Role of recent climate change on carbon sequestration in peatland systems

*Dr Paul H. Lunt, Prof. Ralph M. Fyfe and Dr Alan D. Tappin

* Corresponding author. School of Geography, Earth and Environmental Science, Portland Square, Drake Circus Plymouth University, Plymouth, Devon PL4 8AA. paul.lunt@plymouth.ac.uk. 01782 584580

Highlights

- Mean rates of carbon accumulation since 1850 were 11.26 t ± 0.68 t CO_2e ha^{-1} yr^{-1} for valley mire and 11.77 t ± 0.88 t CO_2e ha^{-1} yr^{-1} for blanket bog
- Contemporary rate of CO_2 sequestration was 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1}
- Past and contemporary peatland carbon sinks were found to be at the upper limits of those reported in the literature
- Recent changes in climate appear to have had minimal impact on the strength of peatland carbon sinks in South West England

Abstract

This paper provides information on the impact of recent climate change on carbon sequestration in peatland systems in South West England. This is important because peatlands have the potential to sequester and hold large quantities of anthropogenically released CO_2. This paper investigates whether there has been a reduction in the strength of carbon sinks in a valley mire and blanket bog; which occur on the limits of the biogeographical envelop for peatlands in Britain. Past rates of carbon accumulation were determined from peat depth and the sequential analysis of peat age, bulk density and carbon content from cores taken from valley mire and blanket bog. At the valley mire site contemporary net ecosystem carbon balance (NECB) was calculated by measuring inputs to the peat body, via net primary productivity (NPP), of *Sphagna*. Losses of C from the peat body were calculated by measuring CH_4, and aquatic carbon; calculated from catchment export of particulate and dissolved organic carbon. The study found similar mean rates of carbon accumulation since 1850 of 11.26 t ± 0.68 t CO_2e ha^{-1} yr^{-1} (307 g C m^{-2} yr^{-1}) in valley mire and 11.77 t ± 0.88 t CO_2e ha^{-1} yr^{-1} (321 g C m^{-2} yr^{-1}) in blanket bog. The mean present-day CO_2 sequestration rate for *Sphagna* on valley mire was calculated to be 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} (249 g C m^{-2} yr^{-1}). Both past and contemporary rates of CO_2 sequestration were found to be at the upper limits of those reported in the literature for temperate peatlands. NPP was found to vary according to microform with higher rates of carbon sequestration found in lawn and hummock microforms compared with pools. Our work suggests that recent changes in the climate appear to have had limited impact on the strength of peatland carbon sinks in South West England.

Key Words

CO_2 sequestration; peatlands; *Sphagnum*; net ecosystem carbon balance; climate change; peat accumulation

The authors use the term net ecosystem carbon balance (NECB), as defined in Chapin *et al.*, (2006) to describe carbon uptake in peatlands. All values for carbon are presented as CO_2 equivalents (t CO_2e ha^{-1} yr^{-1}), where carbon (C) is converted to CO_2 based on molecular mass difference by multiplying the amount of C by 3.667. Where values are cited from the literature the original units are reported, along with converted values in t CO_2e ha^{-1} yr^{-1} for comparison. 'Carbon accumulation' refers to carbon accumulated as peat. The term 'Carbon exchange' has been used where CO_2 fluxes have been measured. 'Carbon balance' is the difference between CO_2 uptake by the peatland ecosystem (photosynthesis) and CO_2 loss to the atmosphere by respiration. ‘Carbon sequestration’ refers to is the removal and storage of carbon from the atmosphere in peat.

1.0 Introduction

Peatlands have the highest carbon storage capacity per unit area of all terrestrial ecosystems (Brooks & Stoneman, 1997; Worrall *et al*. 2009; Yu *et al*. 2011b). Cox *et al*. (2000) estimated globally that 60 gigatonnes of carbon (Gt C) are removed each year from the atmosphere by NPP of photosynthetic plants. Known peatlands are estimated to cover 3–4% of the world’s land area (Gorham, 1991; Parish *et al*. 2008; Xu *et al*. 2018) and contain ~612 Gt C (Yu *et al*. 2011b). Variation in the size of the peatland carbon sink could have a significant cumulative effect on global atmospheric CO_2 concentrations (Chambers & Charman, 2004; Charman *et al*. 2013). Estimates of global carbon accumulation by peatlands vary from 0.09 to 0.5 Gt C yr^{-1} (Gorham, 1991; Yu, 2011a). These figures represent 1–5% of global annual anthropogenic greenhouse gas (GHG) emissions (Friedlingstein *et al*. 2014). Globally, appropriate protection and management of peatlands is one of the most cost-effective measures in reaching the ultimate goal of zero net carbon emissions from the land-use management sector (Ostle *et al*. 2009).

Peatlands cover 24,600 km^2 or ~15% of the land area and store 2.3–3.12 Gt C in the UK (Billett *et al*. 2010; Lindsay & Clough 2017). Peatlands have the potential to sequester and hold large quantities of anthropogenically-released atmospheric CO_2, making a significant contribution to international GHG budgets (Waddington *et al*. 2010; Bain *et al*. 2011; Yu, 2011a). Research on rates of carbon sequestration on peatlands has focused on two approaches: contemporary gaseous exchange of CO_2 using eddy covariance measurements (Billett *et al.* 2010; Helfter *et al.* 2015; Levy & Gray 2015; Wilson *et al.* 2016) and Holocene rates of carbon accumulation established from peat cores (Pendea & Chmura 2012; Charman *et al*. 2013). Chamber studies have also been widely used in the UK and elsewhere to investigate net carbon balance (Rowson *et al*. 2010; Dixon *et al*. 2014; Gatis *et al*. 2015; Green *et al*. 2018).

Net ecosystem carbon balance (NECB: Chapin *et al*. 2006) models can be used to assess contemporary rates of carbon gain and loss from peatlands. In recent years there has been a significant amount of work to understand the factors effecting site-level NECB values. Dinsmore *et al.* (2010) found contemporary site-level NECB of 3.52 t CO_2e ha^{-1} yr^{-1} (352 g CO_2 m^{-2} yr^{-1}) in a UK ombrotrophic peatland whilst Billett *et al.* (2010) report contemporary site-level NECB in two ombrotrophic peatlands of 2.05–2.64 t CO_2e ha^{-1} yr^{-1} (56-72 g C m^{-2} yr^{-1}). Values reported for NECB in boreal and northern continental peatlands of the Northern Hemisphere are typically at the lower end of the range reported for undisturbed peatlands at 0.79 t CO_2e ha^{-1} yr^{-1} (21.5±39.0 g C m^{-2} yr^{-1}) (Roulet *et al*. 2007; Payne *et al.* 2016). These findings suggest that there is a great deal of variability in NECB due to latitude and geographical location as well as mire community type (Billett *et al*. 2010; Dinsmore *et al.* 2010; House *et al.*, 2010; Koehler *et al*. 2011).

Gorham (1991) estimated mean rates of accumulation of 0.84 t CO_2e ha^{-1} yr^{-1} for boreal and subarctic peatlands during the Holocene based on peat cores and these values are broadly similar to NECB for boreal and northern continental peatlands. In Canada, Roulet *et al.* (2007) compared contemporary carbon exchange with apparent C accumulation over 3000 years and found similar levels of carbon accumulation in contemporary site-level net ecosystem C exchange (0.78 t ± 1.43 t CO_2e ha^{-1} yr^{-1}) and dated peat cores (0.8 t ± 0.1–0.51 ± 1.37 t CO_2e ha^{-1} yr^{-1}). In spite of this apparent agreement there is a great deal of variability in rates of peat accumulation from peat cores in response to climate and geographical location (Belyea & Clymo, 2001). For example, Belyea and Malmer (2004) report values between 0.51–2.64 t CO_2e ha^{-1} yr^{-1} (14-72 g C m^{-2} yr^{-1}), with higher rates associated with climatic optima during periods of higher temperatures and rainfall. Levy and Gray (2015) found that the contemporary carbon sink in blanket bog in northern Scotland was larger than estimates from local peat cores, based on peat accumulation over the last several thousand years. Whilst mean rates of carbon accumulation across Holocene time scales appears to match contemporary carbon exchange we can observe significant variation through the course of the Holocene [illustrated by Belyea & Malmer, 2004], with variation in carbon sequestration controlled by changes in net primary productivity forced by temperature and cloudiness variability (Charman *et al*. 2013).

Net primary productivity (NPP) is by far the largest constituent of a NECB model in an active peatland (Moore *et al*. 2002; Nilsson *et al*. 2008; Billett *et al*. 2010). Koehler *et al*. (2011) measured components of site-level NECB over a six year period in an ombrotrophic mire in southern Ireland, and found mean annual carbon uptake was 29.7±30.6 (±1 SD) g C $m^{-2}yr^{-1}$ (1.09 t ± 1.12 t (± 1 SD) CO2e $ha^{-1}yr^{-1}$). The main components of their NECB were as follows: carbon uptake in CO_2 from the atmosphere was 47.8±30.0 g C $m^{-2}yr^{-1}$ (1.75 t ± 0.01 t CO2e $ha^{-1}yr^{-1}$); carbon loss as CH_4 was 4.1±0.5 g C m^{-2} yr^{-1} (0.15 t ± 0.018 t CO2e $ha^{-1}yr^{-1}$); and the carbon exported as stream-dissolved organic carbon (DOC) was a loss of 14.0±1.6g C m^{-2} yr^{-1} (0.51 t ± 0.059 t CO2e $ha^{-1}yr^{-1}$). For two out of the six years, the site was a source of carbon with the sum of CH_4 and DOC flux exceeding the carbon sequestered as CO_2.

In northern peatlands, *Sphagnum* mosses dominate the surface cover of pristine, ombrotrophic bogs and often account for a significant proportion of past accumulated peat. S*phagnum* productivity is controlled by mean annual temperature, precipitation and photosynthetically active radiation (PAR) (Gunnarsson, 2005; Loisel *et al*. 2012; Nijp *et al*. 2015). As previously outlined, Charman *et al*. (2013) found that total carbon accumulated over the last 1000 years is linearly related to growing season length and PAR, demonstrating changes in peat body carbon sequestration with climatic change. Climate change alters rates of carbon sequestration primarily through changes in the frequency and amount of precipitation and secondarily via temperature. Increased mean seasonal temperatures have positive impacts by increasing the length of the growth season and negative impacts by increasing rates of microbial decomposition and evapotranspiration. Blanket bog is a globally restricted peatland habitat confined to cool, high rainfall, typically flat upland areas with low levels of evapotranspiration. In Europe this habitat type typically occurs in oceanic climates along the Atlantic coast of the UK and Ireland with southern limits in Brittany and northern Spain (Joosten *et al.* 2017). It has been suggested that future climatic changes will result in a contraction of the distribution of active blanket bog in the UK towards the north and west, and outside this distribution peatlands may cease active growth (Gallego-Sala *et al*. 2010; Gallego-Sala & Prentice, 2013). An understanding of recent changes in rates of carbon sequestration in regions such as South West England, indicated as marginal to growth, is therefore vital to our understanding of how sensitive these peatlands are to present and future climate change.

This paper addresses the challenge of understanding the impact of recent climatic change in a potentially marginal blanket bog setting (the southwest UK uplands) by adopting a NECB approach and comparing current rates of CO_2 sequestration in *Sphagnum*-dominated south-west UK temperate peatlands to CO_2 equivalent, carbon accumulation rates that occurred at the same sites over the last 160 years and relating these findings to instrumental records of climate change over this period.

