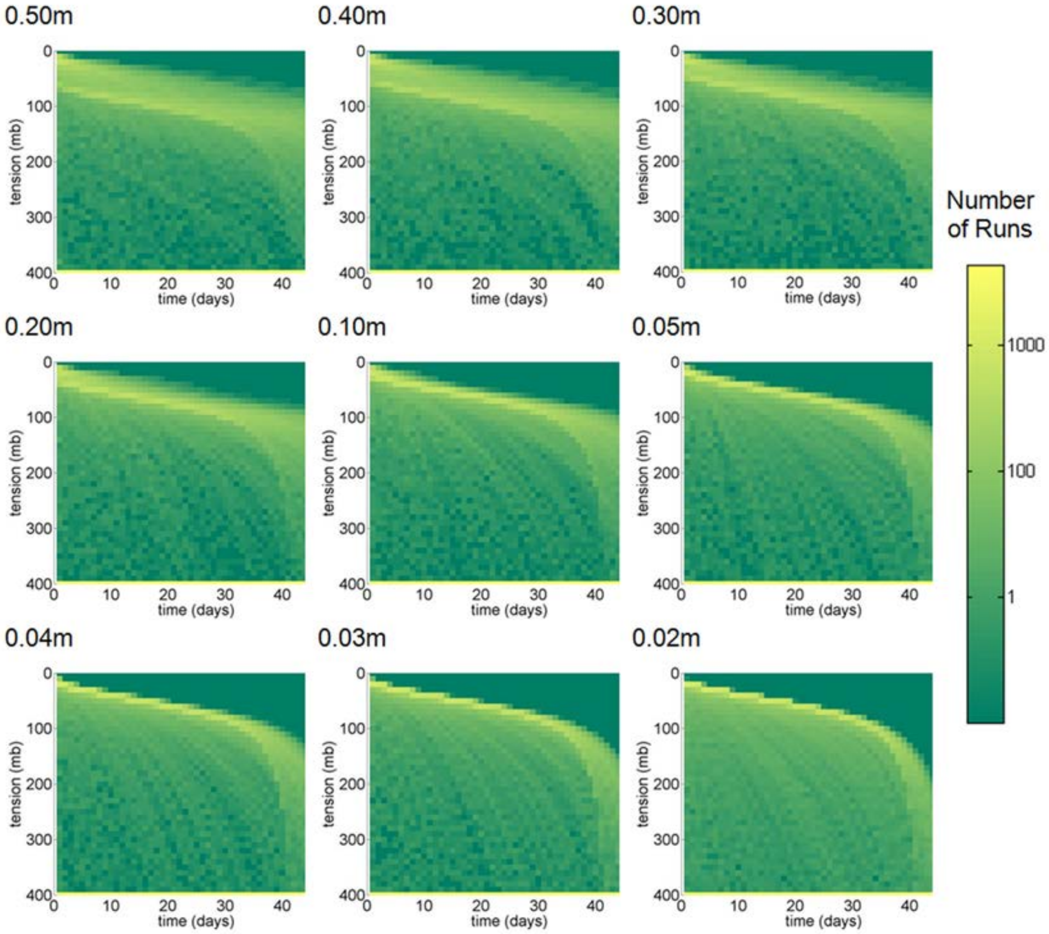


Figure 2 – Probability density plots for near surface tension against time for profiles with a 0.05 m starting water table and different depths of peat overlaying a surficial geology of 0.50 m sand and 0.50 m clay (note log scale color ramp). This shows the bimodal distribution, with a bright yellow line at 400 mb and a second yellow line at ~10 mb at time 0 and gradually increasing in tension over time, with relatively few runs between the two lines. Total 5,000 runs.

