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RESEARCH ARTICLE

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The effect of wetting history, botanical composition and depth on the specific yield of two common types of bog peat

Andy J. Baird[1] | **Alice M. Milner**[2] | **Paul J. Morris**[1] | **Sophie M. Green**[3]

[1]School of Geography, University of Leeds, Leeds, UK

[2]Department of Geography, Royal Holloway, University of London, Egham, UK

[3]School of Natural and Built Environment, Queen's University Belfast, Belfast, UK

Correspondence
Andy J. Baird, School of Geography, University of Leeds, Leeds LS2 9JT, UK.
Email: a.j.baird@leeds.ac.uk

Abstract

Specific yield affects how much the water table rises and falls in response to rainfall, to evaporation and to seepage gains and losses. It also affects the aeration of the soil above the water table. Although widely measured in peat soils, the effect of wetting history on its value has not been investigated. Specific yield has been estimated in many studies by cutting peat cores into layers, and measuring how much water drains from the individual layers after they have been wetted. Specific yield, however, is a phenomenon of the soil profile and not subsections, so this method may not provide a reliable estimate of its value. Few studies have reported on the effect of botanical composition on specific yield, or at least have not controlled for the effect by keeping other peat properties like degree of humification constant. We addressed these questions by measuring specific yield in intact cores of peat in a series of laboratory experiments. Two common but contrasting types of *Sphagnum* peat were investigated that had similar degrees of humification: *Sphagnum medium* peat and *Sphagnum pulchrum* peat. We found that specific yield was highly variable, ranging between 0.16 and 0.62. Specific yield was not affected by wetting history, but was significantly different between the peat types, being on average 0.21 higher in the *S. pulchrum* cores. Specific yield did not vary with depth in the *S. medium* cores but declined linearly with depth at a rate of 0.018 per cm in the *Sphagnum pulchrum* cores. Finally, we found that drainage from the peat profile above the zone through which the water table falls is an important component of specific yield, contributing more than 66%–91% of its value in the *S. pulchrum* peat. Our results show that wetting history probably does not need to be accounted for when estimating specific yield, although further work on this potential effect is recommended. Our work highlights the importance of measuring specific yield using intact cores (field methods may also be appropriate) and suggests that many previous peatland studies may have underestimated its value.

KEYWORDS
depth, peat, shrinkage, specific yield, *Sphagnum*, wetting history

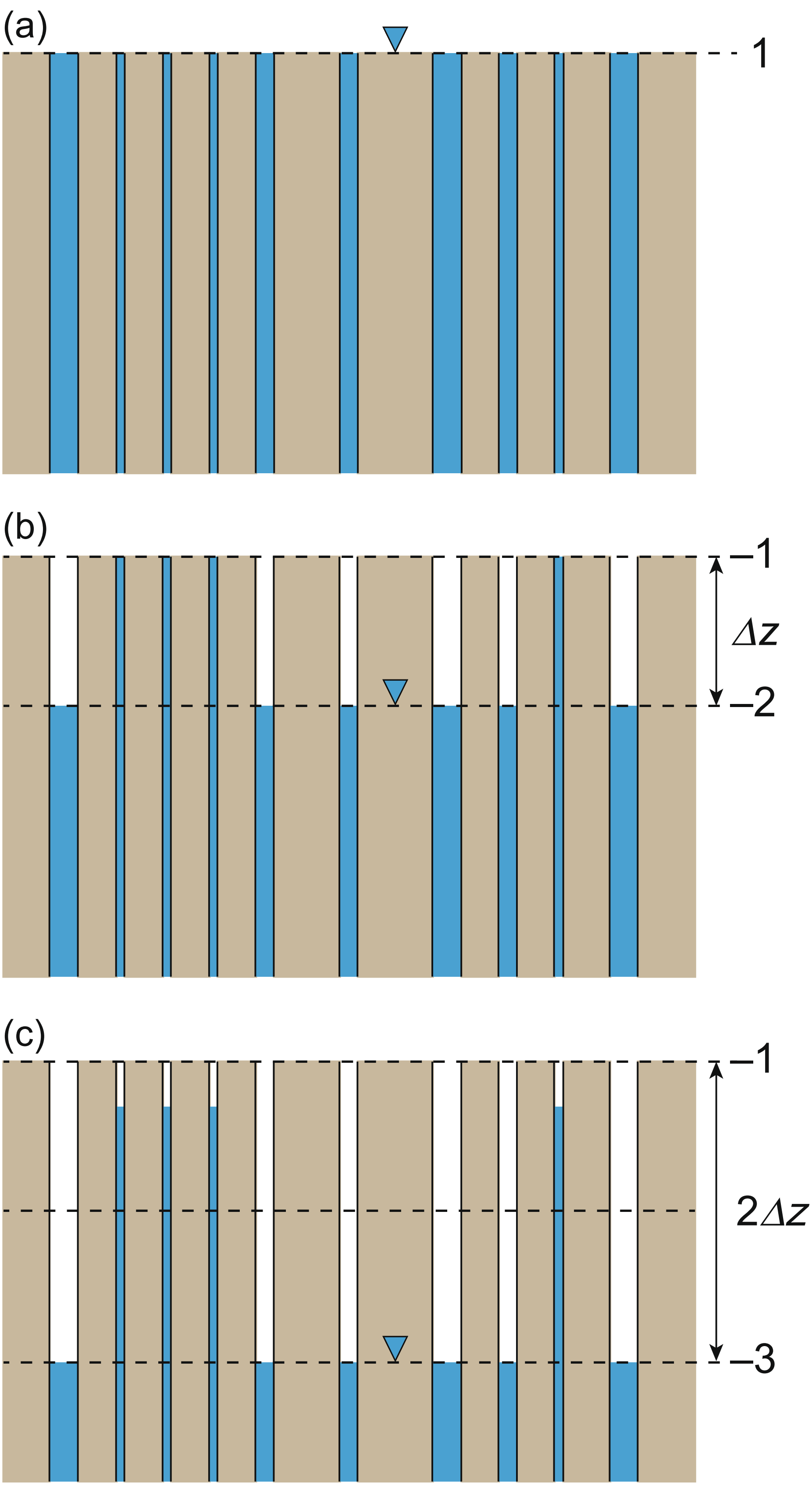

FIGURE 1 Drainage of soil pores during incremental increases in water-table depth. The soil is conceptualized as comprising vertical pores of three different diameters. After a Δz increase in water-table depth from 1 (a) (soil surface) to depth 2 (b), the smallest-diameter pores retain water through capillary action, but all other pores drain. In a further increase in water-table depth from depth 2 to depth 3 (c) by the same increment (Δz), water drains from the largest and middle-sized pores in that part of the soil between 2 and 3, but also from the smallest pores in the zone above (1–2). The smallest pores begin to drain because the height of capillary rise in them is less than the distance between 3 and 1. This figure shows how the pores outside of the zone through which the water table deepens can contribute to S_Y.