1.1 Study site description

Dartmoor represents the largest extent of blanket mire in southern England with an estimated 158 km^2 of peat having a depth greater than 0.4 m (Gatis *et al*. 2019). The upland is composed of an eroded granite plateau, of elevation range 300–623 m, with an annual mean temperature of 8° C at 400 m. Mean monthly air temperatures range from 0.8° C (Feb) to 17.7° C (July) with a mean rainfall of 1974 mm yr^{-1} and ca. 180.9 days of rainfall (> 1 mm), (Met Office 2017: 1971–2000 averages). All months have an average of over 100 mm rainfall, with the four wetter months over 200 mm.

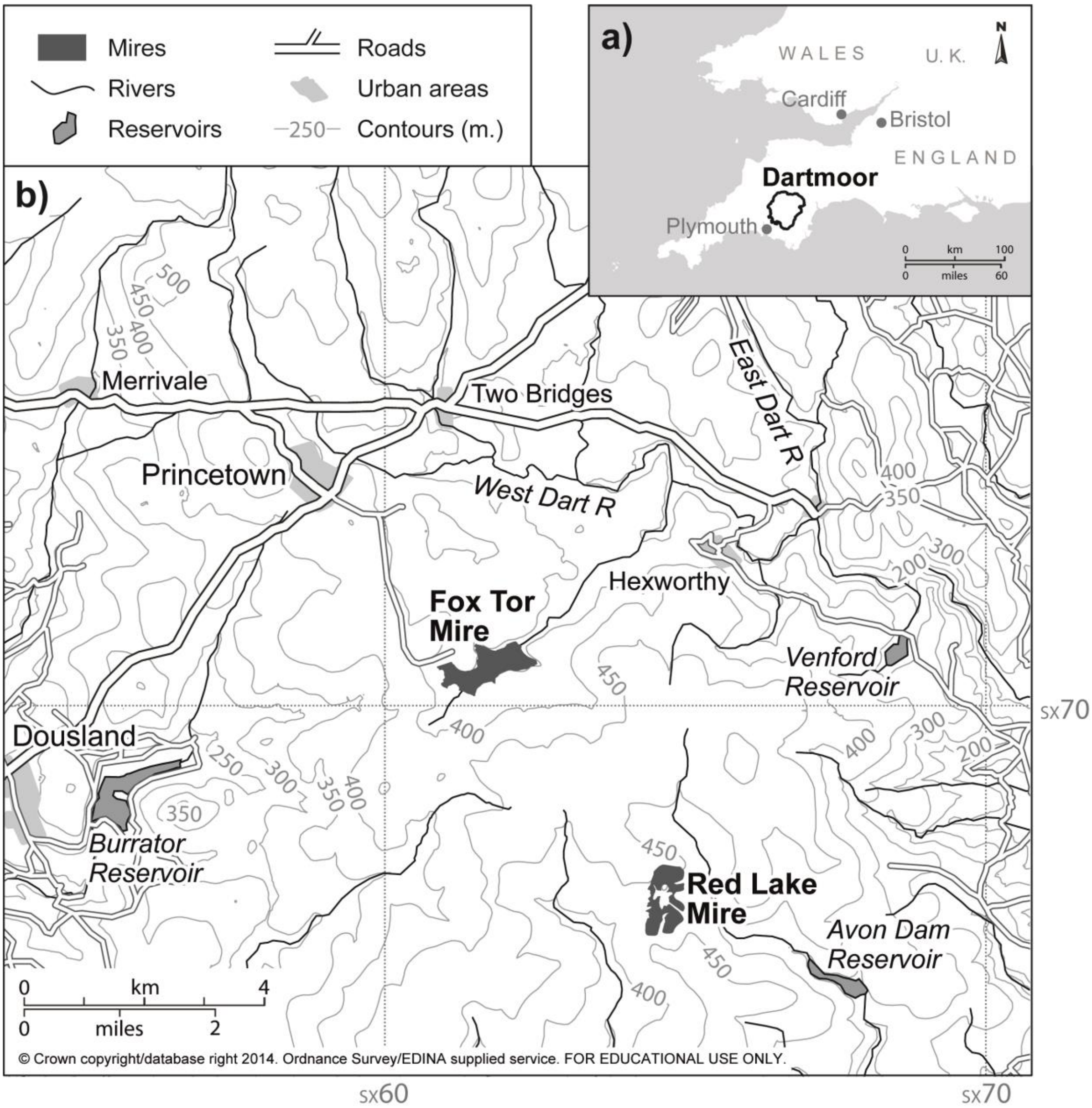

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Fig. 1 (a) Regional map showing the location of Dartmoor within South West England; (b) Locations of Fox Tor Mire and Red Lake Mire study sites

Footnote *Fox Tor Mire provided the inspiration for Arthur Conan Doyle's fictional Grimpen Mire, in the Sherlock Holmes story, The Hound of the Baskervilles.*

Data were collected from two contrasting intact mire sites on Dartmoor, Fox Tor Mire and Red Lake (Fig. 1). Fox Tor Mire is a valley mire, with a 58.3 ha peat body, located 4 km south-east of Princetown (50.517°N, 03.956°W) at an elevation of 351 m. Almost all of the previous peat deposits at Fox Tor Mire were removed during commercial peat mining operations which ceased in the 1850s (Wright, 1884). A layer of mine washings occurred at the base of the peat column, which was dated to a period of extensive mining at White Works on the periphery of the mire, in 1876 (Wright, 1884). All subsequent peat developed in the period following 1876. Plant communities are intermediate between soligenous and ombrogenous mire. Sample areas were permanently saturated and *Sphagnum*-dominated, consisting primarily of National Vegetation Classification (NVC) communities M15b and M6, *Scirpus cespitosus–Erica tetralix* wet heath and *Carex echinata-Sphagnum fallax/denticulatum* mire (Rodwell, 1991). The three dated peat cores were taken from separate areas with surface vegetation typical of nutrient poor fen, constant species included *Eriophorum angustifolium, Sphagnum papillosum, Sphagnum fallax, Sphagnum denticulatum, Molinia caerulea and Menyanthes trifoliata*.

Red Lake Mire is a precipitation-only ombrotrophic blanket bog, situated 8.5 km south-east of Princetown, (50.488°N, 03.910°W) at an elevation of 470 m. The main vegetation community consists of *Scirpus cespitosus–Eriophorum vaginatum* blanket mire (NVC code M17) with a *Sphagnum* base layer overlying a hummock and hollow microtopography. Peat cores were taken from an area to the north of Red Lake, with an intact primary bog surface. Ground and

LIDAR observations showed several drainage ditches local to the area which were infilled with peat-forming vegetation. *Sphagna* were present in all quadrats, with *S. papillosum* (87%) and *S. cuspidatum* (61%) *having the highest abundance. Other constant species included Eriophorum angustifolium* (85%), *E. vaginatum* (71%), *Narthecium ossifragum* (71%) and *Trichophorum cespitosum* (59%).

2.0 Methods

2.1 Measurement of past rates of carbon accumulation

Apparent past rates of carbon accumulation were determined for Red Lake Mire (blanket bog) and Fox Tor Mire (valley mire) using a multi-technique approach on replicate peat cores, extracted using a 5 cm diameter semi-circular Russian peat corer.

Three cores were extracted from three separate areas of Fox Tor Mire. Cores were ~ 150 cm in length and consisted of the entire column of peat, down to the mineral layer. Cores were dated using sequential analysis of concentrations of Spheroidal Carbonaceous Particles (SCPs), combined with the presence of a definitive alluvial deposit dated to 1876.

In addition to the three cores taken for SCP analysis, a further 20 cores were extracted from across Fox Tor Mire. Mean rates of peat accumulation on these cores were determined by the presence of an alluvial mineral layer, widely deposited at the base of peat cores by washings, from the White Works mine on the periphery of the mire. This layer provided a definitive marker dated to 1876.

At Red Lake Mire, four 100 cm long cores were extracted from three separate unmodified active mire areas. Three cores were dated using sequential analysis of SCPs, combined with X-Ray Florescence (XRF) readings and a fourth core was dated using known peaks in the radionuclides ^{210}Pb and ^{137}Cs.

2.1.1 Dating ranges using Spheroidal Carbonaceous Particles (SCPs)

Analysis of SCPs was the principal method used to obtain dates and dating ranges (Swindles, 2010). SCP analysis was undertaken on cores following the method outlined by Rose *et al*. (1995). Peat cores were cut into 2 cm segments at 5 cm intervals throughout their depths. SCP densities and linear accumulation rates were calculated for individual segments down the core.

Laboratory protocol for measurement of bulk density and calculation of ash-free carbon content (g C cm^{-3}) followed the method outlined by Chambers *et al*. (2011). Bulk density (g cm^{-3}) was determined by measuring the dry weight (g) divided by fresh sample volume (cm^3). To increase accuracy, sample volumes were measured by water displacement following the method set out by Buffam *et al.* (2010). Samples were oven dried (100° C) to constant weight and ashed in a furnace at 550° C for 4 hours to determine ash-free dry weight and organic matter content (Chambers *et al.* 2011). Ash-free carbon content (g C cm^{-3}) was calculated by multiplying the bulk density by 51% (mean % fraction of ash-free carbon for *Sphagnum* peat). Carbon masses were up-scaled to t C ha^{-1} cm^{-1}, and converted to CO_2 (t CO_2e ha) (using a carbon mass to CO_2e multiple of 3.667), which was then multiplied by the average accumulation rate (cm yr^{-1}) to produce the average CO_2 accumulation rate (t CO_2e ha^{-1} yr^{-1}) (Pendea & Chmura, 2012).

Equation: Peat Accumulation Rate (AR) in cm yr^{-1}

$$AR = D \div T$$

Where *D* is distance between date markers (cm) and *T* is time between date markers.

CO_2 Accumulation Rate (CO_2AR) in t CO_2e ha^{-1} yr^{-1}

$$CO_2AR = BD \times 0.51 \times 3.667 \times AR \times 100$$

Where BD is Bulk Density (g cm^{-3})

2.2 Estimates of contemporary rates of net ecosystem carbon balance in *Sphagnum*-dominated valley mire

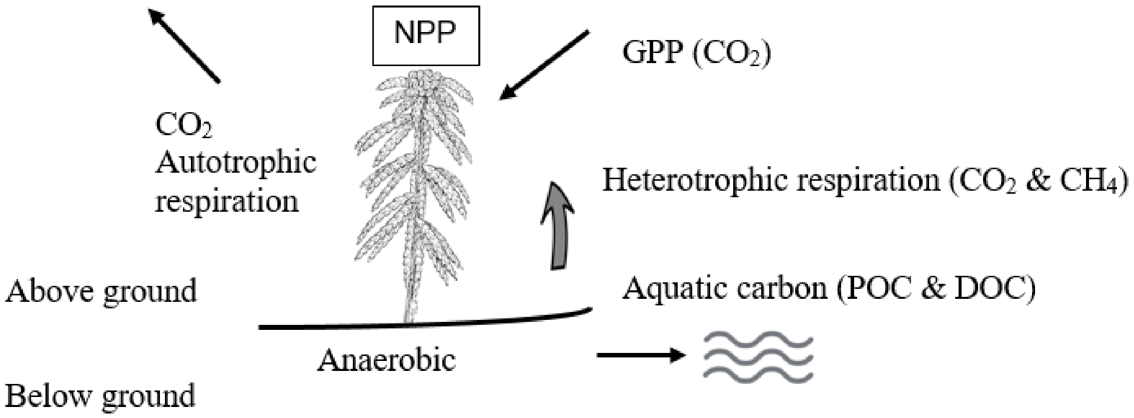

Fig. 2 Schematic representation of peatland carbon exchange. *Net Primary Productivity (NPP) = Gross Primary Productivity (GPP) – Ecosystem Respiration (ER). ER = autotrophic respiration + heterotrophic aerobic respiration + heterotrophic anaerobic respiration.*

Greenhouse gas (GHG) balance measurements, calculated for Fox Tor Mire, were used to produce a model for contemporary net ecosystem carbon balance (NECB). The NECB balance of a peat body is measured by quantifying the amount of gaseous and aquatic C gained or lost (fluxes) per surface unit area (Fig. 2). Values calculated for *Sphagnum* NPP were used as estimates of CO_2e inputs in the peatland model. Export of carbon from the peatland model occurs via methane (CH_4) emissions and aquatic carbon pathways (Fig. 2).

