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Determination of the gas diffusion coefficient of a peat grassland soil

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Summary

Peatland habitats are important carbon stocks that also have the potential to be significant sources of greenhouse gases, particularly when subject to changes such as artificial drainage and application of fertilizer. Models aiming to estimate greenhouse gas release from peatlands require an accurate estimate of the diffusion coefficient of gas transport through soil (D_s). The availability of specific measurements for peatland soils is currently limited. This study measured D_s for a peat soil with an overlying clay horizon and compared values with those from widely available models. The D_s value of a sandy loam reference soil was measured for comparison. Using the Currie (1960) method, D_s was measured between an air-filled porosity (ϵ) range of 0 and 0.5 cm³ cm⁻³. Values of D_s for the peat cores ranged between 3.2×10^{-4} and 4.4×10^{-3} m² hour⁻¹, for loamy clay cores between 0 and 4.7×10^{-3} m² hour⁻¹ and for the sandy reference soil they were between 5.4×10^{-4} and 3.4×10^{-3} m² hour⁻¹. The agreement of measured and modelled values of relative diffusivity (D_s/D_0 , with D_0 the diffusion coefficient through free air) varied with soil type; however, the Campbell (1985) model provided the best replication of measured values for all soils. This research therefore suggests that the use of the Campbell model in the absence of accurately measured D_s and porosity values for a study soil would be appropriate. Future research into methods to reduce shrinkage of peat during measurement and therefore allow measurement of D_s for a greater range of ϵ would be beneficial.

Introduction

Peatland environments are estimated to cover 12% of UK land area and contain 43% of UK terrestrial carbon stocks (Falloon *et al.*, 2006). Land drainage is a major threat to the continued existence of these stocks as it increases loss as carbon dioxide (CO₂) and also promotes the production of nitrous oxide (N₂O), a potent greenhouse gas (Gorham, 1991; Regina *et al.*, 1996). Studies of greenhouse gas emissions from peat soils under drought conditions suggest that CO₂ and N₂O fluxes increase after drought in response both to increased aeration (potential for aerobic microorganism activity) and a greater air-filled porosity, leading to increased gaseous transport through the soil profile (Freeman *et al.*, 1993; Knorr *et al.*, 2008). Studies have shown that greenhouse gas emissions are limited by the wettest soil layer (Turcu *et al.*, 2005; Pihlatie *et al.*, 2007) because diffusive transport of a gas through the air is 10 000 times more effective than through water (Fang & Moncrieff, 1999). For greenhouse

gases, this increased residence time can lead to the bubbling (ebullition) of large quantities of methane (CH₄) through the water-filled porosity and therefore substantial episodic emissions (Kellner *et al.*, 2006), or to increased consumption of N₂O by denitrifying bacteria adapted to anaerobic conditions (Firestone & Davidson, 1989). In order to understand the effect of drainage and related land-use changes on greenhouse gas emissions, in-profile processes of greenhouse gas production and transport must be accurately modelled under varying hydrological conditions for peatland soils. Models developed for this purpose rely on accurate physical parameters for the soils in question. The gaseous diffusion coefficient (D_s) is an important parameter to estimate the transport of gases through soil, because most gas movement is by diffusion through the air or water-filled phases (Fang & Moncrieff, 1999).

The relative diffusivity (D_s/D_0 , with D_0 the diffusion coefficient through free air) is often used instead of D_s when discussing diffusion, in order to remove the complicating factor of which gas was used to calculate D_s . However, D_s/D_0 is rarely measured and is often predicted with models that were developed for mineral soils (Iiyama & Hasegawa, 2005; Li & Kelliher, 2005). Our study

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aimed to measure D_s and calculate D_s/D_0 for a UK peatland site at a range of soil moisture contents to test the hypothesis that there is variation in D_s/D_0 for different moisture contents and soil horizons. The soil of the study site consisted of a deep peat deposit overlain by a layer of alluvial clay. This study therefore presented the opportunity to measure D_s/D_0 for both mineral and peat soil horizons and to compare these measured values with those calculated using models widely used for peat and mineral soils.