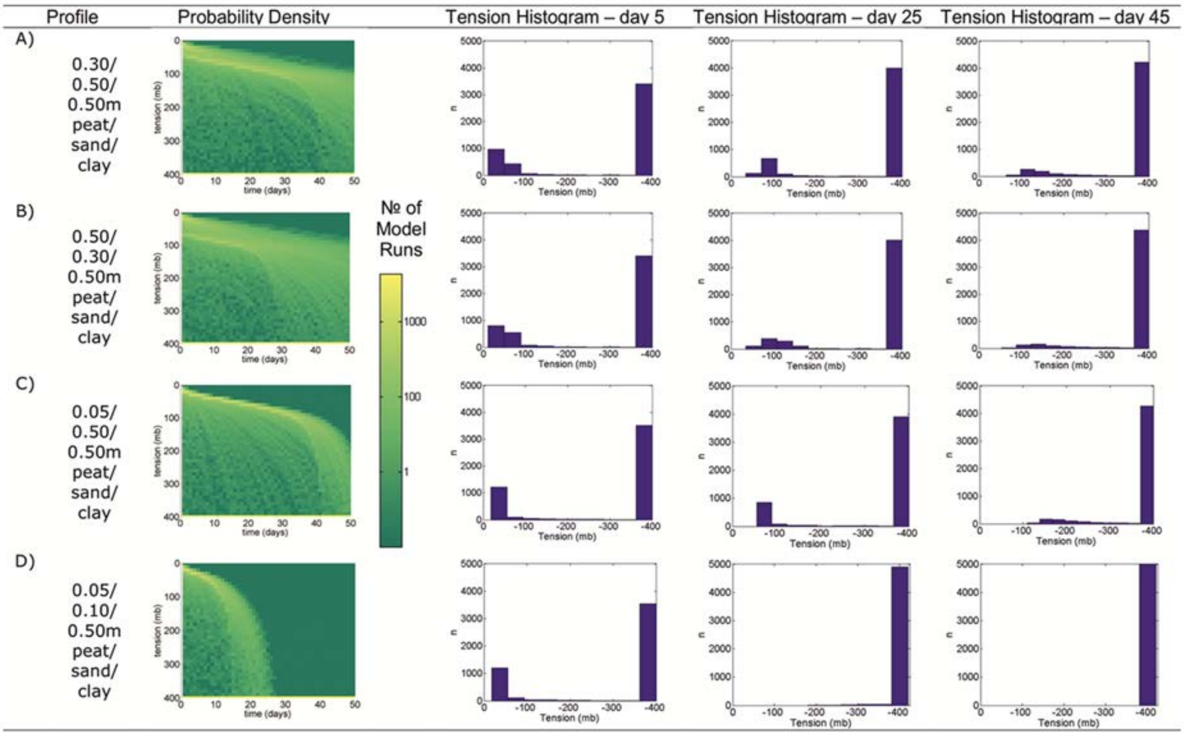


Figure 3 – Probability density plots for surface tension over time and histograms for probabilities of tensions at specific times during the simulations. Plots show the effects on tensions over time of changing material ratios in high hydraulic conductivity storage and reducing the absolute thickness of high hydraulic conductivity storage. A) 0.30/0.50/0.50 m peat/sand/clay, B) 0.50/0.30/0.50 m peat/sand/clay, C) 0.05/0.50/0.50 m peat/sand/clay, D) 0.05/0.10/0.50 m peat/sand/clay. For all simulations there is a -0.05 m starting water table.