1 | INTRODUCTION

The position of the water table in peatlands is an important variable that affects a range of ecological and hydrological processes. Examples include: (i) the effect of water-table depth on plant growth, plant respiration and peat decay (soil respiration) (e.g., Laine et al., 2007; Samaritani et al., 2011; Tuittila et al., 1999), and (ii) the effect of water-table elevation (relative to a datum) on the discharge of water from a peatland into neighbouring water courses (e.g., Fraser et al., 2001). Water tables in peatlands rise and fall with rainfall additions, evapotranspiration losses, and seepage gains and losses. Models based on Darcy's Law may be used to simulate peatland water-table fluctuations. A well-known example is the Boussinesq equation (Baird et al., 2012; McWhorter & Sunada, 1977), which in one spatial dimension is given by:

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(-\frac{K_{av}(d)}{S_y(d)} d \frac{\partial h}{\partial x}\right) + \frac{P-E}{S_y(d)}, \quad (1)$$

where h is the height of the water table above a datum (L), t is time (T), x is horizontal distance (L), K_{av} is average hydraulic conductivity (K) of the soil below the water table ($L\,T^{-1}$), S_y is specific yield ($L^3\,L^{-2}\,L^{-1}$, dimensionless—see Equation (2)), d is the height of the water table above an impermeable substratum (which may be sloping and, therefore, may not coincide with the datum against which h is defined) (L), P is rainfall rate ($L\,T^{-1}$) and E is the rate of evapotranspiration ($L\,T^{-1}$). The Boussinesq equation is based on the Dupuit–Forchheimer approximation of Darcy's law (e.g., McWhorter & Sunada, 1977) and has been found to apply quite well to a range of peatland types (e.g., Fraser et al., 2001; Tiemeyer et al., 2006; Wright et al., 2008).

Specific yield, S_y, may be defined as the amount of water released from (or taken up by) a soil when a unit fall (or rise) of the water table occurs (Youngs et al., 1989). Mathematically, it is defined as:

$$S_y = \frac{V_w}{A\Delta h}, \quad (2)$$

where V_w is the volume of water (L^3) that drains from a column of soil of cross-sectional area A (L^2) when the water table falls by Δh (L). In situations with a rising water table, V_w is the volume of water that must be added to the soil to cause the water table to rise by Δh. As noted by Price (1996), it is tempting to think of V_w as being derived solely from the volume of soil defined by $A\Delta h$ (see also Price et al., 2023). However, water making up V_w may be derived from capillary pores higher in the soil profile, as shown in Figure 1 for the case of a falling water table. The narrower definition of specific yield noted by Price (1996) is sometimes called the drainable porosity (e.g., Bourgault et al., 2017; Price et al., 2023), but the two terms are not used consistently in the literature (see Dos Santos Junior & Youngs, 1969; Taylor, 1960).

In Equation (1), both S_y and K_{av} affect the rate of water-table rise and fall. Although of equal importance mathematically, K varies by many orders of magnitude within and between soil types, whereas S_y typically varies by less than a factor of five (e.g., Dingman, 1994; Fetter, 2001). Therefore, S_y is effectively of secondary importance and, arguably, less attention should be given to its measurement or estimation. However, S_y is an indicator of the degree to which a soil aerates as the water table falls, with the amount of air and oxygen entering the soil being in direct proportion to the value of S_y. Relationships between water-table depth and processes such as soil respiration (see above) are actually relationships in which the water table is a surrogate or proxy for the degree of soil aeration, and some of the unexplained variance in relationships based on water-table depth is likely to be due to variation in degree of aeration above the water table between different soil types. Therefore, although S_y may be less important than K in understanding and predicting water-table dynamics, it is critical to improving understanding of the relationships between biochemical processes and water-table depth. In this article we focus on the determination of S_y in the case of falling water tables.

Specific yield will depend on the nature of the pore network within the soil and may vary both laterally and with depth (e.g., Dettmann & Bechtold, 2016). It may also vary over time for a number of reasons, including the temperature of the water (e.g., Meinzer, 1923 cit. Johnson, 1967) and the degree to which pores below the water table are filled with water. Contrary to classical soil theory, it is unlikely that any soil is completely saturated below the water table. Air may be trapped or encapsulated in a soil during infiltration of rainwater (e.g., Bond & Collis-George, 1981; Constantz et al., 1988; Fayer and Hillel, 1986a, 1986b), giving rise to a condition known as quasi-saturation (Faybishekno, 1995). Bond and Collis-George (1981) cite earlier studies (Peck, 1969; Philip, 1957) to explain the mechanism behind encapsulation. Water percolating into a soil during rainfall tends to 'flood' rapidly through the larger pores, which saturate, thereby blocking the route for the escape of air from smaller pores connected to the larger pores. Air encapsulation can also occur when a soil is wetted from below. For example, Beckwith and Baird (2001) and Baird et al. (2004) found that samples of poorly-decomposed bog peat contained a trapped air content of between 1% and 13% by volume after they had been wetted slowly from their bases.

If encapsulated air resides in pores that would normally drain as the water table falls, encapsulation will have a direct effect on S_y (Faybishenko, 1995). The degree to which air encapsulation occurs will depend on the structure of the soil (Faybishenko, 1995) but is also likely to be related to the speed with which the soil is wetted prior to being drained. For example, Fayer and Hillel (1986a) performed wetting experiments on a sandy loam using sprinklers. Two different sprinkling rates were used, and in each case the water table was raised from a depth of 1.5 m to the surface. Soil water content measurements showed that considerably more air was encapsulated under the higher sprinkling rate, with the difference in volumetric gas content (defined as the volume of gas per unit volume of soil) between the two rates differing by as much as 0.12. Therefore, the wetting history of the soil has the potential to have a significant influence on S_y.

We are not aware of any previous work on the effect of air encapsulation on S_y in peats. A systematic search of the literature confirmed the lack of such work; hence, the first aim of our study was to investigate this effect. We did so for two types of peat typical of those found in many ombrotrophic peatlands. We hypothesised that both peat types would wet up more fully during lower-intensity rainfall than during higher-intensity rainfall. In other words, we hypothesised that S_y would be higher when peat drains after lower-intensity rainfall, and lower when peat drains after higher-intensity rainfall.

The full results of our systematic literature search are given in Data S1. In summary, they show that S_Y has been measured for virtually all peatland types and settings, and spans the full range of possible values. The S_Y of peat can be highly variable between samples, cores, management regime and sites, with values differing according to changes in degree of humification, compaction and peat composition, which explains why many studies focus on the relationship between S_Y and dry bulk density (Liu et al., 2020). Higher values of S_Y are typically associated with the least decomposed peat and also undisturbed or restored peat. Variations according to botanical composition of the peat have also been reported, but these are sometimes confounded by degree of decay. For example, Wilkinson et al. (2019) recorded higher values of S_Y in *Sphagnum fuscum* peat than in *Sphagnum angustifolium* peat. The differences in S_Y were attributed to differences in recalcitrance between the two species, with *S. fuscum* resisting decay and typically having a lower dry bulk density (and, the authors assumed, a greater pore-size) than *S. angustifolium* under similar environmental conditions (Wilkinson et al., 2019). We did not find any studies that directly compared the S_Y of different *Sphagnum* species, while controlling for degree of humification. Wilkinson et al. (2019) is something of an exception: many studies do not report the botanical composition of the peat cores or samples, focussing instead on broad classifications of peatland type and management regimes. Finally, many studies report decreases in S_Y with depth below the peatland surface (e.g., Bourgault et al., 2017; Cobb & Harvey, 2019; Ismail et al., 2021; Schut & Westbrook, 2022), but relationships with depth vary between peat types and are not always evident. Depth dependency may also be related in part to increases in degree of humification with depth.

While it is clear that S_Y varies with peat type, it is less clear how it varies for more subtle differences in peat properties. As we explain in Section 2.2, the two peat types we investigated had similar levels of humification but varied in the species of *Sphagnum* making up the peat, and, for our second aim, we were interested in knowing whether differences in species were reflected in S_Y. Because we measured S_Y for a range of water-table depths we were also able to determine whether S_Y varied with depth and, if so, whether the S_Y-depth relationship was affected by *Sphagnum* type.

Our study had one further aim. As discussed above (Equation (2) and Figure 1) the value of S_Y depends on the drainage of pores throughout the soil profile and not just water released from the zone through which the water table falls. However, it is common to see studies that take peat cores, cut the cores into sections, and measure S_Y for the sections (see Data S1). Such an approach cannot account for the contribution of whole-profile drainage to S_Y, and may give values of S_Y that are too low. Therefore, for our fourth aim we sought to quantify whether whole-profile drainage is an important component of S_Y in common peat types.