Materials and methods

Study site

The study site was a 2-ha field of wet grassland located in West Sedgemoor, Somerset (51°01.26'N, -2°55.38'W). This peatland site is managed for wetland bird conservation by the Royal Society for the Protection of Birds (RSPB) and forms part of the Somerset Levels and Moors Environmentally Sensitive Area (ESA). The peat is mainly black Altcar 1 series fen peat (Fibric Histosol), overlain by an alluvial deposit of silty clay resulting from historical flooding of the River Parrett (Findlay *et al.*, 1984). Additional information on the field site is given in Kechavarzi *et al.* (2007). For comparison, a sandy loam Crediton series soil (Dystric Cambisol) was extracted from a grassland site at Sampford Courtenay, Devon (50° 47.39'N, -3° 56.56'W).

Soil collection and moisture setting

Intact soil cores were removed from a 10 × 2 m² area of the field using 100 cm³ (5-cm diameter) stainless steel bulk density cylinders. Eighteen samples were taken from each depth increment: 5–15, 20–30 and 30–40 cm. The 0–5-cm sample was excluded in order to exclude vegetation from the cores. Eighteen cores of the sandy loam reference soil were removed from 10 to 20-cm soil depth. All cores were stored in sealed bags in a 5°C cold room until required for the experiment. Information on the physical characteristics of the cores is given in Table 1.

The soil cores were saturated by standing in a tray of free water for 3 days prior to moisture setting using tension tables or air drying. The saturated mass of the cores was recorded for use in calculating the water-filled porosity. At the end of the experiment, the soil cores were dried in an oven at 105°C and weighed to provide information for the calculation of dry bulk density, and the moisture loss from saturation was used to calculate water-filled porosity after the methods described in Rowell (1994). The total porosity was calculated from the bulk density measurements and an assumed particle density of 2.65 g cm⁻³ for mineral cores, 1.4 g cm⁻³ for peat cores and 1.57 g cm⁻³ for cores containing the clay-peat boundary (Rowell, 1994).

The soil cores were placed on tension tables that were set up according to the method of Romano *et al.* (2002). The tension tables were 100 × 40 × 7 cm perspex trays with drainage channels cut into the base. A 2.5-cm depth layer of silica flour (grade HPP6) was used as the suction substrate. Suctions of 10 and

Table 1 Average physical characteristics of cores extracted from West Sedgemoor and the reference soil

Soil characteristic	Soil location and depth			
	West Sedgemoor			Sandy loam
	5–15 cm	20–30 cm	30–40 cm	10–20 cm
Texture	Clay loam	Loamy clay	Peat	Sandy loam
Bulk density / g cm ⁻³	0.44 ± 0.020	0.40 ± 0.040	0.14 ± 0.003	1.39 ± 0.020
Porosity (ϕ) / cm ³ cm ⁻³	0.72 ± 0.004	0.75 ± 0.008	0.90 ± 0.002	0.48 ± 0.009
ε range attained / cm ³ cm ⁻³	< 0.01–0.36	< 0.01–0.38	0.06–0.32	0.13–0.66

120 cm were applied to the soils. Some cores were air dried for 2 and 5 days because, during preliminary trials, it was found that large suction (>2 m) were required to drain the West Sedgemoor soils to an ε of 0.2 cm³ cm⁻³. Moreover, 2 m was the limit of suction available on the tension tables used in this experiment. The four moisture treatments resulted in a range of ε values between 0 and 0.40 cm³ cm⁻³ for the West Sedgemoor soils and between 0.10 and 0.67 cm³ cm⁻³ for the reference soil (Table 1). Only values up to 0.50 cm³ cm⁻³ measured from reference soil cores were included in model comparison analysis because of the unavailability of corresponding large ε values for West Sedgemoor cores.

D_s measurement

D_s was measured after the method developed by Currie (1960). Sulphur hexafluoride (SF₆) was chosen as the tracer gas for this study because of its inertness, water insolubility, potential for measurement at small concentrations and negligible concentration in the atmosphere (Rudolph *et al.*, 1996; Nightingale *et al.*, 2000).