2.2.1 Model Formula

Net ecosystem carbon balance NECB = NPP (CO_2 assimilation based on *Sphagnum* growth) - Carbon losses as aquatic DOC & POC – carbon losses as CH_4 and CO_2*

* No measure was taken of direct losses of CO_2 from the peat body resulting from aerobic heterotrophic respiration. Average values for ombrotrophic sites have been used from the literature to quantify potential losses from heterotrophic aerobic respiration (Section 4.4).

2.2.2 Measurement of *Sphagnum* growth and net primary production

Measures of annual increase in *Sphagnum* stem lengths, over a two year period, were used to calculate NPP and provide estimates of present-day levels of CO_2e sequestration. Single-species stands of aquatic and terrestrial *Sphagna* were harvested from replicate 100 cm^2 (1 dm^{-2}) sample areas in December 2012 and 2013. The current year's annual growth was separated from the previous year's growth at the point of 'growth shut down', denoted by a kink in the stem and aggregation of stem branches (Clymo, 1970). Arising's were dried to constant mass, ground to a fine powder and the carbon content analysed in a CHN Elemental Analyser (EA1110). Carbon density was derived by multiplying dry weight (g cm^{-2}) by the carbon content measured for individual species samples. In addition, mean annual increase in stem length (cm yr^{-1}) and mean stem density (number of capitula dm^{-2}) was calculated and presented for each *Sphagnum* species.

2.2.3 Export of aquatic carbon

Continuous stream discharge flow rates were measured for the stream which drained the Fox Tor Mire *Sphagnum* and methane sample sites. Automated samples of drainage water were collected during the summer of 2011, under storm flow and base flow conditions to determine export of DOC and particulate organic carbon (POC). DOC was analysed using a Shimadzu TOC 5000a analyser coupled to an ASI 5000A auto-sampler and a Sievers NCD 255 Detector. POC was collected on filter paper and analysed using a CHN Elemental Analyser (EA1110). The concentrations of DOC and POC, over the monitoring period, were multiplied by the associated stream discharge (Q) to provide continuous load data in mg s^{-1}.

Summer values for continuous load were used to estimate annual load by multiplying mean daily load by the annual discharge (Hope *et al.* 1994). Flux was calculated by dividing load by the peatland area (58.3 ha), giving the flux as Total Organic Carbon (TOC).

2.2.4 Methane emissions associated with *Sphagnum*-dominated microforms

Methane emissions were collected over lawn, pond and hummock microforms, using static chambers, during the summers of 2014 and 2015. Chambers, consisting of transparent 4.5 L PET plastic demijohns with a footprint of 130 mm^2 and a total headspace of ca. 4 L were levelled and inserted into the peat or water surface to a depth of 5 cm (Moore & Roulet, 1991). Floatation aids were attached to the sides of the chambers that were to be placed in the pool microform. Temperatures in the chamber headspace were not dissimilar to ambient temperature, which ranged from 8-24^0C.

A total of 15 chambers were positioned, five replicates over each microform and weekly samples taken. Chambers were fitted with sample points and extracted gas transferred to the laboratory for analysis in sterile vacuum sample bags. Accumulated gas was analysed using a Bruker IFS-66 spectrometer and Fourier Transform Infrared (FT-IR) analysis (as described by Christian *et al*, 2014). Outputs from the FT-IR were calibrated using a series of known concentrations of CH_4. Methane values were converted from a volume to a mass using the Ideal Gas Law $PV = nRT$; where P = atmospheric pressure (Pa), V = volume (m^3), n = molar mass (g mol^{-1}), R is the ideal gas constant (m^3 Pa K^{-1} mol^{-1}), and T = temperature of the gas (K). CH_4 fluxes were converted to CO_2 equivalent values (t CO_2e ha^{-1} yr^{-1}) using a global warming potential (GWP) of 28 times that of CO_2 over a 100 year period (Myhre *et al*. 2013).

2.3 Statistical Analyses

All statistical comparison ($P \leq 0.05$) of rates of carbon sequestration between sites and between past and contemporary periods were evaluated using Kruskal-Wallis and Mann-Whitney *U*-tests. Site measures of central tendency and variation are reported as mean ± standard error (SE) with replicate numbers (n) unless otherwise indicated.

3.0 Results

3.1 Past rates of CO_2 accumulation in valley mire and blanket bog

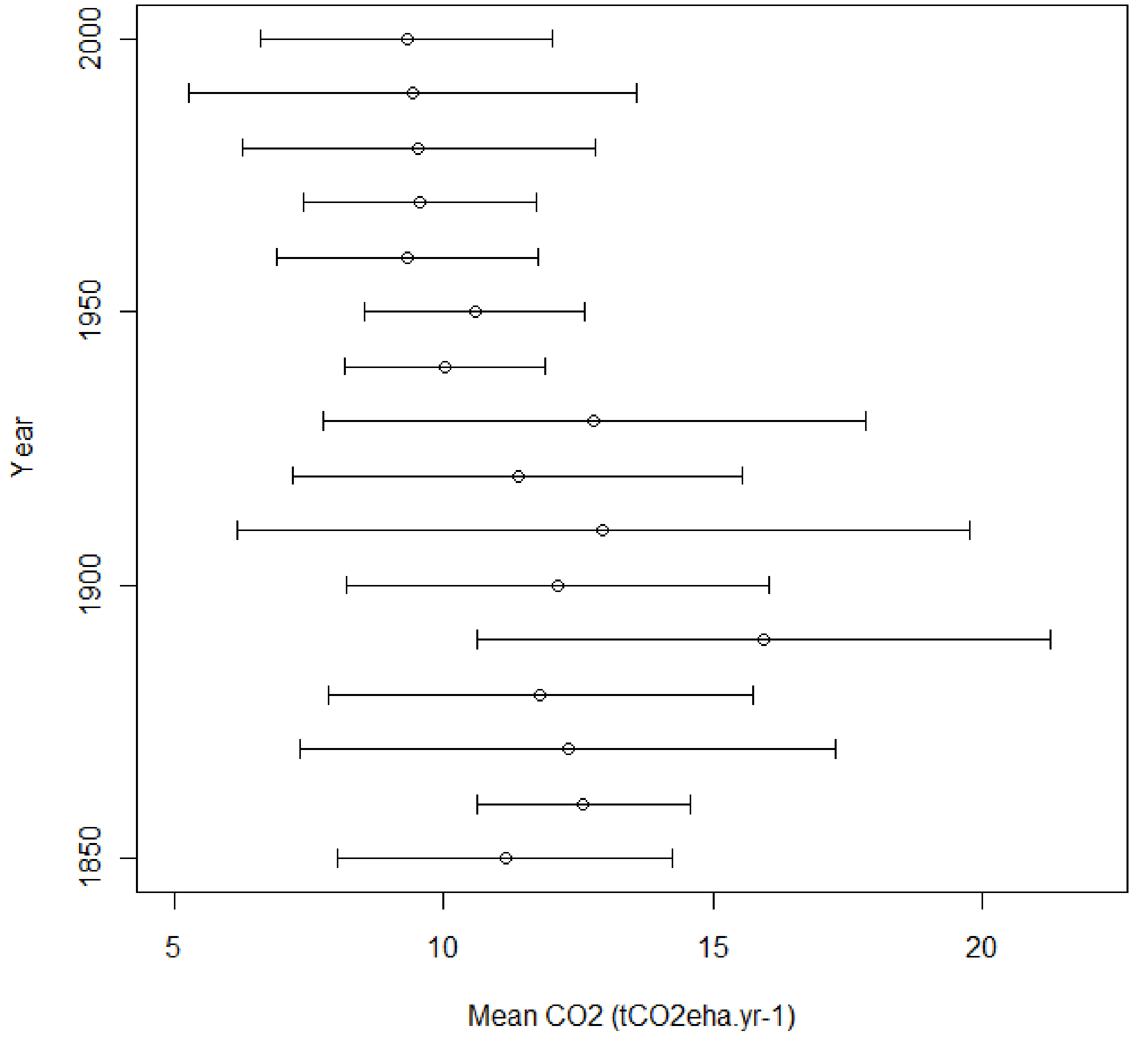

Fig. 3 Past rates of carbon accumulation (expressed as CO_2e) at the valley mire site (1850–2010). *Data were obtained from Fox Tor Mire, Dartmoor, via sequential analyses of carbon densities in peat core segments dated using SCP techniques. Values represent the means of three cores taken in 2011. Error bars represent ± 1 standard deviation.*

Mean rates of CO_2 accumulation in the valley mire (Fig. 3) appear stable around 12 t CO_2e ha^{-1} yr^{-1} until 1930. Fig. 3 shows a step change in the mean rate of CO_2 sequestration from 1940 onwards, with a decrease to a mean of less than 10 t CO_2e ha^{-1} yr^{-1}. There is a large variability around the means, particularly in the late 1800s and early 1900s with maximum values for CO_2 sequestration of 21.6 t CO_2e ha^{-1} yr^{-1} and minimum values of 5.7 t CO_2e ha^{-1} yr^{-1}. The alluvial marker showed mean depths of peat of 127.5cm and rates of peat accumulation of 9.51 mm ± 2 mm yr^{-1} (Table 1). This rate was broadly in agreement with mean peat accumulation rates determined using the SCP dating method (7.86 mm ± 0.23 mm yr^{-1}), providing validation of this method; values were considerably higher than rates for valley mire in the published literature (Gorham, 1991; Barber *et al.* 1994; Tallis, 1998). Bulk density was comparatively low at 0.079 ± 0.004 g cm^{-3} dry matter (Table 1), compared to values published in the literature.