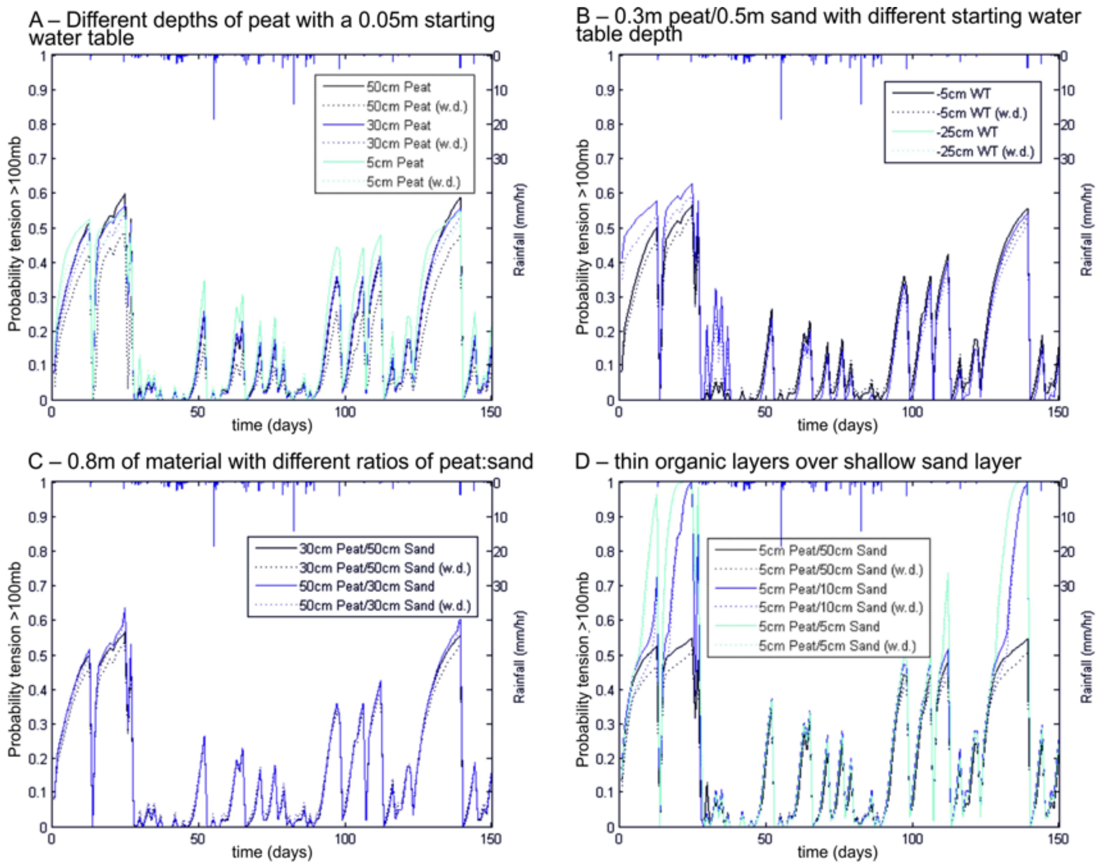


Figure 4 - Probability plots of near surface stress for growing season simulations with rainfall on second y-axis. A) 0.05 m starting water table and different depths of peat, B) 0.3 m peat, 0.5 m sand with different starting water tables, C) different proportions of peat and sand for the same absolute depth, D) thin layers of peat. Well decomposed peat indicated by w.d..