In summary, our study addressed four research questions:

1. Is peat S_Y affected by wetting history in two common peat types?
2. Does peat S_Y vary according to the *Sphagnum* species making up the two peat types?
3. Does peat S_Y vary systematically with depth, and does any depth relationship depend on the *Sphagnum* type making up the peat?
4. To what extent does S_Y depend on drainage of the peat profile above the zone through which the water table falls?

2 | MATERIALS AND METHODS

2.1 | Specific yield as defined by measurement method

The specific yield of a soil may be estimated from in situ water-table dynamics using the water-table fluctuation (WTF) method, or it may be measured in the laboratory using drain down and re-fill experiments. When horizontal gradients in water-table position are shallow (i.e., $\partial h/\partial x$ is close to zero), rises of the water table during rainfall can be described by a simplified version of Equation (1):

$$\frac{\partial h}{\partial t} = \frac{P}{S_Y(d)}. \tag{3}$$

If the time course of h and P are measured, S_Y may be estimated (Vorob'ev, 1963; Youngs et al., 1989). Alternatively, during dry periods, if the evapotranspiration rate (E) is known, S_Y can be calculated using:

$$\frac{\partial h}{\partial t} = \frac{E}{S_Y(d)}. \tag{4}$$

Vorob'ev (1963) noted that Equation 3 (more specifically, the time-integrated version of the equation) is prone to error because the amount of water arriving at the water table will be less than P due to interception by peatland vegetation. In both equations (and in Equation (1)) it is also assumed that the water content in capillary pores above the water table is in equilibrium with the water table. This assumption may not always be met, especially when the water table is relatively deep (Vorob'ev, 1963). If the water table is sufficiently far below the soil surface, the moisture content of the soil can be 'decoupled' from the water table. Such decoupling occurs when evapotranspirative losses reduce the water content of the uppermost part of the soil profile while the water table remains stable. Despite these limitations, the WTF method, especially Equation (3), can be used successfully if consideration is given to the size of the rainfall event (the larger the rainfall event, the less, as a proportion, the effect of interception on the calculated value of S_Y) and the time taken for the water table to respond to rainfall (see Bourgault et al., 2017).

Another drawback of the WTF method (apart from having an unfortunate acronym) is that a long data series is typically needed before S_Y for all depths in a soil profile can be estimated (Vorob'ev, 1963). If quicker results are required, then one of two laboratory methods is commonly used (for other methods, see Vorob'ev (1963)). In the first, intact cores of soil are extracted from the field and then, in the laboratory, subdivided vertically into a series of

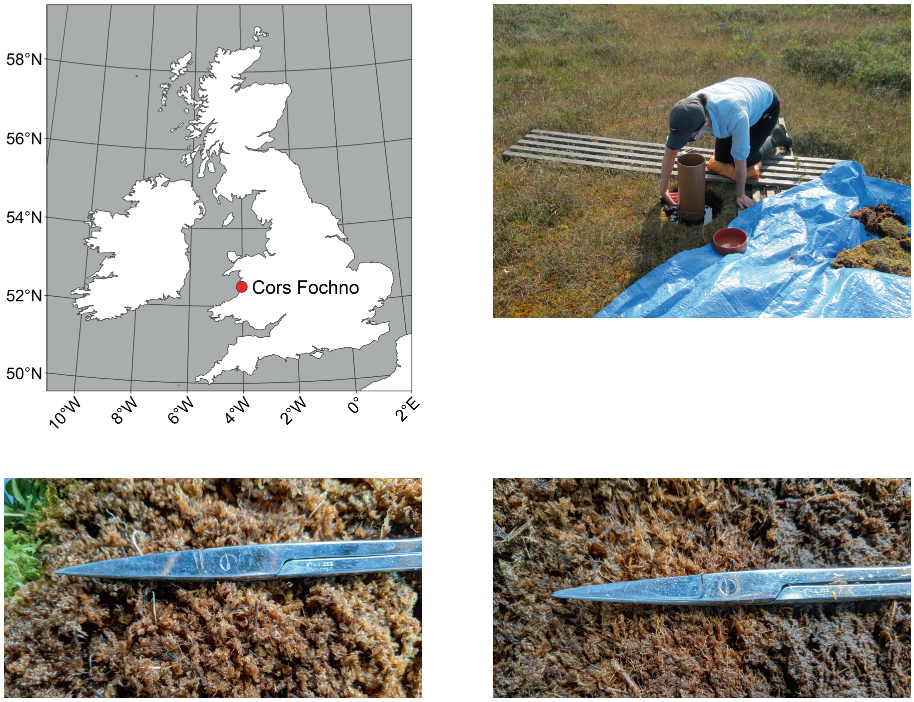

FIGURE 2 Top left: Location of the field site within the UK. Top right: Collecting one of the *S. pulchrum* samples. Bottom left: *Sphagnum medium* peat. Bottom right: *Sphagnum pulchrum* peat. The distance from the centre of the screw to the pointed tip of the scissors in each close-up picture is 5.1 cm. The surface of each peat sample is leftwards.

subsamples, z_1–z_2, z_2–z_3, z_3–z_4, …, z_{n-1}–z_n, where z_i denotes depth below the soil surface ($i = 1, \ldots, n$). Each subsample is wetted from its base, after which it is allowed to drain under gravity, with S_y being the volume of drained water divided by the subsample volume (Bourgault et al., 2017). This subsampling and wet-and-drain approach assumes that the S_y associated with a fall in the water table through sample z_i–z_{i+1} comprises water released solely from the soil between z_i and z_{i+1}, and not from elsewhere in the soil column. As noted above (Section 1), and shown in Figure 1, this may not be the case, and it is possible that S_y could be underestimated, and possibly grossly underestimated, using this approach. An alternative method that avoids this problem is to leave the soil core intact and to place it in a tank fitted with a basal drainage pipe to which is fitted a flexible pipe that can be lowered in increments (Bourgault et al., 2017; Taylor, 1960). The pipe outlet is first held at the same level as the soil surface. The sample is then wetted to bring the water table to the soil surface. The pipe outlet can then be lowered in increments, and the amount of water that drains from each increment recorded. Equation (2) will then give S_y. We chose this method for testing our research questions, and we describe the experimental setup in detail in Sections 2.3 and 2.4.

2.2 | Field site

We took peat cores for our S_y experiments from Cors Fochno raised bog in West Wales. All of the cores were taken from a 100 m × 100 m area centred on 52°30′11.33″N 4°00′41.41″W (Figure 2). This part of the bog has never been cut for peat and is in a near-natural condition, comprising a mosaic of hummocks, ridges, lawns and hollows (see Baird et al., 2016). We chose two types of microform for detailed study. Four cores were taken from small lawns in which *Sphagnum magellanicum* Brid. was identified as the dominant plant type (bottom left in Figure 2), and four from wet lawns/hollows in which *Sphagnum pulchrum* (Lindb. ex Braithw.) Warnst. was the dominant species (bottom right in Figure 2). In both peat types the dominant plant remains comprising the upper ~20 cm of the peat profile were the same as the surface vegetation. Since our samples were collected and the experiments completed, we became aware that *S. magellanicum* in the northern hemisphere actually comprises two species: *Sphagnum divinum* (sp. *nov.*) and *Sphagnum medium* Limpr. (Hassel et al., 2018). Our samples were not stored so we were unable to check again the identification of the *Sphagnum* species. However, in subsequent surveys by others at the site, only *S. medium* has been found. Therefore, we have assumed that our '*S. magellanicum*' samples were *S. medium*, and refer to them as such throughout.