Table 1 Rates of peat growth, bulk density, carbon accumulation and CO_2 sequestration in valley mire (1876–2010). *Estimates were based on an alluvial clay marker dated to 1876. Values represent the means of 20 cores at all depths. Values ± mean show standard error.*

Number of peat cores	Rate of peat accumulation (mm yr^{-1})	Bulk density of peat (g cm^{-3})	Ash-free carbon content (%)	Carbon accumulation (t C ha^{-1} yr^{-1})	CO_2 sequestration (t CO_2e ha^{-1} yr^{-1})
20	9.51 ± 2	0.079 ± 0.004	51 ± 3.49	3.61 ± 0.45	13.23 ± 1.64

Using the mean accumulation rate of 11.26 t ± 0.68 t CO_2e ha^{-1} yr^{-1} (307 g C m^{-2} yr^{-1}), calculated using the SCP method, (Fig. 3), we can estimate that 88,000 tonnes of CO_2 have been sequestered in the valley mire over the 134 years (1876-2010) https://plymu.ni/peat-animation .

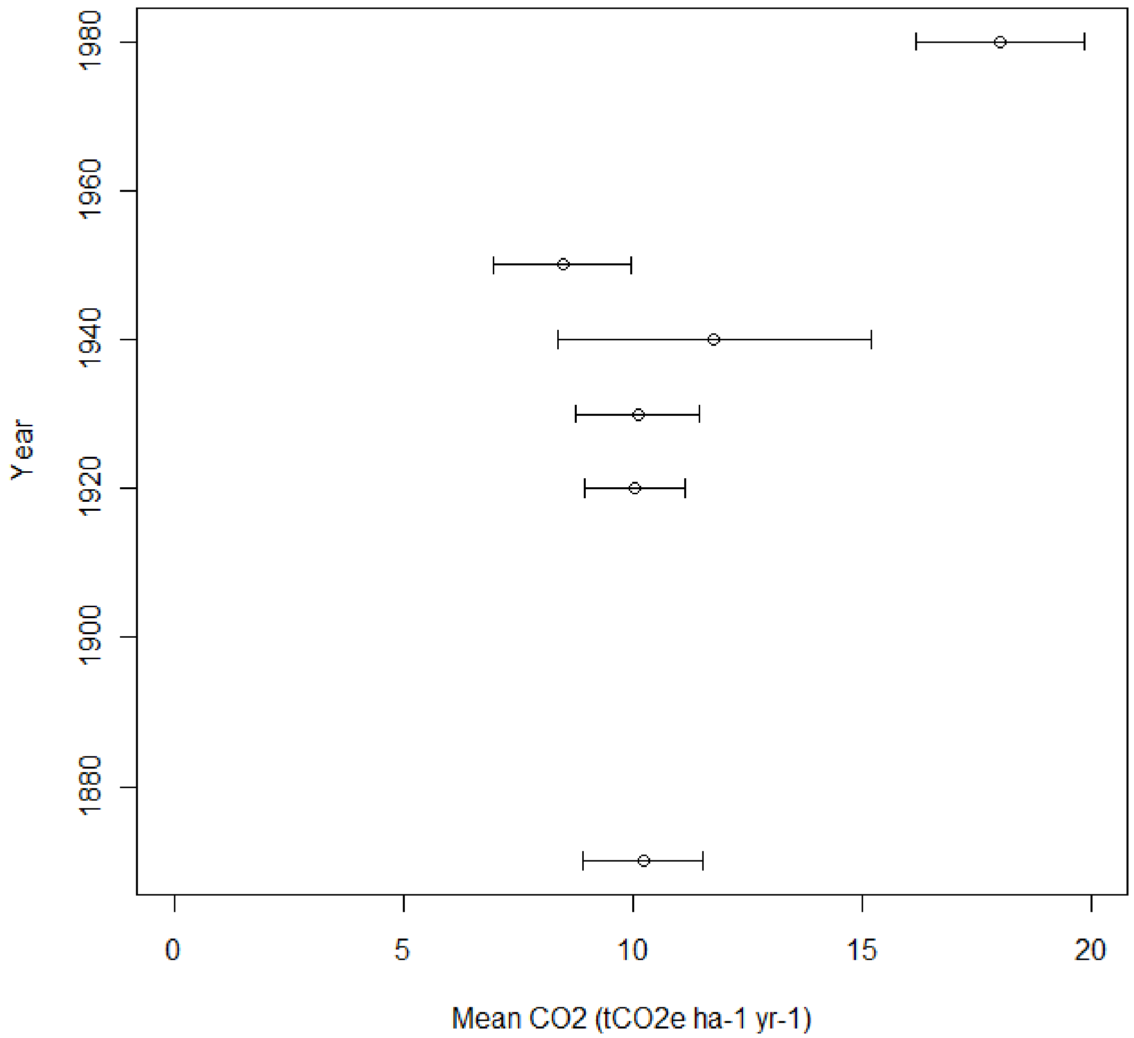

Fig. 4 Past rates of carbon accumulation (expressed as CO_2e) at the blanket bog site (1850–1980 AD). *Data were obtained from Red Lake Mire, Dartmoor, via sequential analyses of carbon densities in peat core segments dated using SCP techniques. Values represent the means of four cores taken in 2011. Error bars represent ± 1 standard deviation.*

Rates of CO_2 sequestration in blanket bog ranged from 7.3 to 19.2 t CO_2e ha^{-1} yr^{-1} (Fig. 4). Mean values of ~10 t CO_2e ha^{-1} yr^{-1} occur until 1950. The most recent record from 1980 showed an apparent increase to 18 t CO_2e ha^{-1} yr^{-1}. Rose and Appleby (2005) acknowledge that SCP dating methods are only accurate to within 15 years of the actual date. Any error could be further compounded in the surface peat layers, where there is greater physical difficulty in obtaining intact cores, due to the abundance of *Eriophorum* roots.

Table 2 Mean rates of peat accumulation and CO_2 sequestration (1850–2010) in blanket bog dated using the spheroidal carbonaceous particle (SCP) method. *Values ± mean show standard error.*

	Core 1	Core 2	Core 3	Core 4	**Mean**
Peat accumulation mm yr^{-1}	6.83	6.97	6.97	5.7	**6.62 ± 0.31**
CO_2 sequestration t CO_2e ha^{-1} yr^{-1}	11.92 ± 1.69	11.72 ± 2.26	11.74 ± 2.4	11.74 ± 1.79	**11.77 ± 0.88**

Mean rates of peat accumulation (Table 1) were significantly higher (9.51 ± 2 mm yr^{-1}) in the less consolidated valley mire peat compared to values shown in Table 2, for the higher density blanket bog peat cores (6.62 mm ± 0.31 mm yr^{-1}). However, means rate of CO_2 sequestration for valley mire (Table 1) and blanket bog were not significantly different ($P \leqslant 0.05$).

3.2 Net primary productivity of *Sphagnum* species on blanket bog and valley mire sites

Table 3 Capitulum density and annual increase in stem length for four *Sphagnum* species on Dartmoor. *Samples were collected from blanket bog and valley mire sites in the Decembers* *of 2012 and 2013. Values following the means shown as ± denote standard error. Values with different letters differ significantly ($P \leq 0.05$). Differences of variables were analysed with the Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988).*

	Sphagnum cuspidatum	*Sphagnum denticulatum*	*Sphagnum papillosum*	*Sphagnum capillifolium var. rubellum*
Number of replicate sample plots (dm^{-2})	26	26	26	26
Mean density of capitulum (dm^{-1})	103 ± 9.8b	60 ± 6.2a	105 ± 11.1b	117 ± 19.2b
Number of stem measurements	272	272	272	272
Mean annual growth of stem (cm yr^{-1})	6.9 ± 0.22b	5.5 ± 0.11a	7.35 ± 0.17c	6.85 ± 0.37b

Sphagnum capillifolium var. rubellum had the highest capitulum density followed by *S. papillosum and S. cuspidatum* (Table 3). *S. denticulatum* was found to have a significantly ($P \leqslant 0.05$) lower capitulum density when compared with the three other species. *S. papillosum* had the highest annual increase in length of 7.35 cm ± 0.17 cm yr^{-1}, which was significantly greater than the three other species. Krebs *et al*. (2016) reported that globally rates of growth of *S. papillosum* range from 0.4 cm to 4.6 cm yr^{-1}, with mean capitulum density ranging from 125 dm^{-2} to 175 dm^{-2}. In Georgia, Black Sea, Krebs *et al*. (2016) found a mean increase in stem length of 5 cm yr^{-1} for *S. papillosum* with a range from 2.3 cm ± 1.3 cm to 10.2 cm ± 3.0 cm yr^{-1} and significantly higher mean values of over 12 cm yr^{-1} for *S. palustre.*

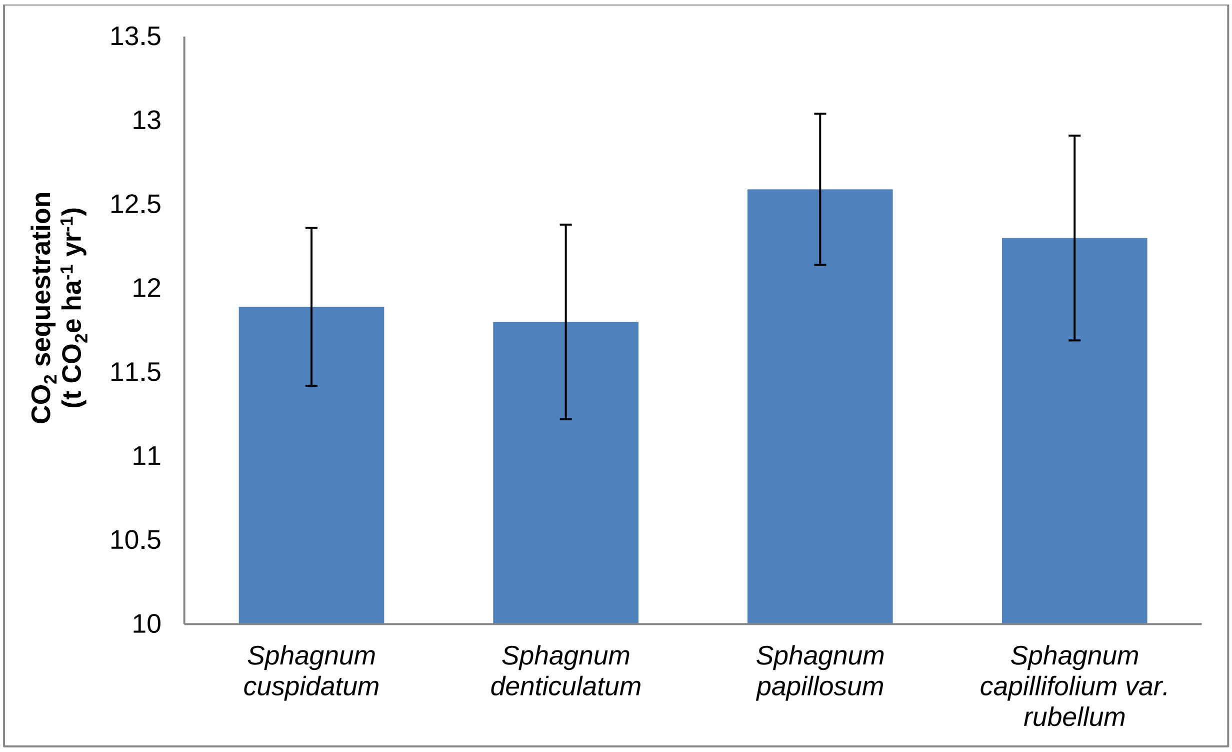

Fig. 5 Mean rates of net primary productivity of four *Sphagnum* species on Dartmoor, during 2012 and 2013. *Samples were collected from blanket bog and valley mire sites in the Decembers of 2012 and 2013 and are based on 1 year's growth. Bars show standard error plus and minus the mean. Values represent the means for replicated sample plots (dm*^{2}*); S. cuspidatum n = 25, S. denticulatum n = 10, S. papillosum n = 24 and S. capillifolium var. rubellum n = 15. No significant differences (*$P \leq 0.05$*) were found in NPP between the four species, using the Kruskal Wallis test.*

Fig. 5 shows that *S. papillosum* had the highest NPP (12.59 t ± 0.45 t CO_2e ha^{-1} yr^{-1}), followed by *S. capillifolium var. rubellum* (12.3 t ± 0.61 t CO_2e ha^{-1} yr^{-1}) and, the aquatic *Sphagna*: *S. cuspidatum* (11.89 t ± 0.47 t CO_2e ha^{-1} yr^{-1}) and *S. denticulatum* (11.8 t ± 0.58 t CO_2e ha^{-1} yr^{-1}). Rates were not found to be significantly different at $P \leqslant 0.05$. Higher rates of NPP were found for *S. papillosum* (16.11 t ± 0.45 t CO_2e ha^{-1} yr^{-1}) in the lawn microform compared with *S. papillosum* in hummock microform (9.06 t CO_2e ha^{-1} yr^{-1}).