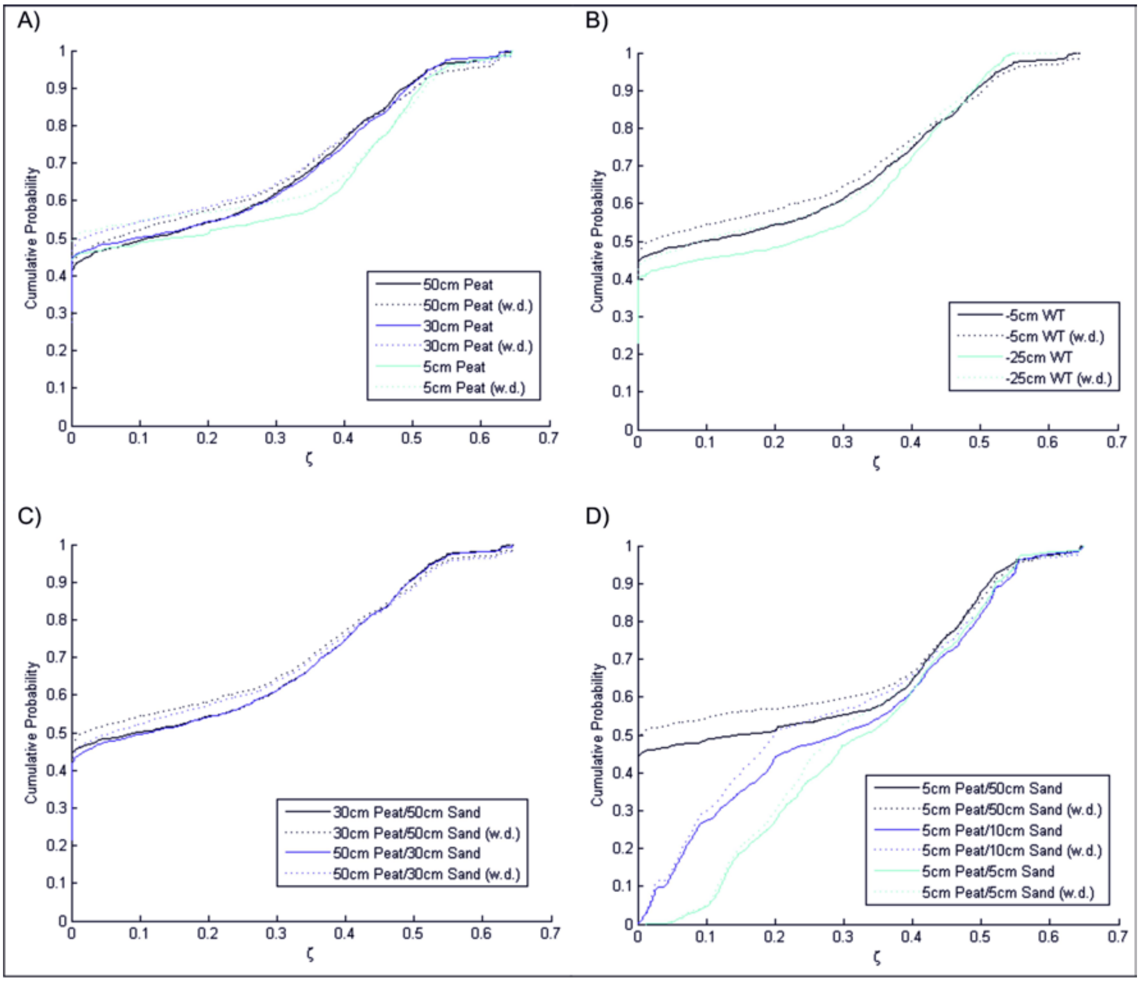


Figure 5 – Cumulative probability plots for mean dynamic stress over a simulated growing season. A) 0.05 m starting water table and different depths of peat, B) 0.30 m peat, 0.50 m sand with different starting water tables, C) different proportions of peat and sand for the same absolute depth, D) thin layers of peat and sand over clay. Well decomposed peat = w.d.

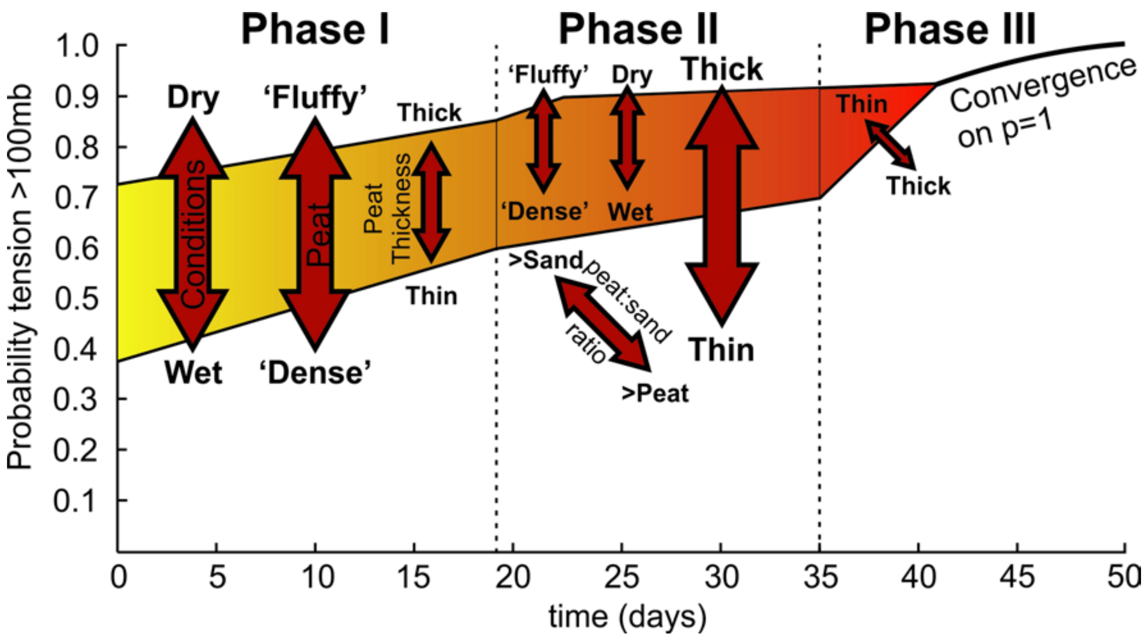


Figure 6 – conceptual model showing how peat properties and antecedent conditions affect the range of probabilities of high tensions occurring in peat profiles over prolonged drought. The size of the arrows indicates the influence of each effect during each phase of evaporation.