S. medium is from section Sphagnum, while *S. pulchrum* is from section Cuspidata. The litter types from these two sections break down differently from each other. In the former, plant structures tend to remain intact until decay is advanced and collapse occurs. In the latter, the branch leaves tend to detach early during decay, forming an unstructured mass or 'mush'. Because of these physical differences the two peat types can be expected to differ in their values of S_y and their effect on air encapsulation (Research Questions 1 and 2), which is why they were chosen. The degree of humification assessed using the von Post H scale (following tab. 5.2 in Rydin and Jeglum (2006)) was similar for both peats, varying between H1 and H4 from the surface to a depth of 20 cm.

The cores were taken using 40-cm long polyvinyl chloride (PVC) tubes with an inside diameter of 15.2 cm. They were extracted using the scissor method described in Green and Baird (2013). Briefly, this involves placing the PVC cylinder vertically on the peat surface and cutting the peat around the outer edge of the cylinder to a depth of approximately 2 cm using gardening scissors. The cylinder is then pushed into the cut peat. In a circle with a diameter *c.* 20 cm wider than the cylinder, the peat is cut to a depth of 2 cm. The peat between this outer circle and the cylinder is then cut out, creating an annular hole 2 cm deep (top right, Figure 2). The process is repeated until the cylinder is fully inserted into the peatland, after which a hole is dug alongside the cylinder using a spade. The peat along the base of the cylinder is then cut using scissors and the core extracted. After extraction, the cores, still in their PVC cylinders, were placed in tight-fitting waterproof plastic bags for transport to the laboratory, where they were fitted with basal plates that formed a water-tight seal. Before experimentation, the cores were kept outside in the shade of a building and supplied with run-off water from the roof of the building (see below). The water table was maintained within ∼10 cm of the surface of the cores until they were used in the experiments. The cores were denoted M1, M2, M3, M4 (*S. medium* cores) and P1, P2, P3, P4 (*S. pulchrum* cores).

2.3 | Experimental design

Unpublished water-table data from the field site suggest that the water table in the central area from which the cores were taken rarely falls more than 15–20 cm below the ground surface in lawns and hollows. Therefore, we confined our measurements of S_y to this part of the peat profile. We used the 'alternative' laboratory method noted above in Section 2.1, which employs intact cores that are not sliced into subsections. To estimate S_y, we raised the water table to a core's surface using a rainfall simulator (Section 2.4), and then lowered it in ∼3–4 cm increments, measuring how much water flowed from the peat after each new water-table setting. Lowering in increments allowed us to test Research Question 3. For each increment, Equation (2) was then applied to obtain S_y.

Each core was subjected to four experimental runs. In the first run on the *S. medium* samples, each core was wetted up using a high rainfall rate (High1) (Section 2.4). The succeeding runs were: low rainfall rate (Low1), high rainfall rate (High2), low rainfall rate (Low2). For the *S. pulchrum* runs, the order was high (High1), high (High2), low (Low1) and low (Low2). The top of the peat samples in all cases was below the top of the cylinder holding the sample, and varied over time (see Sections 2.4 and 2.5). The surface of a peat soil on which *Sphagnum* is growing is difficult to define and could be anywhere from the uppermost part of the *Sphagnum* capitula to the base of the gaps between the capitula if such gaps exist (depending on *Sphagnum* species). Because of this uncertainty we used the top of the PVC cylinder as a fixed reference for measuring water-table position. We also used an operational definition of the peat surface, as explained at the end of the next section.

We standardized pre-run conditions. Prior to each run we first let each core drain so that the water table was ∼19–20 cm below the top of the cylinder. The water table was then raised to the peat surface using artificial rainfall under the high application rate (see Section 2.4), after which the water table was lowered in ∼3–4 cm increments every 60 min. At the lowest water-table setting, the core was left for 12 h for the *S. medium* samples or 17–18 h for the *S. pulchrum* samples, the difference in duration between the two *Sphagnum* types reflecting how long we thought it might take for drainage to occur. Because of its 'mushier' structure (Section 2.2) we expected the hydraulic conductivity to be lower and drainage to take longer in the *S. pulchrum* samples. In practice, drainage occurred rapidly in both peat types (Section 2.4). After drainage, the run was started, and the water table raised again to the core surface using one of the two rainfall rates (Section 2.4).

Finally, in three of the cores, we measured the volumetric water content (θ) of the uppermost peat to investigate whether it continued to drain as the water table was lowered deeper in the profile (Research Question 4).

2.4 | Laboratory equipment and measurements

Filtered roof run-off water (with a typical pH of ∼7.2 and electrical conductivity of ∼150 μS cm^{-1}) was used for the artificial rainfall and was delivered to each core using a rainfall simulator comprising a shallow circular (flat-bottomed) trough drilled with 16 0.2-cm diameter holes. Water was syringed into the trough after which it dripped through the holes onto the peat surface. To space the holes, we used a 'circles within circles arrangement' as shown in Figure 3, with the holes drilled in the centre of imaginary circles packed onto the circular base of the trough. Two nominal rainfall rates were chosen: 4 and 0.8 cm h^{-1}. The higher rate was achieved via adding 120 mL of water to the trough every 10 min, while the latter used 120-mL additions every 50 min in one set of runs (Low1 for all of the *S. medium* cores) and 60-mL additions every 25 min in all other cases. For both rates, rainfall was added until the water table reached the peat surface. These rates were partly chosen for practicality, with wetting to the peat surface from an initial depth of 20 cm taking about 9 h for the lower intensity, and about 1 h 40 mins for the higher intensity. Intensities of 0.8 cm h^{-1} are not uncommon in the UK, but intensities of 4 cm h^{-1} for more than an hour are extremely rare. Our use of the high rainfall rate therefore represents an end member that we used to stress-test the experimental system, and to provide a strong contrast in wetting history between the two treatments.

Water table control in the cores was achieved by drilling seven 0.63-cm diameter holes in the PVC holder 20 cm below the top of the cylinder (Figure 3). The holes were drilled in a line, with the centre of each hole 1 cm from its neighbour. Into each hole was pushed one end of a 35-cm long silicone tube which had an inside diameter of 0.33 cm at the point where it was squeezed in the PVC cylinder. The other end of each tube was fitted into a modified hollow Duplo™ plastic brick that had been drilled with eight holes. The eighth hole acted as a drainage hole from which water could flow or drip into a tube terminating in a graduated 300 mL beaker. Lowering of the brick, and therefore the outflow level, caused water to flow from the core, through the seven silicone tubes and into the internal volume of the hollow brick, and thence out through the drainage hole. Once flow

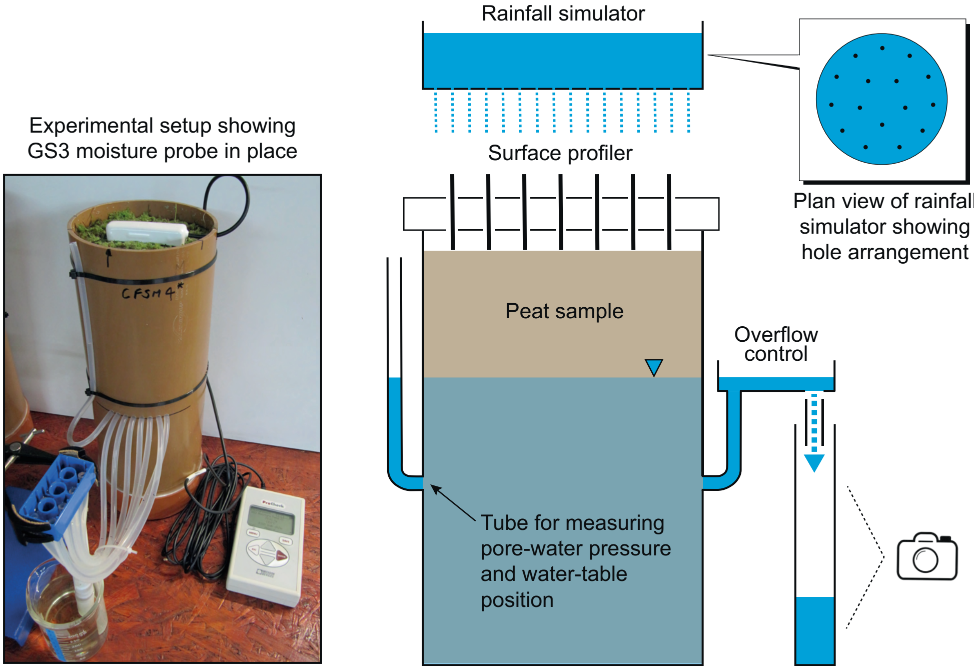

FIGURE 3 The experimental setup. The rainfall simulator and surface profiler were used separately at different times during the course of the experiment (see text). Inset photo shows core M4 fitted with a GS3 probe in the Low2 run.