3.3 Net ecosystem carbon balance for the valley mire

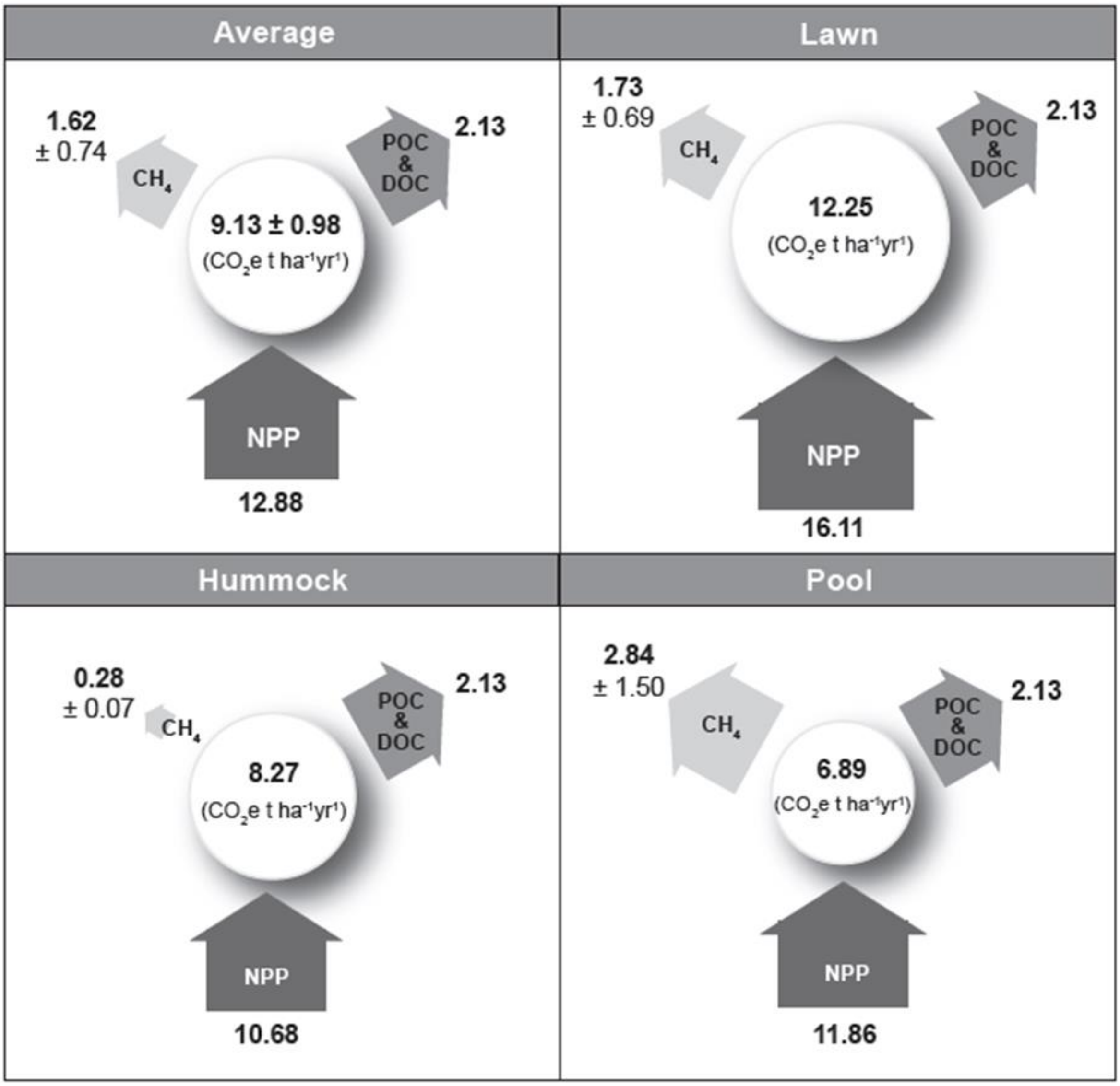

Fig. 6 Net ecosystem carbon balance for three peatland microforms (2011–2015). All values are in *t* CO_2e ha^{-1} yr^{1}*. Net primary productivity (NPP) of the Sphagnum species from each microform were calculated from annual stem increment data. Mean NPP of Sphagnum capillifollium var. rubellum (12.3 t ± 0.61 t* CO_2e $ha^{-1}yr^{-1}$*) and Sphagnum papillosum (9.06 t* CO_2e $ha^{-1}yr^{1}$*) for hummock microforms; Sphagnum papillosum (16.11 t ± 0.45 t* CO_2e ha^{-1} yr^{1}*) for lawn microforms; and Sphagnum cuspidatum (11.89 t ± 0.47 t* CO_2e ha^{-1} yr^{-1}*) and Sphagnum denticulatum (11.8 t ± 0.58 t* CO_2e ha^{-1} yr^{-1}*)*

for pool microforms. Aquatic loss of carbon of 2.13 t CO_2e *ha*$^{-1}$ *yr*$^{-1}$ *was calculated from annual export of POC and DOC estimated for the entire peat body.* CH_4 *emissions were monitored for microforms during 2014 and 2015 and converted to* CO_2e *.* CO_2e *losses from* CH_4*, POC and DOC were subtracted from NPP* CO_2e *inputs to give NECB values.*

The values in the central circles of the NECB model (Fig. 6) show that all three of the *Sphagnum*-dominated microforms in the valley mire were significant sinks for CO_2 during the study period, with mean sequestration rates of 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} (249 g C m^{-2} yr^{-1}). The lawn microform was found to be the largest sink for CO_2, followed by the hummock and pool microforms, due largely to higher rates of *Sphagnum* NPP (Fig. 6). Average summer CH_4 emissions were highest for the pool microform, 2.84 t ± 1.5 t CO_2e ha^{-1} yr^{-1}, and lowest for the hummock microform, 0.28 t ± 0.07 t CO_2e ha^{-1} yr^{-1}; the lawn microform had intermediate losses of CH_4 at 1.73 t ± 0.69 t CO_2e ha^{-1}yr^{-1}.

4.0 Discussion

4.1 Past rates of peat accumulation

Actively growing peatlands sequester carbon, accumulating organic mass as the excess of vegetation production over decay. In temperate peatlands, peat accumulation rates vary according to differences in growing season, depth of oxygen diffusion, microform and plant species composition (Clymo, 1984; Tallis, 1998; Charman, 2002; Ukonmaanaho *et al*. 2006; Chambers *et al*. 2011). Our study suggests that since the industrial revolution (1850), rates of peat accumulation averaged 9.51 mm ± 2 mm yr^{-1} for valley mire (Table 1) and 6.62 mm ± 0.31 mm yr^{-1} for blanket bog (Table 2). These rates far exceed the average historical rates described for more northerly, boreal and continental peatlands (Gorham, 1991; Clymo *et al*. 1998; Tallis, 1998; Roulet *et al*. 2007). Higher values were estimated by

Botch and Masing (1983) of up to 3 mm yr^{-1} for boreal mires and 30.3 mm yr^{-1} for lowland warm and humid mires in Georgia, Black Sea (Krebs *et al*. 2016). Long-term records for temperate systems suggest an average peat accumulation of 0.2–1 mm yr^{-1} (Aaby & Tauber, 1975), with blanket bogs reported as having a large range 0.1–1.2 mm yr^{-1} (Tallis, 1998) and raised mires at rates of 0.5–1 mm yr^{-1} (Charman, 2002; Roulet *et al*. 2007). The surface profile and vegetation composition of mires are in a constant state of change as shifts in peat accumulation rates are influenced by various factors, including changes in climate (Clymo & Pearce, 1995). Vegetation on the peat surface may show poor affiliation with depth of peat . Under natural conditions, acrotelm peat layers tend to show higher rates of carbon accumulation than the catotelm layers. This may arise because the fresh peat at the base of the acrotelm is still subject to occasional aerobic decomposition, or because of differences in vegetation composition in the past, or because there have been periods in the past when conditions were sub-optimal for peat formation (Charman, 2002; Holden *et al*. 2007; Lindsay, 2010; Charman *et al*. 2013).

4.2 Comparison of past rates of carbon accumulation

Our calculations of past (1850–2010) rates of carbon accumulation in temperate mires show similar rates for valley mire, 11.26 t ± 0.68 t CO_2e ha^{-1} yr^{-1} (307 g C m^{-2} yr^{-1}) (Fig. 3) and blanket bog, 11.77 t ± 0.88 t CO_2e ha^{-1} yr^{-1} (321 g C m^{-2} yr^{-1}) (Table 2). When compared to CO_2 sequestration recorded for boreal and high latitude northern peatlands (Gorham, 1991; Vitt *et al*. 2000; Turunen *et al*. 2002), our rates are at the upper limits of those recorded. According to Roulet *et al*. (2007) the rate of C accumulation in northern peatlands, over the last 6–8 thousand years, is estimated to be 0.73–1.1 t CO_2e ha^{-1} yr^{-1} (20–30 g C m^{-2} yr^{-1}), with CO_2 sequestration rates for two peat cores in Ontario, Canada for the time interval 3000–400 BP of 0.8 t ± 0.1 (SD) t CO_2e ha^{-1} yr^{-1} and 0.51 t ± 1.37 t CO_2e ha^{-1} yr^{-1}. Values of

< 1 t CO_2e ha^{-1} yr^{-1}, are typically reported for long-term peat records in northern and boreal peatlands.

Utstøl-Klein *et al*. (2015) reported peat growth and C accumulation for 1978–1995 of 8.38 t CO_2e ha^{-1} yr^{-1} (230 g C m^{-2} yr^{-1}) and for 1995–2012 of 13.56 t CO_2e ha^{-1} yr^{-1} (370 g C m^{-2} yr^{-1}) in *Sphagnum*-dominated boreal peatland in south-east Norway. These values are similar to those reported for contemporary CO_2 sequestration in our study. Utstøl-Klein *et al*. (2015) and Helfter *et al.* (2015) suggested that higher rates of C accumulation were associated with increased precipitation. McNeil and Waddington (2003) concluded that *Sphagnum* photosynthesis was greatest at wetter sites and that drying and wetting cycles negatively affect *Sphagnum* NPP and net ecosystem CO_2 exchange.

