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Short Communication.

# **Peatland initiation and carbon accumulation in the Falkland Islands**.

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## ABSTRACT

The Falkland Islands in the South Atlantic Ocean contain extensive peatlands at the edge of their global climatic envelope, but the long-term carbon dynamics of these sites is poorly quantified. We present new data for ten sites, compile previously-published data and produce a new synthesis. Many peatlands in the Falkland Islands developed notably early, with a fifth of basal $^{14}C$ dates pre-Holocene. Falkland Islands peats have high ash content, high carbon content and high bulk density compared to global norms. In many sites carbon accumulation rates are extremely low, which may partly relate to low average rainfall, or to carbon loss through burning and aeolian processes. However, in coastal Tussac peatlands carbon accumulation can be extremely rapid. Our re-analysis of published data from Beauchene Island, the southernmost of the Falkland Islands, yields an exceptional long-term apparent carbon accumulation rate of 139 g C $m^{-2}$ $yr^{-1}$, to our knowledge the highest recorded for any global peatland. This high accumulation might relate to the combination of a long growing-season and marine nutrient inputs. Given extensive coverage and carbon-dense peats the carbon stock of Falkland Islands peatlands is clearly considerable but robust quantification will require the development of a reliable peat map. Falkland Island peatlands challenge many standard assumptions and deserve more detailed study.

**KEYWORDS**: South Atlantic; Carbon accumulation; Bog; Peat; Holocene.

## HIGHLIGHTS:

- The Falkland Islands contain extensive and poorly-understood peatlands.
- Peatlands are notably old with many pre-Holocene in age.
- Long-term carbon accumulation rate is very variable between sites.
- One site has the highest recorded carbon accumulation rate for any global peatland.
- These unusual peatlands deserve further study.

## INTRODUCTION

Global peatlands currently store around 400-600 Gt of carbon and the long-term evolution of this carbon pool has been an important focus for palaeoenvironmental research (Gorham, 1991; MacDonald et al., 2006; Yu, 2012). The most extensive peatlands today are in the northern boreal zone, in particular Western Siberia and the Hudson Bay Lowlands (Packalen et al., 2014; Sheng et al., 2004), with other substantial areas in the humid tropics of equatorial Southeast Asia, Africa and South America (Dargie et al., 2017; Page et al., 2011). Peatlands also occur in the high southern latitudes of Australasia, Africa and South America with Yu et al. (2011) estimating the carbon stock of these peatlands as 13-18 GtC. The largest proportion of this southern peatland carbon pool is located in South America where peatlands developed early, have accumulated carbon at a notably rapid rate and exist in a distinct climatic envelope (Loisel and Yu, 2013; Yu et al., 2011). Southern hemisphere peatlands are generally under-researched and there is a clear imperative to improve understanding both in order to fill gaps in global databases and to understand carbon accumulation in distinctive and unusual peat-forming environments.

The focus of this study is the Falkland Islands in the South Atlantic Ocean, located 500 km east of mainland South America (~51°41'S, 59°10'W). Peatlands are extensive in the archipelago to the extent that the Falkland Islands have been identified as having the highest proportional peat coverage of any nation or territory (Joosten, 2010; McAdam, 2013). However, there are open questions around whether these peatlands are continuing to accumulate carbon and how their carbon stock has been affected by climate change and land management (Otley et al., 2008). The peatland landscapes of the islands are unusual and varied, including some highly atypical peatland habitats with very tall grasses and extensive influence from marine birds and mammals (McAdam, 2013; Smith and Karlsson, 2017). Prior to the first European settlement in the mid-18th century there were no mammalian herbivores on the islands, and the introduction of extensive livestock grazing has therefore led to major ecological change. Despite the presence of highly unusual peatland types, their extensive area, widespread evidence of human-induced modification, and the status of the islands as an Overseas Territory of the United Kingdom – which has considerable peat research capacity – surprisingly little research has been conducted. The carbon stock, current greenhouse gas balance, timing of peat development and rate of carbon accumulation in Falkland Island peatlands are all largely unquantified. Here we present new data and a synthesis of the fragmentary existing data in order to provide an initial assessment of peatland developmental history and long-term carbon accumulation.