into the beaker stopped, the water table in the peat core was at the same level as the outflow level. An eighth silicone tube was attached to the side of the PVC cylinder through a further 0.63-cm diameter hole and was used to measure the pore-water pressure at a depth of 20 cm (Figure 3); this tube also gave the position of the water table after any drainage from the core had ceased and conditions had become hydrostatic.

To prevent evaporation losses, the collection beaker was fitted with a polythene disk. For the *S. medium* samples, the outflow level was lowered at ~3–4 cm intervals every 12 h, while for the *S. pulchrum* samples the interval was 24 h. The differences reflected original expectations on how long it would take water to drain from the samples, and the practicalities of taking measurements (see also Section 2.3). The volume of water draining after each lowering of the water-table—that is, V_W (Equation (2))—was calculated by weighing each beaker to the nearest 0.1 g (balance repeatability: 0.1 g; linearity: ±0.2 g), assuming a water density of 1 g cm^{-3} and subtracting the dry weight of the beaker.

The plastic brick was held in a clamp attached to a boss fitted to a retort stand. It proved unexpectedly difficult using this setup to lower the bricks by the same amount (within 1–2 mm) across the cores and runs. However, the water-table position was measured for each position of the brick, and these depths were incorporated into the statistical analysis (Section 2.5).

The rate of water draining out of the core after each incremental lowering was recorded using a GoPro™ Hero™ 4 camera in time-lapse mode recording at 60-s intervals (Figure 3). The images from the camera were then used to read off the level in the outflow beakers. The time-lapse data showed that the drainage periods of 12 h (*S. medium* samples) and 24 h (*S. pulchrum* samples) were ample for all cores and all settings. In almost all cases, flow from a core stopped well within 2 or 3 h after the outflow had been lowered. For example, Figure 4

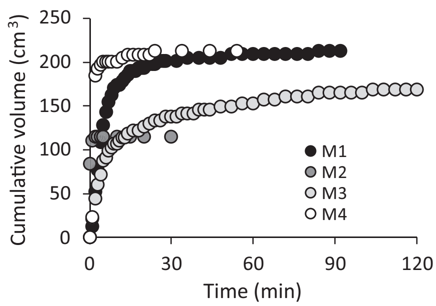

FIGURE 4 Drainage from the four *Sphagnum medium* cores in a pre-experiment run when the water level was lowered from near the peat surface to a depth of ~4 cm.

shows drainage from the four *S. medium* cores in a pre-experiment run when the water table was lowered from the peat surface to a depth of ~4 cm, with flow ceasing within a period ranging from a few minutes to about 2 h. As with the beakers, the surface of each peat core was covered with a polythene disk during each run to prevent evapotranspiration losses.

To address Research Question 4, we measured the moisture content in the upper 5.5 cm of one *S. pulchrum* core (P4) for each of the four runs and in two *S. medium* cores (M1 and M4) in the last run (Low2). If the effect shown in Figure 1 occurs, there will be decreases in water content of the upper 5.5 cm of peat as the water table is lowered below this depth. To estimate peat volumetric water content (θ) of the upper 5.5 cm of peat we used a Decagon Devices (now part of Meter Group, Pullman, WA, USA) GS3 capacitance probe, which measures the apparent dielectric constant, K_a, of the peat-water-air mixture (denoted $K_{a,bulk}$). The GS3 has a manufacturer's quoted accuracy of ±1 K_a units for K_a from 1 to 40 and ±15% from 40 to 80 but has been shown to be much better than this in the upper range in independent tests conducted by Dettmann and Bechtold (2018). Our own tests on the two probes used in this experiment found that they give K_a values within 2 K_a units of the expected value over the 1–80 K_a range. For K_a values greater than 80, errors increased substantially. However, K_a measured for peats (using highly accurate time domain reflectometry; e.g., Beckwith and Baird (2001)) typically does not exceed ~75. Therefore, we concluded the probes were suitable for our purposes.

We used the following three-phase mixing model (Kellner & Lundin, 2001) to covert K_a readings into θ:

$$\theta = \frac{K^{\alpha}_{\mathrm{a,bulk}} - \left((1-f)K^{\alpha}_{\mathrm{a,peat}}\right) - fK^{\alpha}_{\mathrm{a,air}}}{K^{\alpha}_{\mathrm{a,water}} - K^{\alpha}_{\mathrm{a,air}}}, \tag{5}$$

where α is a geometry parameter (see Kellner & Lundin, 2001), f is total porosity, 'peat' denotes peat solids, and 'water' and 'air' are obvious. We used a value of $K_{\mathrm{a,peat}}$ of 5.0 following Kellner and Lundin (2001) and found that $\alpha = 0.24$ provided a good fit to unpublished calibration data collected over the 5–70 $K_{\mathrm{a,bulk}}$ range from a poorly-decomposed *Sphagnum capillifolium* (Ehrh.) Hedw. peat (all estimated θ values were within 0.055 of measured, and the median percentage error was less than 5%). Beckwith and Baird (2001) observed a shallower decline in θ in a poorly-decomposed *Sphagnum cuspidatum* Ehrh. ex Hoffm. peat over the 30–75 $K_{\mathrm{a,bulk}}$ range than predicted by Equation (5) with $\alpha = 0.24$. However, θ-$K_{\mathrm{a,bulk}}$ relationships presented by other authors, such as Pepin et al. (1992) tend to show a substantially steeper decline, suggesting Equation (5) ($\alpha = 0.24$) is conservative when used to determine the effect shown in Figure 1. That is, for any given change in $K_{\mathrm{a,bulk}}$, θ in Equation (5) will change less than in other functions developed for peats; thus, less apparent drainage will occur as the water table falls (deepens).

As noted in Section 2.3, the surface of a peat soil can be difficult to define. Peat can also shrink and swell in response to changes in water content and this, in addition to S_y, can affect the position of the water table relative to the peat surface and peat water storage (e.g., Price et al., 2023; Price & Schlotzhauer, 1999). Therefore, the height of the peat surface was measured for each water-table position in each core and each experimental run. Surface height was measured relative to the top of the PVC holder using a PVC frame into which seven holes had been drilled (the 'surface profiler' shown in Figure 3). A 2.7-g, 0.45-cm-diameter plastic rod could be inserted vertically through the holes. To make measurements, the frame was fitted onto the top of the PVC holder and the rod inserted into each hole in turn. When in contact with the peat surface the length of rod above the horizontal surface of the upper part of the frame was measured: the lower the peat surface, the less the rod protruded above the top of the frame and vice versa. The frame and rod arrangement was calibrated to give heights of the peat surface relative to the base of the core. We regard these measurements as providing an 'operational' (method-dependent) indication of the peat surface. The rod tended to bend some of the uppermost branches of the *Sphagnum* capitula, and was too wide for some gaps between capitula. A rod of a different diameter or weight would have given a different estimate of the surface.