4.3 Net Primary Productivity (NPP) of *Sphagnum*

Fig. 5 shows that present-day mean rates of *Sphagnum* NPP for the southern moors ranged from 11.8 t ± 0.58 t CO_2e ha^{-1} yr^{-1} for the aquatic species, *Sphagnum denticulatum,* to 12.59 t ± 0.45 t CO_2e ha^{-1} yr^{-1} for the lawn species, *Sphagnum papillosum,* with *Sphagnum capillifolium var. rubellum* (12.3 t ± 0.61 t CO_2e ha^{-1} yr^{-1}) and *Sphagnum cuspidatum* (11.89 t ± 0.47 t CO_2e ha^{-1} yr^{-1}) intermediate. These rates for contemporary NPP are similar to past rates of carbon accumulation occurring on site during the last 160 years. Krebs *et al*. (2016) reported mean global NPP of *S. papillosum* to be 3.81 t CO_2e ha^{-1} yr^{-1} (204 g dry weight m^{-2} yr^{-1}) with a range of 0.54–9.15 t CO_2e ha^{-1} yr^{-1} (29–490 g dry weight m^{-2} yr^{-1}). Gunnarsson (2005) suggested a mean global NPP for *Sphagnum* of 3.74–5.6 t CO_2e ha^{-1} yr^{-1} (2–3 t dry weight m^{-2} yr^{-1}). Krebs *et al*. (2016) recorded the highest *Sphagna* productivity in warm and humid peatlands in southern Georgia, Black Sea, with NPP for *S. papillosum* of 5.03–10.24 t CO_2e ha^{-1} yr^{-1} (269–548 g dry weight m^{-2} yr^{-1}) and for *S. palustre* of 7.23–14.72 t CO_2e ha^{-1} yr^{-1} (387–788 g dry weight m^{-2} yr^{-1}); rates closer to our NPP values for *S.*

papillosum. Lütt (1992) reported CO_2 sequestration rates of 3.21–4.11 t CO_2e ha^{-1} yr^{-1} (172–220 g dry weight m^{-2} yr^{-1}) for *S. papillosum* in northern Germany, at similar latitudes to the UK but with a less favourable continental climate. In the UK, Clymo (1970) reported values of 11.4 t CO_2e ha^{-1} yr^{-1} (610 g dry weight m^{-2} yr^{-1}) for transplanted *Sphagnum*. There is a great deal of variability in the literature reflecting local growth conditions (Gunnarson, 2005; Loisel *et al*. 2012; Campbell, 2014; Nijp *et al*. 2015; Krebs *et al*. 2016), the methodology used and difficulty in assessing annual increases in *Sphagnum* growth (Clymo, 1970). However, our mean values for *Sphagnum* NPP are over twice those of global means reported by Gunnarsson (2005) and suggest that means reported from the literature may well provide an underestimate of contemporary rates of carbon sequestration occurring under optimal conditions in temperate peatlands. Similar values of 8.58 t CO_2e ha^{-1} yr^{-1} (234 g C m^{-2} y^{-1}) have been reported for a raised bog in New Zealand (Campbell *et al.* 2014), ascribed to the mild climate and long growing season at temperate sites, showing the sensitivity of ombrotrophic peat growth to climatic conditions.

4.4 Net Ecosystem Carbon Balance (NECB)

Mean contemporary CO_2 sequestration rates for *Sphagna* in the valley mire were calculated to be 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} from the NECB model (Fig. 6). This value does not take into account aerobic heterotrophic respiration. Ecosystem respiration is one of the major fluxes in peatland net ecosystem CO_2 exchange (composed of autotrophic + heterotrophic respiration), comprising of up to 80% of exchange (Riutta et al. 2007; Wilson *et al*. 2016; Kandel *et al*. 2018). By not accounting for the aerobic heterotrophic component of respiration in our model, the calculated value of 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} is likely to be the maximum value for the contribution of carbon sequestration to long-term carbon storage. Taking an upper estimate for aerobic respiration from the literature of 50% of heterotrophic respiration (Riutta *et al*. 2007;

Laine *et al*. 2009; Minke *et al*. 2016; Wilson *et al*. 2016), it is possible that 3.65 t CO_2e ha^{-1} yr^{-1} (40% of annual NPP) could be lost from the acrotelm via aerobic heterotrophic microbial decomposition. This would leave a minimum contribution of 5.48 t CO_2e ha^{-1} yr^{-1}. However, values at the lower end of the range 9.13 - 5.48 t CO_2e ha^{-1} yr^{-1}, are unlikely in the pool and lawn microforms, where levels of aerobic heterotrophic respiration will be low in the permanently saturated conditions (Laine *et al.* 2009; Wilson *et al*. 2016). Wilson *et al*. (2016) found considerable spatial and temporal variation in the annual NECB with the highest uptake observed in *Eriophorum angustifolium* dominated intact sites in 2009 (6.25 t CO_2-eq ha^{-1} yr^{-1}). Vegetation at the Fox Tor valley mire site consisted of a mosaic of mire communities including *Eriophorum* sp., other Cyperaceae and dwarf shrub species. As reported by Wilson *et al.* (2016) many of these vascular plant species have higher growth rates than *Sphagna* and where present with *Sphagnum* mosses are likely to lead to increased overall NPP.

NECB and its components in peatlands are known to vary considerably between sites (Limpens *et al*. 2008; Lund *et al*. 2009), as well as inter-annually within sites. During a two-year study of NECB in an intact low-lying ombrotrophic mire in Scotland, Dinsmore *et al*. (2010) found that the peatland acted as a net CO_2e sink of 3.52 t CO_2e ha^{-1} yr^{-1}. Run-off of DOC was found to be the principal route for loss of carbon, accounting for 24% of the uptake via NECB, with an estimated 12% evasion of carbon from the stream surface. Gaseous emissions of CH_4 and N_2O combined returned 4% of CO_2e. In our study the valley mire peatland acted as a carbon sink with a mean for peatland microforms of 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} (Fig. 6). This value was over twice that recorded by Dinsmore *et al*. (2010) for Scottish ombrotrophic mire. Our value for carbon sequestration of 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} is at the upper limits of reported values, but is consistent with the figure of 11.26 t ± 0.64 t CO_2e ha^{-1} yr^{-1}, derived from the analysis of dated cores at the same valley mire site. This current study and that of Dinsmore *et al.* (2010) found that annual rates of carbon sequestration accounted for 60-70% of NPP. As in Dinsmore *et al*. (2010) the most significant loss of C from the peat body in our study occurred via the aquatic C pathway (Fig.6). Export of aquatic carbon accounted for 17% of the NEE. Under base flow conditions in our study, DOC and POC loads contributed equal proportions of the total organic carbon load (48% and 51%, respectively). Dinsmore *et al*. (2010) and Pawson *et al*. (2008) found higher losses of carbon under storm flow conditions and concluded that the release of POC was episodic. Evans and Warburton (2007) found that the POC component contributed on average 60% of the total organic carbon load on degraded peatland. Higher peat temperatures and water table draw-down produce higher soil DOC concentrations, indicating either increased biological production or increased aerobic oxidation (Fenner *et al*. 2005; Evans & Warburton, 2007; Limpens *et al*. 2008).

In our study, variation in microform was observed with export of CO_2 as CH_4, accounting for over 24% of NECB for the pool microform, 11% for the lawn microform and 2% for the hummock microform (Fig. 6). This variation in CH_4 export for microforms is consistent with that reported by other authors (Laine *et al*. 2009; Levy & Gray, 2015; Kendal *et al*. 2018) who found that depth of water table was the key determinant of CH_4 export.

4.5 Optimal conditions for *Sphagnum* growth

S*phagnum* productivity is controlled by mean annual temperature, precipitation and photosynthetically active radiation (PAR) (Gunnarsson, 2005; Loisel *et al*. 2012; Nijp *et al*. 2015; Zhao *et al*. 2016). Dartmoor has limited seasonal variability and high precipitation, providing waterlogged conditions to retard decomposition processes and giving rise to an extended growing period. Lund *et al.* (2009) for northern peatland and tundra found that the length of the growing season was the most important variable describing the spatial variation in summertime gross primary production.

Table 4 Changes in total seasonal precipitation from Dartmoor National Park (DNP) and Plymouth between 1961 and 2015. *Values show % change from the mean, calculated by subtracting the 1961–2015 mean from the 1961 - 2015 trend (linear least squares fit). Values in brackets show the change in actual rainfall (mm). Statistically significant linear trends, using the seasonal Mann Kendall test, are denoted* $**P \leq 0.01$, $*P \leq 0.05$. Data source Met Office (2016).

		% change in total precipitation (mm)				
Location	**Elevation**	**Spring**	**Summer**	**Autumn**	**Winter**	**Annual**
Plymouth Mountbatten	50 m	-5.4 (11)	13.6 (26.3)	7.7 (22.1)	5.6 (17.9)	5.2 (52.4)
Double Waters (DNP)	355 m	6 (21)	*23.2 (82.7)	**20.3 (106.3)	**20.9 (20.9)	**18.3 (208.4)
Hurston Ridge (DNP)	418 m	-1.5 (5.8)	12.6 (40.1)	10 (56.4)	13.9 (97.6)	**10.6 (208.4)
Princetown (DNP)	433 m	6.6 (26.1)	18.8 (74.5)	*14.5 (81.1)	*17.3 (106)	**14.8 (289.7)
White Ridge (DNP)	488 m	-3.6 (15.3)	13.3 (47)	8.2 (49.3)	11.3 (85.4)	7.8 (166.7)

Table 4 shows a significant increase in annual rainfall in three of the four Dartmoor sites. A significant seasonal increase occurred in summer, autumn and winter at the Double Waters site and autumn and winter at Princetown. Current climatic models for the UK (Murphy *et al.* 2018), predict ensemble-mean reductions of 26% for summer rainfall and therefore a projected potential reduction in the size of the bioclimatic envelope for UK blanket bog (Gallego-Sala & Prentice, 2013). If such projections prove correct this may make peatlands in the southwest of the UK marginal for future peat growth (Gallego-Sala *et al.* 2010). Table 4 shows a trend of increasing rainfall for all seasons apart from spring (March-May). Particularly noteworthy are the increases in summer rainfall (June-August); which is significant at Double Waters, the most westerly windward upland site. Across all sites, average annual rainfall for 1961–2010 was 1968 mm, compared with the mean for the study period (2011–2015) of 2165 mm, an increase of 10%.

South west UK has an optimal climate for *Sphagnum* growth with a long growing season associated with a warm, wet climate and limited seasonal variability compared with boreal and continental climates (Charman *et al*. 2013). In recent decades, Dartmoor has seen an increase in the length of the growing season for *Sphagnum* (number of days with minimum air temperatures above freezing), an increase in total rainfall and an increase in the number of contiguous days with rainfall. Krebs *et al*. (2016) modelled global biomass productivity of *S. papillosum* and found a step change increase in carbon sequestration when the mean duration of contiguous days with rain is longer than three days during the growth period.