The chambers from the denitrification incubation system (DENIS) based at North Wyke Research, Devon (Cardenas *et al.*, 2003), were adapted for the purpose of this experiment to function

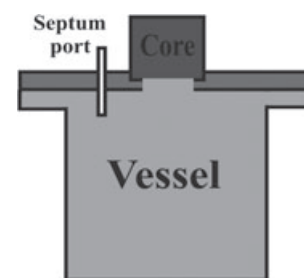


Figure 1 Schematic of the Currie (1960) apparatus. The core is a 100-cm³ stainless steel bulk density container open at both ends. The vessel is a 2-litre capacity stainless steel container with a septum port for the introduction of a tracer gas. Once the soil core is inserted on to a shelf cut into the lid and sealed in place with silicone sealant, the only way for an introduced tracer gas to escape the vessel is through the soil core.

as the Currie apparatus (Figure 1). A hole of the same diameter as the soil core was cut into the stainless steel lids of the 2-litre capacity vessels with a narrow shelf on which the soil core could sit. A septum port was fitted into the lid through which the standard could be injected and samples removed. Silicone grease was used around the join between the soil core and the vessel lid in order to seal the cores into place and to ensure the seams were gas tight. The vessels were tested for leaks using helium prior to commencement of the experiment. The modified chambers were housed in a constant temperature room at 19°C.

Twelve soil cores (three of each soil type), subjected to the same moisture-setting procedure of 10-cm suction on a tension table, were weighed and placed on the vessel lids simultaneously. The vessels were aligned in two rows of six and the soil cores were arranged at random. At the start of the experiment, 120 ml 2% SF₆ in N₂ was injected into each vessel via the septum port to achieve an approximate target starting concentration of 1400 µl l⁻¹. Two to three minutes later two 10-ml gas samples were taken from the vessel headspace and analysed. The average of these two samples represented the t=0 concentration for that diffusion vessel. The vessel headspaces were then sampled at intervals that were dependent upon the moisture treatment. The 10-cm suction and 150-cm suction cores were sampled once daily for 5 days. The 2-day air-dried cores were sampled twice daily for 1 day then daily for 4 days. The 5-day air-dried cores were sampled twice daily for 2 days. No more than 3% of the total volume of the vessel was removed by the end of the experimental period. Each sample was immediately manually injected into the gas chromatograph (GC): a Shimadzu GC-8A (Shimadzu, Columbia, USA) fitted with a thermal conductivity detector (TCD) and connected to a Spectra-Physics SP4290 integrator (Newport, Spectra-Physics Ltd, Harwell, UK). The GC was calibrated daily with an assumed linear relationship between ambient air (with a negligible SF₆ content), 0.2 and 2% SF₆ in N₂ (British Oxygen Company Gases, Guildford, UK). A 0.2% standard was also injected at the start and completion of each sampling time.

Three additional cores subjected to the same moisture treatment as the experimental cores were placed alongside the vessels. These were weighed twice daily to determine moisture loss from the experimental cores. A volume of water equal to the moisture loss calculated was added to the surface of the experimental cores to maintain initial moisture content. Where soils shrunk before the experiment, silicone sealant was inserted into the cracks and the soil re-weighed. Dry masses were taken with and without the added silicone to ensure accuracy.

The natural logs of the concentrations of SF₆ in the vessel were plotted against time for each moisture treatment. D_s was then calculated from the slope of the linear portion of this depletion curve after the method described by Rolston & Moldrup (2002). The D_0 value for SF₆ was taken to be 0.093 cm² s⁻¹ (Rudolph *et al.*, 1996).