Finally, the water level used at the beginning of each experimental run was set such that all microtopographic elements of the *Sphagnum* canopy were submerged, which meant that the starting position of the water table was higher (nearer the top of the cylinder) than the peat surface as measured using the profiler described above. When we talk of raising the water table to the 'peat surface', in Section 2.3 for example, we mean this higher level. This distinction becomes important in some of the interpretation of the GS3 probe results in Section 3.2.

2.5 | Data analysis

Research Questions 1, 2 and 3 can be addressed in part using a statistical analysis of our laboratory data. We developed a general linear model with S_y as the response variable. The predictor variables are the categorical distinction between high and low rainfall rates (to address Research Question 1), the categorical distinction between the *S. medium* and *S. pulchrum* peat types (Research Question 2), a continuous representation of the measured water-table depth during each determination of S_y, and a two-way interaction between water-table depth and peat type (Research Question 3). We fitted the model using the *lm* function in R version 4.3.1 (R Core Team, 2023). We then used the *Anova* function from the R package *car* version 3.1-2 (Fox & Weisberg, 2019) to calculate F statistics and associated significance for each variable, based on Type-III sum of squares ANOVA (Analysis of Variance). We used the *glht* function from the R package *multcomp* version 1.4-25 (Hothorn et al., 2008) to perform post hoc t-tests between levels of categorical variables identified by the ANOVA as being significant ($p < 0.05$ threshold). To assess model bias, we used the *CCC* function from the R package *DescTools* (version 0.99.49) to calculate Lin's concordance correlation coefficient between measured and modelled values of S_y.

3 | RESULTS

3.1 | Research questions 1–3: Variations in specific yield

In total, 160 determinations of S_y were made across all the experimental runs (2 peat types × 5 water-table settings × 2 rainfall settings × 2 experimental runs per rainfall setting × 4 peat sample replicates). The full data set is shown in Figure 5. There was wide variation in S_y, with values ranging from a low of 0.16 to a high of 0.62. The uppermost part of the peat profile showed the greatest scatter in values, although the bottom part of the profile in the *S. medium* samples also showed considerable variation. In terms of Research Question 1 there are no obvious systematic differences in S_y according to wetting history; that is, there is a lot of overlap between the runs with high-intensity rainfall and those with low-intensity rainfall. There does, however, appear to be a difference in S_y between the two peat types (Research Question 2). For the three shallowest depths the *S. pulchrum* samples have generally higher values of S_y, although there is some overlap. For the deepest two depths the situation is reversed, with somewhat higher values for the *S. medium* samples. The *S. medium* samples do not show any systematic variation with depth, whereas the *S. pulchrum* ones appear to show an approximately linear decline with increasing water-table depth (Research Question 3).

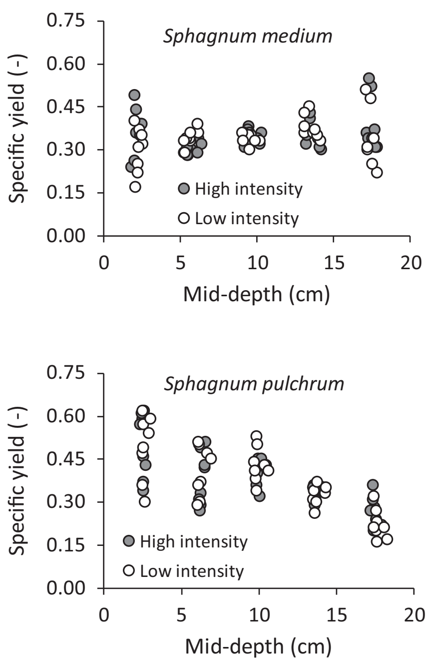

FIGURE 5 Specific yield against depth for the *Sphagnum medium* (upper plot) and *Sphagnum pulchrum* (lower plot) samples. The mid-depth is the average of each pair of water table settings (distance from top of the cylinder) for which each value of S_y was calculated (Section 2.3 and Equation (2)). Two runs were conducted for each wetting up rainfall intensity; however, the run numbers are not distinguished here (see Data S2).

Analysis of the general linear model confirms the trends that are apparent from a visual appraisal of Figure 5. The effect of rainfall rate (Research Question 1) was highly non-significant ($F = 0.355$, $p = 0.552$). The effect of peat type (Research Question 2) was highly significant ($F = 80.2$, $p \approx 1 \times 10^{-15}$); a post hoc *t*-test indicates that S_y is on average 0.209 higher in *S. pulchrum* peat than in *S. medium* peat ($t = 8.96$, $p < 0.001$) (see also Figure 5). The main effect of depth is marginally non-significant ($F = 3.73$, $p = 0.055$), but the interaction between peat type and depth (Research Question 3) is highly significant ($F = 73.0$, $p \approx 1 \times 10^{-14}$); a post hoc *t*-test indicates that S_y in *S. pulchrum* peat declines significantly ($p < 0.001$) with increasing depth at a rate of 0.018 per cm depth, while S_y shows no significant relationship to depth in *S. medium* peat. The model has moderate explanatory power when regressing predicted values on observations (multiple $r^2 = 0.422$), and moderate levels of bias (Lin's concordance correlation coefficient = 0.594). Table 1 provides further details of the general linear model.

3.2 | Research question 4: Variations in near-surface volumetric water content during water-table lowering

Substantial drainage of the peat profile above the zone through which the water table deepens occurred in core P4 (*S. pulchrum*) in every experimental run (Figure 6). For example, when the water table dropped between the third and fourth positions—that is, from depths of ~8 cm to depths of ~12 cm—well below the near-surface peat sampled by the GS3 probe, there was a decline in volumetric water content (θ) of 0.21, 0.27, 0.25 and 0.31 for Runs 1–4, respectively (Figure 6). The specific yield for core P4 for this water-table interval was 0.32, 0.36, 0.38 and 0.34 (Table S1). Therefore, drainage from the uppermost part of the profile represented at least 66, 75, 66 and 91 percent of S_y, confirming the importance of the effect explained in Figure 1. It is notable too that there is consistency in drainage behaviour between runs, with overlap in the value of θ from the separate

TABLE 1 Summary of the general linear model. *p* (*F*) indicates significance of a variable according to ANOVA; *p* (*t*) indicates significance of a level of a categorical variable according to post hoc *t*-tests. Levels marked with an asterisk * (high rainfall rate, and *S. medium* in both the peat type main effect and the interaction) are reference categories and so have no parameter estimate, standard error or associated post hoc test statistics.

	ANOVA					Post hoc tests	
Variable	*F*	*p* (*F*)	Level	Estimate	Std. err.	*t*	*p* (*t*)
Intercept	353	$\sim 2 \times 10^{-16}$	–	0.322	0.017	–	–
Rainfall rate	0.355	0.552	High*	–	–	–	–
			Low	−0.00665	0.0112	–	–
Peat type	80.2	$\sim 1 \times 10^{-15}$	*S. medium**	–	–	–	–
			S. pulchrum	0.209	0.0234	8.96	<0.001
Depth	3.73	0.055	–	0.00280	0.00145	–	–
Peat type × depth	73.0	$\sim 1 \times 10^{-14}$	*S. medium**	–	–	–	–
			S. pulchrum	−0.0177	0.00208	−8.541	<0.001

runs, despite the two different wetting histories (Runs 1 and 2 had high rainfall intensities, and Runs 3 and 4 low rainfall intensities).