4.6 Response of modelled peatland bioclimatic envelope to climate change

Many authors working with global climate models propose that there may be a decline in the strength of high latitude and tropical peatland carbon sinks throughout the 21st century (Friedlingstein *et al*. 2006; Canadell *et al*. 2007; Limpens *et al*. 2008; Clark *et al*. 2010; House *et al*. 2010). Gallego-Sala and Prentice (2013) suggested that blanket bogs in south-west UK are at the lower limit of bioclimatic space and that, when future climate change scenarios were applied, a decline in the area of blanket peat was, according to their model, projected under both UKCIP02 high and low emission scenarios (Hulme *et al*. 2002). These modelled predictions do not appear to fit with the findings presented in this study for blanket bog in South West England. Our results for contemporary rates of carbon sequestration suggest that recent climate change may be having a positive effect on *Sphagnum* NPP and rates of carbon sequestration in rain-fed peatlands, due to increased precipitation and an extension in the length of the growing period for *Sphagnum* (Campbell *et al*. 2014; Krebs *et* *al*. 2016). Contrary to the bioclimatic envelope model predictions of Clark *et al*. (2010) and House *et al*. (2010), our findings suggest that blanket bogs in south-west UK may have the potential to act as a significant sink for CO_2 under present upland climatic trends.

There is agreement amongst climate scientists that peatlands have had an important role in past global cooling and that they have potential for significant negative feedbacks to the climate system (Freeman *et al*., 1993; Gorham, 1995; Fenner, 2005; Roulet *et al*. 2007; Limpens *et al*. 2008; Yu *et al*. 2012; Charman *et al*. 2013). Peatland ecosystems are the most efficient carbon store of all terrestrial ecosystems (Brooks & Stoneman, 1997; Worrall *et al*. 2003) and retaining active peatlands is one of the most cost-effective measures in achieving zero net global carbon emissions (Ostle *et al*. 2009; Lindsay, 2010). Actively growing peatlands are important in the global C cycle, capturing atmospheric CO_2 emissions and have the potential to make a significant contribution over 100-year timescales.

5.0 Conclusions and future research challenges

This paper reports mean rates of CO_2 sequestration for *Sphagna* of 9.13 t ± 0.98 t CO_2e ha^{-1} yr^{-1} and carbon accumulation rates from peat cores dated to 1850 of 11.26 t ± 0.68 t CO_2e ha^{-1} yr^{-1} for valley mire and 11.77 t ± 0.88 t CO_2e ha^{-1} yr^{-1} for blanket bog from an oceanic peatland setting in southwest England. These values are much higher than the uncertainty range for rates of carbon accumulation in undrained/rewetted peatlands reported in the IPCC Wetlands Supplement met-analysis (Blain *et al.* 2014). The IPCC values do not incorporate local variability and are much lower than values for temperate peatlands reported recently (Laine *et al.* 2009; Campbell *et al*. 2014; Wilson *et al.* 2016). Our findings, together with other studies (Levy & Gray 2015; Ratcliffe *et al*. 2018), where NEE and NECB models have been used to measure the strengths of carbon sinks, suggest that using past rates of peat growth based on peat cores provides an underestimate of contemporary rates of CO_2 sequestration.

Recent changes in climate appear to have had no impact on the strength of peatland carbon sinks in South West England. Past and contemporary peatland carbon sinks on our study sites located in South West England were found to be at the upper limits of those reported in the literature for temperate peatlands. This finding suggest that recent bioclimatic envelope models (Clarke *et al.* 2010; House *et al.* 2010; Gallego-Saga *et al*. 2013) may underestimate the potential future contribution that UK peatlands can make to carbon sequestration under observed climatic trends. Temperate oceanic peatlands offer one of the more viable and achievable options for long term storage of carbon fixed by photosynthesis under present climate trends.

This study highlights how peatland carbon sinks have responded to anthropogenic climate change and historic anthropogenic impacts, comparing contemporary rates of carbon sequestration with past rates of carbon accumulation for the same site. Findings suggest that, contrary to expectations based on bioclimatic envelope models, peatland carbon sequestration rates in South West England are stable and possibly increasing, due to amongst other factors, altered patterns of precipitation amount and frequency .

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7.0 References

Aaby B, Tauber H (1975) Rates of peat formation in relation to humification and local environment as shown by study of a raised bog in Denmark. Boreas, **4**, 1–17.

Bain CG, Bonn A, Stoneman R, Chapman S, *et al*. (2011) *IUCN UK Commission of Inquiry on Peatlands*, 1–112. IUCN UK Peatland Programme, Edinburgh.

Barber KE, Chambers FM, Maddy D, *et al*. (1994) A sensitive high-resolution record of late-Holocene climatic change from a raised bog in northern England. The Holocene, **4**, 200–207.

Belyea L, Clymo RS (2001) Feedback control in the rate of peat formation. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, **268**, 1315–1321.

Belyea LR, Malmer N (2004) Carbon sequestration in peatland: patterns and mechanisms of response to climate change. Global Change Biology, **10**, 1043–1052.

Billett MF, Charman DJ, Clark JM, Evans CD *et al*. (2010) Carbon balance of UK peatlands: current state of knowledge and future research challenges. Climate Research, **45**, 13–29.

Blain D, Murdiyarso D, Couwenberg J *et al*. (2014) Chapter 3. Rewetted organic soils. In: Hiraishi T, Krug T, Tanabe K, *et al.* (eds.), *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Intergovernmental Panel on Climate Change, Switzerland.

Botch MS, Masing VV (1983) Mire ecosystems in the U.S.S.R. In: *Mires; swamp, bog, fen and moor; regional studies* (ed AJP Gore), Ecosystems of the world, **48**, 95–152. Elsevier, Oxford, UK.

Brooks S, Stoneman R (1997) *Conserving Bogs: The Management Handbook*. The Stationary Office Limited, Edinburgh, UK.

Buffam I, Carpenter SR, Yeck W, Hanson PC, Turner MG (2010) Filling holes in regional carbon budgets: predicting peat depth in a north-temperate lake district. Journal of Geophysical Research: Biogeosciences, **115**, G01005, doi: 01010.01029/ 02009JG001034.

Campbell D, Smith J, Goodrich J, Wall A, Schipper L (2014) Year-round growing conditions explains large CO_2 sink strength in a New Zealand raised peat bog. Agricultural and Forest Meteorology, 192–193. 59–68. 10.1016/j.agrformet.2014.03.003.

Canadell JG, Pataki D, Gifford R, Houghton RA, Lou Y, Raupach MR, Smith P, Steffen W (2007) Terrestrial Ecosystems in a Changing World. *International Geosphere–Biosphere Programme Series* (eds Canadell J G, Pataki D, Pitelka L) pp. 59–78, Springer, Berlin, Germany.

Chambers F, Charman D (2004) Holocene environmental change: contributions from the peatland archive. The Holocene, **14** (1), 1–6.

Chambers FM, Beilman DW, Yu Z (2011) Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics. Mires and Peat, **7**, 1–10.

Chapin FS, Woodwell GM, Randerson JT, *et al*. (2006) Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems, **9**, 1041–1050.

Charman D (2002) *Peatlands and Environmental Change*, pp. 1–301. John Wiley & Sons Ltd, Chichester, UK

Charman DJ, Beilman DW, Blaauw M *et al.* (2013) Climate-related changes in peatland carbon accumulation during the last millennium. Biogeosciences, **10** (2), 929–944.

Christian MM, Pejcic B, Esteban L, Delle Piane C, Raven M, Mizaikoff B (2014) Infrared Attenuated Total Reflectance Spectroscopy: An Innovative Strategy for Analyzing Mineral Components in Energy Relevant Systems. Scientific Reports, **4**, Article number 6764.

Clark JM, Gallego-Sala AV, Allott TEH *et al*. (2010) Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models. Climate Research, **45,** 131–150.

Clymo RS (1970) The Growth of Sphagnum: Methods of Measurement. Journal of Ecology, **58** (1), 13–49.

Clymo RS (1984) The limits to peat bog growth. *Proceedings of the Royal Society of London B*, **303**, 605–654.

Clymo RS, Pearce DME (1995) Methane and carbon dioxide production in, transport through, and efflux from a peatland. *Philosophical Translations of the Royal Society of London A*, **351**, 249–259.

Clymo RS, Turunen J, Tolonen K (1998) Carbon accumulation in peatland, Oikos, **81**, 368–388.

Cox P, Betts R, Jones C, Spall S, Totterdell I (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, **408**, 184–187.

Dinsmore KJ, Billett MF, Skiba UM, Rees RM, Helfter C (2010) Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment. Global Change Biology, **16**, 2750–2762.

Dixon, S.D., Qassim, S.M., Rowson, J.G., Worrall, F., Evans, M.G., Boothroyd, I.M. & Bonn, A. (2014) Restoration effects on water table depths and CO_2 fluxes from climatically marginal blanket bog. *Biogeochemistry*, 118(1-3), 159-176.EMASyst (1996) Elemental Analyser Data System, Operation and Installation Manual, Version 4.5.01

Evans M, & Warburton J (2007) *The geomorphology of upland peat: pattern, process, form*, pp. 262. Blackwell, Oxford.

Fenner N, Freeman C, Reynolds B (2005) Hydrological effects on the diversity of phenolic degrading bacteria in a peatland, implications for carbon cycling. Soil Biology and Biochemistry, **37**, 1277–87.

Freeman C, Lock MA, Reynolds B (1993) Fluxes of CO_2, CH_4 and N_2O from a Welsh peatland following simulation of water table draw down – potential feedback to climatic-change. Biogeochemistry, **19**, 51–60.

Friedlingstein P, Cox PM, Betts RA *et al.* (2006) Climate–carbon cycle feedback analysis: Results from the C^4MIP model intercomparison. Journal of Climate, **19**, 3337–3353.

Friedlingstein PRM, Andrew J, Rogelj GP *et al.* (2014) Persistent growth of CO_2 emissions and implications for reaching climate targets. Nature Geoscience, **7**, 709–715.

Joosten H, Tanneberger F, Moen A (eds.) (2017) In *Mires and peatlands of Europe: Status, distribution and conservation* (2017) Stuttgart: Schweitzerbart Science Publishers), 780pp.

Gallego-Sala AV, Clark JM, House JI, Orr HG, Prentice IC, Smith P, Farewell T, Chapman SJ (2010) Bioclimatic envelope model of climate change impacts on blanket peat distribution in Great Britain. Climate Research, **45**, 151-162.

Gallego-Sala AV, Prentice IC (2013). Blanket peat biome endangered by climate change. Nature Climate Change, **3**(2), 152-155. DOI: 10.1038/NCLIMATE1672.

Gatis N, Luscombe D, Carless D, Parry LE, Fyfe RM, Harrod T, Brazier RE, Anderson K (2019) Mapping upland peat depth using airborne radiometric and LiDAR survey data Geoderma, **335**, 78-87.

Gatis N, Luscombe DJ, Grand-Clement E, Hartley IP, Anderson K, Smith D, Brazier RE (2015) The effect of drainage ditches on vegetation diversity and CO_2 fluxes in a *Molinia caerulea*-dominated peatland. Ecohydrology, **9** (3), DOI: 10.1002/eco.1643.

Gorham E (1991) Northern peatlands: role in the carbon cycle and probable responses to climate warming. Ecological Applications, **1**, 182–195.

Gorham E (1995) The biogeochemistry of northern peatlands and its possible response to global warming. In: *Biotic Feedbacks in the Global Climatic System* (eds Woodwell GM, Mackenzie FT), pp. 169–187. Oxford University Press, New York.