D_s/D_0 modelling

For the purpose of comparison, the calculated D_s/D_0 values were compared with values calculated with the three widely used models of Millington & Quirk (1961), Campbell (1985) and Moldrup *et al.* (1999). The Campbell (1985) model is given as:

$$D_s/D_0 = a(\varepsilon^b), \quad (1)$$

where ε is the air-filled porosity (cm³ cm⁻³) and a and b are coefficients for pore tortuosity and pore size distribution, respectively. Commonly used values for a and b are 0.9 and 2.3, respectively (Campbell, 1985; Price *et al.*, 2004; Li & Kelliher, 2005). The Millington & Quirk (1961) model is:

$$D_s/D_0 = \varepsilon^{10/3}/\varphi^2, \quad (2)$$

where ε is the air-filled porosity (cm³ cm⁻³) and φ is the total porosity (cm³ cm⁻³). Finally, the Buckingham-Burdine-Campbell (BBC) model (Moldrup *et al.*, 1999) is:

$$D_s/D_0 = \varphi^2 (\varepsilon/\varphi)^{(2+3/b)} \quad (3)$$

Statistical analyses

All statistical analyses were carried out using Genstat (13th edition, 2010). In order to calculate the linear portion of the SF₆ depletion curve a 'line plus exponential' model was fitted to the data. In some saturated cores, a model could not be fitted because SF₆ in the vessel was not depleted. In these cases D_s was assumed to be 0. Genstat was also used to calculate D_s and generate the standard error for both the calculation and the model fit. Where the generated standard error from the calculation was greater than 10%, this D_s value was not used in further calculations. Lin's concordance (Lin, 1989, 2000) analyses were used to examine the agreement between measured and modelled values of D_s after techniques described by Dhanoa *et al.* (1999).

Results and discussion

Measured values for D_s and D_s/D_0

Values of D_s for the peat cores (30–40 cm) ranged between 3.2×10^{-4} and 4.4×10^{-3} m² hour⁻¹, for the peat/clay cores (20–30 cm) ranged between 0 and 4.1×10^{-3} m² hour⁻¹ and for the loamy clay cores (5–15 cm) ranged between 0 and 4.7×10^{-3} m² hour⁻¹. The sandy reference soil had values of D_s between 5.4×10^{-4} and 3.4×10^{-3} m² hour⁻¹ for ε up to 0.5 cm³ cm⁻³, and D_s up to 7.4×10^{-3} m² hour⁻¹ at ε up to 0.7 cm³ cm⁻³ (Figure 2). The D_s values were within similar ranges for all cores at ε up to 0.5 cm³ cm⁻³ and increased with increasing ε . The D_s/D_0 values between 0 and 0.16 (Figure 3) were within ranges previously found in the literature (Rudolph *et al.*, 1996; Caron & Nkongolo, 2004; Iiyama & Hasegawa, 2005).