The data in Figure 6 appear to suggest that no drainage of the near-surface peat occurred when the water table dropped between the first and second positions in each run. The S_y values for each run as the water table dropped between these intervals were 0.37, 0.34, 0.30 and 0.36 (Runs 1–4 respectively), the intervals being: 0.75–4.30 cm (mid value of 2.53) (Run 1), 0.70–4.35 cm (2.53) (Run 2), 0.75–4.50 cm (2.63) (Run 3) and 0.75–4.25 cm (2.50) (Run 4). The GS3 probe was inserted 5.5 cm below the peat surface. The peat surface for P4 ranged between 1.1 and 1.7 cm below the top of the cylinder for each run (Section 3.3 and Table 2), meaning the GS3 probe extended to depths of between 6.6 and 7.2 cm below the top of the cylinder; that is, the probe extended 2.3–3.0 cm below the water table after the drop in water table from the first to the second position. Allowing for a capillary fringe, it is to be expected that little or no drainage would occur for much of the peat around the GS3 probes. Additionally, and importantly, the probe registered a decline in K_a value between the first and second water-table position, but as noted in Section 2.4 above, the function used to model θ (K_a) is conservative and probably gives values of θ that are too high in the wet end of the range.

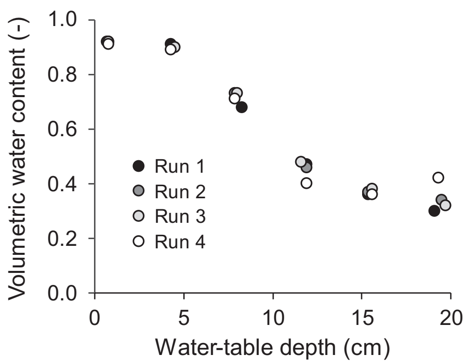

FIGURE 6 Volumetric water content of the near-surface peat versus depth of the water table from the top of the cylinder for sample P4 (*S. pulchrum*) for each of the four experimental runs.

A similar pattern in drainage of the near-surface peat, but with less overall loss of water, occurred in cores M1 and M4 for their last experimental run (Figure 7). Most drainage occurred when the water table deepened from 7.8 to 11.95 cm (M1) and 7.0 to 11.5 cm (M4). These depths are well below the base of the GS3 probe and show again that profile drainage is occurring, confirming the effect shown in Figure 1. As with core P4, there was an apparent lack of water loss as the water table was lowered from the surface, which can be explained in a similar way. However, this behaviour was more pronounced in M1 and M4 than in P4, with θ remaining unchanged at water-table depths of between 7 and 8 cm. We are unsure why this was the case. However, we noticed that the *S. medium* peat was firmer than the *S. pulchrum* peat and more resistant to insertion of the prongs of the GS3 probe. It is possible that the peat in and immediately around the prongs was compressed slightly during the probe insertion and stayed compressed through the experimental run. This compressed

TABLE 2 Highest and lowest average surface levels (average of seven rod positions) for each peat sample for each experimental run.

	***Sphagnum medium* samples**			***Sphagnum pulchrum* samples**		
Run	**Sample code**	**Highest average surface level (cm)**	**Lowest average surface level (cm)**	**Sample code**	**Highest average surface level (cm)**	**Lowest average surface level (cm)**
1	M1	38.3	38.0	P1	38.7	38.1
1	M2	39.0	38.9	P2	38.9	38.6
1	M3	39.0	38.7	P3	38.4	37.8
1	M4	38.4	38.2	P4	38.9	38.4
2	M1	38.4	38.1	P1	38.5	37.9
2	M2	39.1	38.9	P2	38.8	38.5
2	M3	39.0	38.6	P3	38.1	37.5
2	M4	38.4	38.2	P4	38.7	38.3
3	M1	38.3	38.1	P1	38.3	37.7
3	M2	39.1	38.9	P2	38.7	38.4
3	M3	38.8	38.5	P3	37.8	37.1
3	M4	38.3	38.2	P4	38.5	38.0
4	M1	38.2	38.0	P1	38.1	37.4
4	M2	39.0	38.9	P2	38.6	38.2
4	M3	38.9	38.5	P3	37.6	36.9
4	M4	38.1	38.0	P4	38.3	37.8
Overall mean:		38.6	38.4		38.4	37.9

Note: The heights are given relative to the base of the PVC cylinder (40 cm represents the top of the cylinder).

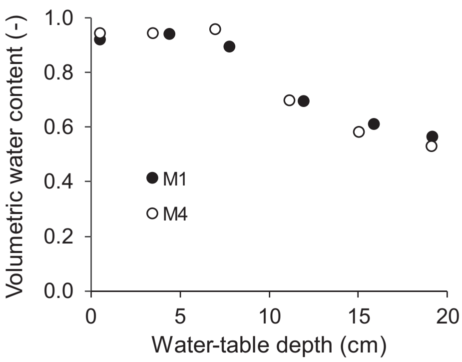

FIGURE 7 Volumetric water content of the near-surface peat versus depth of the water table from the top of the cylinder for cores M1 and M4 (*S. medium*) for the last experimental run (Low2) on these samples.

peat around the prongs may have retained water via capillary action as the uncompressed peat beyond the probe drained.

3.3 | Peat shrinkage during the experimental runs

We observed some vertical shrinkage in all of the peat samples during each experimental run as the water table was lowered from a depth of ∼0.7 cm to one of ∼19.5 cm from the top of the PVC cylinder. Shrinkage of the *S. medium* samples varied between 0.1 and 0.4 cm (based on the average of the seven rod positions), with an overall average of just over 0.2 cm. For the *S. pulchrum* samples it ranged between 0.3 and 0.7 cm, with an overall average of just over 0.5 cm (Table 2). Figure 8 shows the response of sample P1 during the first experimental run. Here the surface was 0.6 cm lower at the end of the experiment than at the beginning, so it represents one of the more 'extreme' cases from the overall dataset.

4 | FURTHER INTERPRETATION AND DISCUSSION

We found that the effect of wetting history on soil moisture content, and therefore S_y, observed by Fayer and Hillel (1986a) (see Section 1) did not occur in the two peat types studied here. There was quite substantial variation in S_y between runs for particular depths (Figure 5), but these variations were not related to wetting history. Although there was a fivefold difference in wetting rate between the low-intensity and high-intensity runs, it is possible that differences in the degree to which the peat wets up only occurs at lower and more realistic rainfall intensities. Delivering rainfall at lower intensities than used here can present technical challenges, but is worth attempting because there may be threshold behaviour in how a peat wets up during rainfall; that is, below the lower-intensity rainfall used here, there may be a rainfall rate at which the peat wets more thoroughly than we observed. Other peat types, especially non-*Sphagnum* peats, should also be tested for a wetting history effect.

As anticipated, and despite the high variability at some depths, the contrasting structures of the two peat types led to large and significant differences in S_y (Research Question 2). However, based on the lack of structure of the *S. pulchrum* samples (the mushy mass of leaves) they might have been expected to have a lower S_y than the *S. medium* samples, but the opposite was the case.

The difference in depth dependency (Research Question 3) between the two peat types is perhaps not surprising. We were unable to measure the depth variation in dry bulk density of the peat samples after the experiments had concluded because of difficulties in subsampling. In the case of the *S. pulchrum* cores, in particular, the peat slumped and deformed when being extruded from the cylinders, so it was not possible to obtain undamaged slices that could be dried and weighed. However, based on this observation, we might expect the *S. pulchrum* peat to have compressed during its formation such that its dry bulk density increases with depth. As shown in the systematic search from the literature (see Data S1) a relationship between S_y and dry bulk density has been reported in many studies, albeit based in some cases on methods of measuring S_y that are flawed (see below). Visually, the *S. medium* samples had greater structural integrity than the *S. pulchrum* samples (Section 2.2) and were also more resistant to the insertion of the GS3 probes (Section 3.2). It is possible, therefore, that their dry bulk density did not decline over the depth range studied, which would explain the lack of a decline in S_y (Sections 2.2 and 3.2).