Green SM, Baird AJ, Evans CD, Peacock M, Holden J, Chapman PJ, Smart RP (2018) Methane and carbon dioxide fluxes from open and blocked ditches in a blanket bog. Plant and Soil, **424** (1-2), 619-638. 10.1007/s11104-017-3543-z.

Gunnarsson U (2005) Global patterns of *Sphagnum* productivity. Journal of Bryology, **27**, 269–279.

Helfter C, Campbell C, Dinsmore KJ, Drewer J, Coyle M, Anderson M, Skiba U, Nemitz E, Billett MF, Sutton MA (2015) Drivers of long-term variability in CO_2 net ecosystem exchange in a temperate peatland, Biogeosciences, **12**, 1799-1811, https://doi.org/10.5194/bg-12-1799-2015

Holden J, Shotbolt L, Bonn A, Burt TP *et al*. (2007) Environmental change in moorland landscapes. Earth-Science Reviews, **2**, 75–100.

Hope D, Billett, MF, Cresser MS (1994) A review of the export of carbon in river water: Fluxes and processes. Environmental Pollution, 84: 301-324.

House JI, Orr HG, Clark JM, Gallego-Sala AV, Freeman C, Prentice IC, Smith P (2010) Climate change and the British Uplands: evidence for decision-making. Climate Research, **45**, 3–12.

Hulme M, Jenkins GL, Lu X, Turnpenny JR *et al.* (2002) *Climate change scenarios for the United Kingdom: the UKCIP02 scientific report*, pp. 1–124. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

Janssens IA, Freibauer A, Schlamadinger B *et al*. (2005) The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences, **2**, 15–26.

Kandel, T.P., Lærke, P.E. & Elsgaard, L. (2018) Annual emissions of CO_2, CH_4 and N_2O from a temperate peat bog: Comparison of an undrained and four drained sites under permanent grass and arable crop rotations with cereals and potato. Agricultural and Forest Meteorology, 256–257, 470-481.

Koehler AK, Sottocornola M, Kiely G (2011) How strong is the current carbon sequestration of an Atlantic blanket bog? Global Change Biology, **17**, 309–319. doi:10.1111/j.1365-2486.2010.02180.x

Krebs M, Gaudig G, Joosten H (2016) Record growth of *Sphagnum papillosum* in Georgia (Transcaucasus): rain frequency, temperature and microform as key drivers in natural bogs. Mires and Peat, **18** (4), 1–16.

Laine A, Byrne KA, Kiely G, Tuittila ES (2009) The short-term effect of altered water level on carbon dioxide and methane fluxes in a blanket bog. Suo, **60**, 65-83.

Levy PE, Gray A (2015) Greenhouse gas balance of a semi-natural peatbog in northern Scotland. Environmental Research Letters, **10** (9). https://doi.org/10.1088/1748-9326/10/9/094019

Limpens J, Berendse F, Blodau C *et al*. (2008) Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences, **5**, 1475–1491.

Lindsay R (2010) Peatbogs and carbon: a critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change. *Report to RSPB Scotland*, pp.1–344. Edinburgh.

Lindsay R, Clough J (2017) In Mires and peatlands of Europe: Status, distribution and conservation (2017) H Joosten, F Tanneberger and A Moen A (eds.) Stuttgart: Schweitzerbart Science Publishers), 780pp.

Loisel J, Gallego-Sala AV, Yu Z (2012) Global-scale pattern of peatland *Sphagnum* growth driven by photosynthetically active radiation and growing season length. Biogeosciences, **9**, 2737–2746.

Lund M, Lafleur PM, Roulet NT *et al*. (2009) Variability in exchange of CO_2 across twelve northern peatland and tundra sites. Global Change Biology, **16**, 2436–2448.

Lütt S (1992) Produktionsbiologische Untersuchungen zur Sukzession der Torfstichvegetation in Schleswig-Holstein (Research on Productivity of the Succession of Peat Pit Vegetation in Schleswig-Holstein), pp. 250. Mitteilungen der Arbeitsgemeinschaft Geobotanik in Schleswig-Holstein und Hamburg, 43, Kiel.

McNeil P, Waddington J M (2003) Moisture controls on *Sphagnum* growth and CO_2 exchange on a cutover bog. Journal of Applied Ecology, **40**, 354–367.

Met Office (2017) Historic regional climate data. [Online] <http://www.metoffice.gov.uk/datapoint/product/regional-climate> [accessed 20/11/2018]

Minke M, Augustin J, Burlo A, Yarmashuk T, Chuvashova H, Thiele A, Freibauer A, Tikhonov V, Hoffmann M (2016) Water level, vegetation composition, and plant productivity explain greenhouse gas fluxes in temperate cutover fens after inundation. Biogeosciences, **13** (13), 3945-3970.

Moore TR, Bubier JL, Frolking SE, Lafleur PM, Roulet NT (2002) Plant biomass and production and CO_2 exchange in an ombrotrophic bog. Journal of Ecology, **90**, 25–36.

Moore TR, Roulet NT (1991) A comparison of dynamic and static chambers for the measurement of methane flux from subarctic fens. Atmosphere-ocean, **29**, 102–109.

Murphy JM, Harris GR, Sexton DMH *et al.* (2018) UKCP18 Land Projections: Science Report. Met Office Hadley Centre, Exeter. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf (last accessed 03/12/18)

Myhre G, Shindell D, Bréon FM *et al*. (2013) Anthropogenic and Natural Radiative Forcing. In: Stocker T. F., Qin D., Plattner G.-K., *et al.* (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659-740 pp.

Nijp JJ, Limpens J, Metselaar K, Peichl M, Nilsson MB, van der Zee SE, Berendse F (2015) Rain events decrease boreal peatland net CO_2 uptake through reduced light availability. Global Change Biology, **21**, 2309–2320.

Nilsson M, Sagerfors J, Buffam I *et al*. (2008) Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire – a significant sink after accounting for all C-fluxes. Global Change Biology, **14**, 1–16.

Ostle NJ, Levy PE, Evans CD, Smith P (2009) UK land, sea and soil carbon sequestration. Land Use Policy, **265,** 274–283.

Parish F, Sirin A, Charman D, Joosten H, Minayeva T, Silvius M, Stringer L (eds) (2008) Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen. Available at: <http://www.imcg.net/media/download_gallery/books/assessment_peatland.pdf.> [16/11/2018]

Pawson RR, Lord DR, Evans MG, Allott TEH (2008) Fluvial organic carbon flux from an eroding peatland catchment, southern Pennines, UK. Hydrology and Earth System Sciences, **12**, 625–634.

Payne RJ, Malysheva E, Tsyganov A, Pampura T, Novenko E, Volkova E, Babeshko K, Mazei Y (2016) A multi-proxy record of Holocene environmental change, peatland development and carbon accumulation from Staroselsky Moch peatland, Russia. The Holocene, **26**, 314–326.

Pendea IF, Chmura GI (2012) A high-resolution record of carbon accumulation rates during boreal peatland initiation. Biogeosciences, **9**, 2711–2717.

Ratcliffe J, Andersen R, Anderson R *et al.* (2018). Contemporary carbon fluxes do not reflect the long-term carbon balance for an Atlantic blanket bog. The Holocene, **28** (1), 140-149. DOI: 10.1177/0959683617715689

Riutta T, Laine J, Tuittila ES (2007) Sensitivity of CO_2 exchange of fen ecosystem components to water level variation. Ecosystems, **10**, 718-733.

Rodwell JS (ed) 1991 British Plant Communities Volume 2. Mires and Heaths Cambridge University Press.

Rose NL, Appleby PG (2005) Regional applications of lake sediment dating by spheroidal carbonaceous particle analysis. I: United Kingdom. Journal of Paleolimnology, **34**, 349–361.

Rose NL, Harlock S, Appleby PG, Battarbee RW (1995) Dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle (SCP) concentration profiles. The Holocene, **5**, 328–335.

Roulet NT, Lafleur PM, Richard PJH, Moore TR, Humphreys ER, Bubier J (2007) Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biology, **13**, 397–411.

Rowson JG, Gibson HS, Worrall F, Ostle N, Burt TP, Adamson JK (2010) The complete carbon budget of a drained peat catchment. Soil Use and Management, **26**, 261-273.

Siegel S, Castellan NJ Jr (1988) *Nonparametric statistics for the behavioural sciences*, 2nd edn., pp. 399. McGraw-Hill, New York, USA.

Swindles G (2010) Dating recent peat profiles using spheroidal carbonaceous particles (SCPs). Mires and Peat, **7** (3), 1–5.

Tallis JH (1998) Growth and degradation of British and Irish blanket mires. Environmental Reviews, **6**, 81–122.

Turunen J, Tomppo E, Tolonen K *et al*. (2002) Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions. The Holocene, **12**, 69–80.

Ukonmaanaho L, Nieminen TM, Rausch N, Cheburkin A, Le Roux G, Shotyk W (2006) Recent organic matter accumulation in relation to some climatic factors in ombrotrophic peat bogs near heavy metal emission sources in Finland. Global and Planetary Change, **53** (4), 259–268.

Utstøl-Klein S, Halvorsen R, Ohlson M (2015) Increase in carbon accumulation in a boreal peatland following a period of wetter climate and long-term decrease in nitrogen deposition. New Phytologist, **206**, 1238–1246.

Vitt DH, Halsey LA, Bauer IE, Campbell C (2000) Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences, **37**, 683–693.

Waddington JM, Strack M, Greenwood MJ (2010) Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO_2 exchange to ecosystem-scale restoration. Journal of Geophysical Research, **115**, 1–13. doi:10.1029/2009JG001090.

Wilson D, Farrell C, Fallon D, Moser G, Muller C, Renou-Wilson F (2016) Multi-year greenhouse gas balances at a rewetted temperate peatland. Global Change Biology, **22**, 4080-4095, DOI: 10.1111/gcb.13325.

Worrall F, Burt TP, Rowson JG, Warburton J, Adamson JK (2009) The multi-annual carbon budget of a peat-covered catchment. Science of the Total Environment, **407**, 4084–4094.

Worrall F, Reed M, Warburton J *et al*. (2003) Carbon budget for a British upland peat catchment. The Science of the Total Environment, **312**, 133–146.

Wright WHK (1884). The Western Antiquary, Volume 3. Publisher Latimer & Son, Plymouth. Sonhttps://archive.org/details/westernantiquar06wriggoog Last accessed 19/10/18

Xu J, Morris PJ, Liu J, Holden J (2018) PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. Catena, **160**, 134-140. Doi.org/10.1016/j.catena.2017.09.010

Yu Z (2011a) Holocene carbon flux histories of the world's peatlands: Global carbon-cycle implications. The Holocene, **21** (5), 761–774.

Yu Z, Beilman DW, Frolking S, MacDonald GM, Roulet NT, Camill P, Charman DJ (2011b) Peatlands and Their Role in the Global Carbon Cycle. Eos, Transactions American Geophysical Union, **92** (12), 97.

Yu ZC 2012. Northern peatland carbon stocks and dynamics: A review. Biogeosciences, **9**, 4071–4085.

Zhao J, Peichl M, Öquist M, Nilsson MB (2016) Gross primary production controls the subsequent winter CO_2 exchange in a boreal peatland. Global Change Biology, **22** (12). doi:10.1111/gcb.13308.