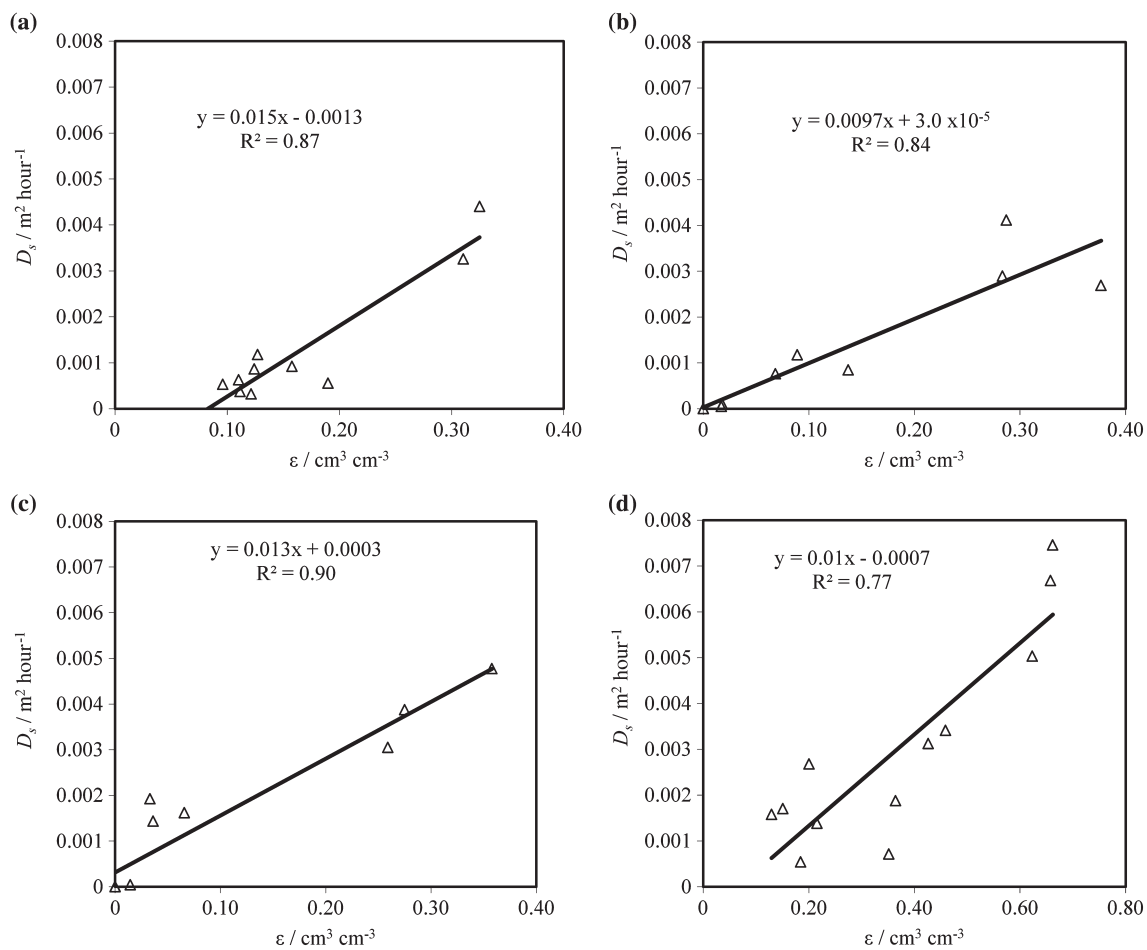


Figure 2 Triangles represent measured D_s values ($\text{m}^2 \text{hour}^{-1}$) for (a) 30–40 cm peat, (b) 2–30 cm clay/peat, (c) 5–15 cm clay loam and (d) the sandy loam soil plotted against ε . A best-fit linear regression line is also shown in the figures.

The spread of D_s values for a similar ε may indicate that the Currie method will not allow an accurate detection of small D_s values (Figure 2). This is particularly an issue for the sandy soil (Figure 2d). This may be because a moisture gradient inside the soil core forms or there is shrinkage associated with drying of peat soils whilst on the diffusion apparatus and therefore the difficulty of accurately estimating ε for the whole core (Rolston & Moldrup, 2002; Allaire *et al.*, 2008). Attempts were made to reduce the effects of moisture loss on ε by adding water during the experiment; cores lost between 2 and 23% (typically 8%) of their starting moisture content during the course of the experiment. The greatest amount of moisture was lost from the saturated sandy soil cores. Caron & Nkongolo (2004) proposed that accurate measurements of soil moisture within a core (in their case using TDR probes) with a suitable model for D_s/D_0 may be more useful than D_s/D_0 measurement. Improvements to D_s measurement methodology that targets the prevention of moisture gradient formation would be beneficial. In order to prevent a moisture gradient forming, the core would have to be on the apparatus for less time and therefore a two-chamber

approach would be required with the soil core closed to the atmosphere and a system in place to ensure rapid flow of tracer gas through the core from the injection chamber to the measurement chamber (Bonroy *et al.*, 2011). Alternatively, humidified air could be passed continually over the surface of a core open to the atmosphere (Rolston & Moldrup, 2002), although this would require careful monitoring to ensure that the humidity is suitable. Complementary measurements to characterize the distribution of tracer gas inside a larger core with an established moisture gradient (Allaire *et al.*, 2008) would provide useful information on how gases move within soils that is applicable to field conditions.