Although a small data set, the θ measurements (Figures 6 and 7) (Research Question 4) show that for some depths a large part of the value of S_y is derived from drainage of water from the peat profile above the zone through which the water table falls ($A\Delta h$ in Equation (2)); that is, that the effect shown in Figure 1 is important. Using a gamma radiation absorbance method to measure θ, Hayward and Clymo (1982) recorded similar declines in a *Sphagnum capillifolium* peat. Our results and the prior work of Hayward and Clymo (1982) mean that, for *Sphagnum* peats, estimates of S_y measured for discrete subsamples from a core may be in error (see Section 2.1) and should not be used in water-table models, such as Equation (1). The effect shown in Figure 1 may not apply to all peats, but unless it can be demonstrated that it is unimportant, we recommend using either the WTF method or the column drain-down method (Sections 2.1 and 2.4) for measuring S_y.

In recent years there has been interest in relating a variety of peat hydraulic properties to more readily-measured metrics such as degree of humification and dry bulk density (e.g., Liu & Lennartz, 2019; Morris et al., 2022; Wang et al., 2021). It would be very useful if similar relationships could be established for S_y via a meta-analysis, but our data show that any such analysis must account for the fact that S_y depends on the properties of the peat profile and not just the zone through which the water table falls (or rises). As already noted, determinations of S_y that have been made on subsamples from cores will be in error, and the same is true of any relationship between such S_y estimates

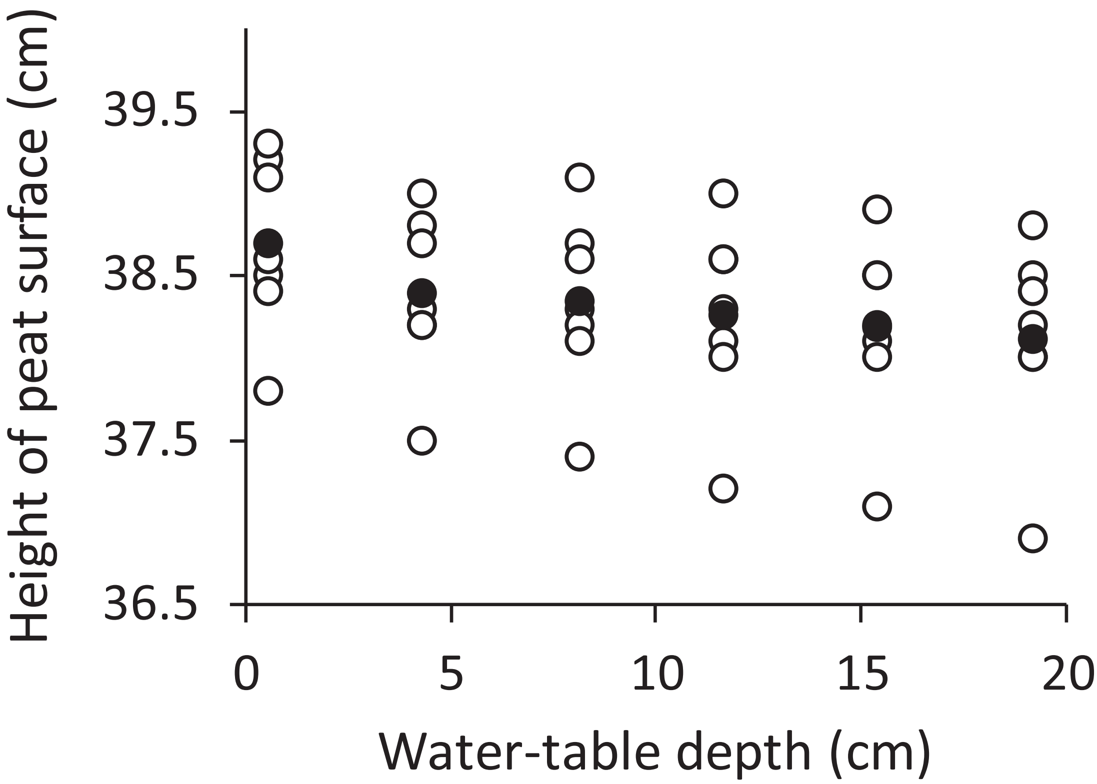

FIGURE 8 Shrinkage in core P1 (*S. pulchrum*) during the first run (following high-intensity rainfall). The height of the peat surface is relative to the base of the 40-cm high cylinder, while the water table is the depth below the top of the cylinder. Water tables were lowered (deepened) through the run. Each white-filled circle represents a hole location from the surface profiler ($n = 7$; Section 2.4). The average is shown by the black-filled circles.

and other physical properties of the subsamples. Nevertheless, relationships between S_y and depth below the surface, and between S_y and *general* peat type, may be worth exploring in meta-analyses.

Finally, what are the implications of the shrinkage data? In terms of understanding water storage within the peat profile, the importance of shrinkage will depend on the cause. The shrinkage observed in the experimental runs could have been caused by shrinkage of the peat above the water table where water is held under tension. This change in water storage is accounted for in the measurement of S_y. However, as demonstrated by Price and Schlotzhauer (1999), it is also possible that the shrinkage was due to compression of the peat below the water table as the latter fell. Such changes in peat volume are due to a non-zero specific storage (S_s), defined as the volume of water that a unit volume of soil below the water table releases per unit fall in hydraulic head (water table) (Freeze & Cherry, 1979). S_s can be calculated using (Price & Schlotzhauer, 1999):

$$S_s = {}^{\partial z}\!/_{\partial h}\!/_b, \quad (6)$$

where z is now the height of the peat surface, h is the elevation of the water table, and b is the thickness of the peat below the starting position of the water table. Using the measurements already reported (Table 2 and Data S2), S_s was estimated to be 2.8×10^{-4} and 6.9×10^{-4} cm^{-1}, respectively, for the *S. medium* and *S. pulchrum* samples. Price and Schlotzhauer (1999) report a value of 7.4×10^{-4} cm^{-1} for a cutover plateau bog in Lac Saint-Jean in Québec, Canada. These values can be compared directly with S_y if multiplied by the thickness of the peat below the initial position of the water table, which gives 0.01 and 0.03, which are at 15 and 6 times lower than the lowest recorded value of S_y (Section 3.2). Therefore, S_s would appear to be unimportant in the Cors Fochno peat. However, at the field site the peat is much thicker than the cores, reaching depths of 600–650 cm, giving values of $S_s \times b$ of 0.18 and 0.45, so equivalent to the values of S_y recorded in the experiments. This extrapolation assumes that all of the 600–650 cm depth of peat at the site has the same structural properties as recorded for the surface peat, which is unlikely to be the case (Baird et al., 2016; Kettridge et al., 2012; Mighall et al., 2009). Also, as noted above, the observed lowering of the peat surface could be largely or wholly due to shrinkage in the zone above the water table. Further work on this effect is recommended.

5 | CONCLUSION

Falling-water-table experiments with intact peat cores showed large variability in measured specific yield, which ranged between 0.16 and

0.62 across 160 measurements. Statistical analysis indicates that, contrary to our expectations, specific yield did not vary significantly according to the rate at which the cores were wetted up using simulated rainfall prior to our drawdown measurements. The average specific yield of *Sphagnum pulchrum* peat was significantly higher than that of *Sphagnum medium* peat from the same site. However, specific yield declined significantly with water-table depth in the *Sphagnum pulchrum* samples, whereas the *Sphagnum medium* peat showed no relationship between specific yield and depth. Monitoring near-surface volumetric water content while the experimental water table is slowly drawn down shows that pores as much as 15–20 cm above the water table may continue to be drained, and therefore contribute to the phenomenon of specific yield. This finding indicates that measurements based on short subsamples taken from longer cores risk underestimating specific yield.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

ORCID

Andy J. Baird https://orcid.org/0000-0001-8198-3229

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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