Comparison of measured and modelled D_s/D_0

The agreement between measured and modelled values of D_s/D_0 varied with soil type (Figure 3). At air-filled porosities close to zero, the measured D_s/D_0 values for all soils were often larger than those predicted by modelling, perhaps as a result of the difficulties with drying during these experiments. For all soils the best fit was with the Campbell (1985) model (Table 2).

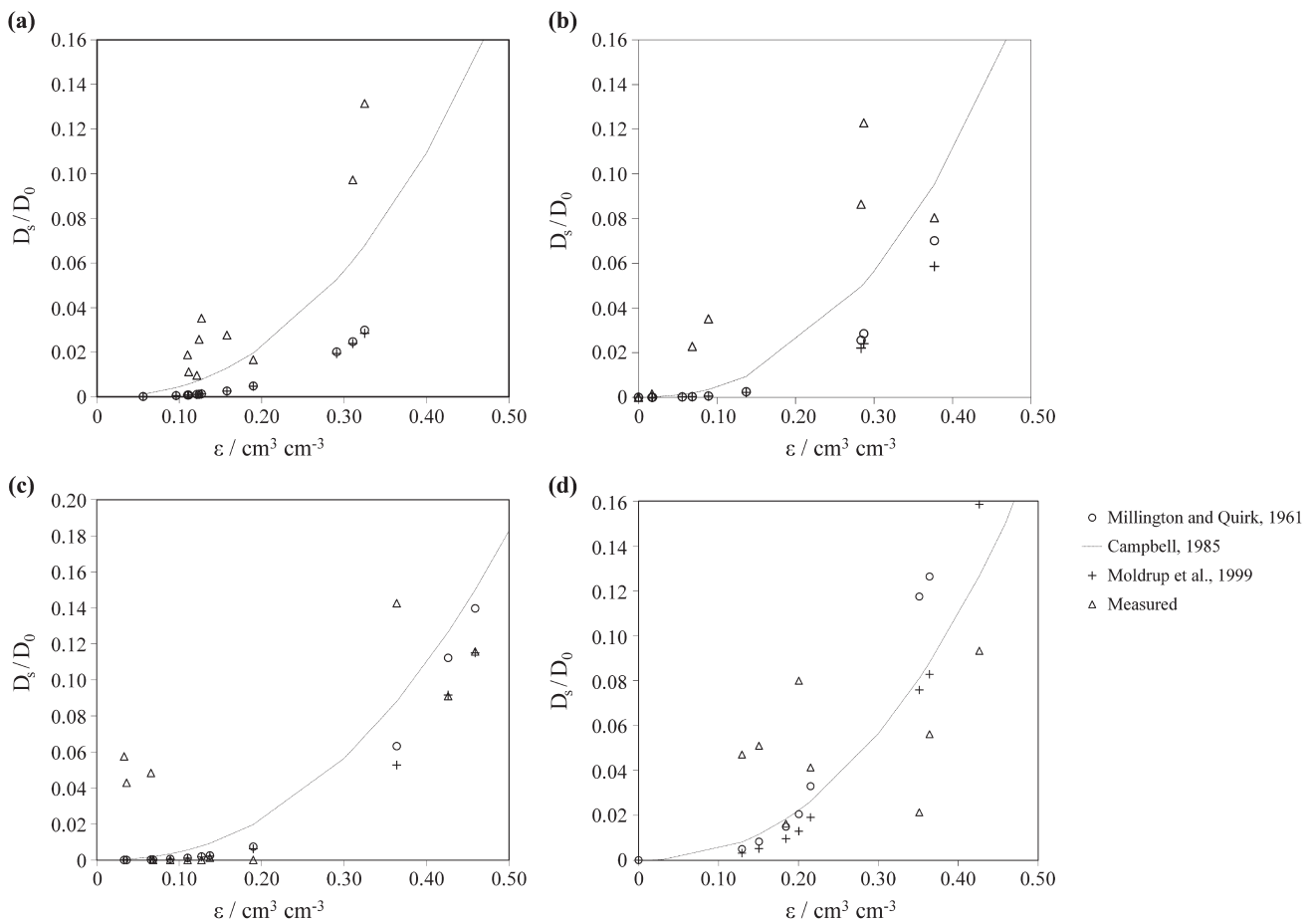


Figure 3 Modelled and measured D_s/D_0 values for (a) 30–40 cm peat, (b) 20–30 cm clay/peat, (c) 5–15 cm clay loam and (d) the sandy loam soil plotted against ϵ .

This model provided the best fit despite the reliance on standard coefficients for a and b ; however, the model is widely used in the literature (Dunfield *et al.*, 1995; Price *et al.*, 2004; Li & Kelliher, 2005). The poor fit with the Millington & Quirk (1961) and Moldrup *et al.* (1999) models may have resulted from the difficulties associated with calculating an accurate porosity for peat and clay soils. This supports the use of the Campbell (1985) model for these soils in the absence of accurate porosity values.

The use of models to provide the D_s/D_0 of a soil is widespread in the literature, particularly as interest has developed in the use of Fick's Law:

$$F = -D_s (dx/dz), \quad (4)$$

where F is the gaseous flux ($\text{mg m}^{-2} \text{day}^{-1}$), D_s is the diffusion coefficient of study soil ($\text{m}^2 \text{day}^{-1}$), x is the measured or estimated concentration of target gas (mg m^{-3}) and z is the soil depth (m) for greenhouse gas flux determination (Li & Kelliher, 2005; Pingintha *et al.*, 2010). Many such studies suggest that reliance on modelled D_s/D_0 is a potential source of significant error in their gradient calculations (Jassal *et al.*, 2005; DeSutter *et al.*, 2008). These are

Table 2 Lin's concordance coefficient^a for each modelled D_s/D_0 compared with the measured D_s/D_0

Soil (depth)	Model		
	Millington & Quirk (1961)	Moldrup <i>et al.</i> (1999)	Campbell (1985)
Loamy clay (5–15 cm)	0.75	0.70	0.79
Clay/peat (20–30 cm)	0.40	0.35	0.62
Peat (30–40 cm)	0.30	0.29	0.71
Sandy loam	0.31	0.49	0.52

^aLin's concordance coefficient is a measure of the degree of agreement between two continuous variables that takes into account both correspondence between the two variables and divergence from the 1:1 agreement line. A value of 1 indicates perfect agreement and a value of 0 indicates an absence of concordance.

strong cases for providing, at the very least, a benchmark soil-specific D_s with which to compare modelled values before using the gradient method. The D_s values generated by our research provide such information for a UK lowland peatland environment. Although there was uncertainty as a result of drying and shrinkage,

the Currie method provides a simple and inexpensive approach to attaining measurements and informing the choice of model for such environments. In order to verify the use of D_s/D_0 models at ε greater than 0.5, some of the difficulties associated with providing cores at larger values of ε would need to be addressed. The future of D_s measurement is likely to lie in two-chamber methods with automated systems in place to ensure accuracy and provide measurements more quickly, reducing the possibility of moisture gradient formation in the soil core (Bonroy *et al.*, 2011).

Conclusion

This study reported values of D_s and D_s/D_0 for the West Sedgemoor study soil within the ranges reported for other soils. The Currie method was a successful method for D_s determination; variability in the results may be explained by moisture losses during the experiment or difficulties in attaining an accurate porosity value for clay and peat. The results of this experiment suggest that the Campbell (1985) model is reliable in predicting D_s/D_0 within a ε range of 0 to $0.5 \text{ cm}^3 \text{ cm}^{-3}$; however, further research using a closed chamber, automated system for D_s/D_0 measurement (Bonroy *et al.*, 2011) would be useful to determine the accuracy of models for ε outside of this range. This would be particularly useful for peat and clay soils as the shorter time required for measurement would reduce difficulties associated with moisture loss and shrinkage. Further research into the importance of soil type as a control of gas movement through the profile of peatland soils, conducted at a greater range of air-filled porosities, would be useful to further clarify the findings of the present study. Such research will provide valuable information for use in studies examining transport of greenhouse gases through peatlands and inform the development of models to estimate greenhouse gas loss in future climates.

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