## SITES AND METHODS

Our sampling focussed on East Falkland, the largest island containing the greatest peat area, and aimed to sample a range of peatlands spanning much of the island (Table 1; Supplementary Fig. 2). We sampled five sites with vegetation dominated by Whitegrass (*Cortaderia pilosa*); typically in shallow basins, often with shallow peats. We sampled three sites with deeper peats and more varied vegetation, including the shrub *Empetrum rubrum* ('Diddle Dee'), the monocot *Astelia pumila* and a variety of graminoids, forbs and bryophytes. We sampled one coastal site with vegetation a near-monoculture of Tussac grass (*Poa flabellata*). These coastal peatlands are relatively restricted in distribution around the coastal fringe of the islands but have high above-ground carbon stocks and can have deep peats (<11m)(Smith and Clymo, 1984; Smith and Karlsson, 2017). Finally, we sampled one site in a valley system with closely-cropped graminoid vegetation (Table 1).

Cores were extracted from a representative location in each site using a Russian-pattern peat corer (Aaby and Digerfeldt, 1986) and were subsampled in the field into 10 cm sections (Fig. 1). Additional samples (c. 4 $cm^2$) were taken from the interface of the lowermost peat and underlying sediment for dating. In the laboratory, sample volumes were determined by water displacement and samples oven dried at 105 °C to calculate dry bulk density (Chambers et al., 2011). Sub-samples were ground and incinerated at 550 °C to calculate loss on ignition (LOI) and a subset of 91 samples (60%) spread evenly across all the cores was analysed for carbon content using an Elementar vario MACRO elemental analyser with glutamic acid and peaty soil standards (Chambers et al., 2011). There was a strong and significant linear relationship between loss on ignition and carbon content ($r=0.98$, $p<0.001$) which was used to calculate carbon content for all samples without direct measurements (Supplementary Fig. 3). Carbon density was calculated as the product of bulk density and measured or modelled carbon content. Core carbon stock was calculated as the product of mean carbon density and depth. Basal peat was disaggregated and inspected under low-powered microscopy before being prepared for AMS $^{14}C$ dating using an acid-base-acid protocol (Brock et al., 2016). For four sites (SSX, SWI, ORQ, DPO [Table 1]) it was possible to identify macrofossils suitable for dating, typically above-ground graminoid fragments. For the remaining six sites no suitable macrofossils could be identified so we dated the humate fraction of bulk peat following the removal of roots (Loisel et al., 2017; Shore et al., 1995). The resulting $^{14}C$ dates were calibrated using the SHCal13 curve (Reimer et al., 2013) in Bchron (Parnell, 2016). The full-core long-term apparent rate of carbon accumulation (here termed $LARCA_{FC}$) was calculated by dividing carbon stock by the calibrated basal date. To account for the complexity of the calibrated radiocarbon age estimates we re-sampled the individual probability distributions 1000 times and calculated $LARCA_{FC}$ for each; we present results on this basis as the mean and the 5$^{th}$ and 95$^{th}$ percentiles. We also calculated $LARCA_{FC}$ for a previously-published record from Beauchene Island (Smith and Prince, 1985; Smith and Clymo, 1984) by converting wet to dry bulk density on the basis of moisture content, converting loss on ignition to carbon content using the relationship derived in this study and interpolating between the measured depths. To test the representativeness of the core dataset in terms of peat depth we compared the dated core depths to a larger dataset of 805 depth measurements from 371 locations in East Falkland (Supplementary Fig. 2). Depth measurements in this dataset were made using either an avalanche probe or a soil corer, with a maximum recording depth of 2.5 m. Measurements were typically made along transects at a range of upland and lowland locations spanning peat/non-peat transitions. This dataset includes variable numbers of measurements in each peatland so we calculated site mean depths and compared these values to our dated core dataset using kernel density plots. The depth dataset is not considered to be representative of the peatland areas as a whole, but is both considerably larger than the core dataset and includes other areas of the island.

In parallel with our primary data collection we conducted a systematic search of the literature. We compiled datasets of $^{14}C$ dates representing peat initiation and individual site age-profiles and calibrated these dates based on the SHCal13 curve (Reimer et al., 2013) in Bchron (Parnell, 2016). Using both new and published basal peat radiocarbon dates we constructed a cumulative Summed Probability Distribution (cSPD) to quantify the timing of peat initiation in the Falkland Islands (Reyes and Cooke, 2011). To place these results in context we also constructed cSPDs for global and extra-tropical South American peatlands based on the database of Treat et al. (2017). For each site containing at least two dated depths we constructed a Bayesian age-depth model using Bacon with default priors for accumulation rate and memory, accepting alternate suggestions where initial screening suggested these were inappropriate (Blaauw and Christen, 2011; Goring et al., 2012). We assigned the peat surface a calendar date based on the year of first data publication, unless peat was overlain by other sediment.

Quantifying temporal change in carbon accumulation requires cores with data on carbon density and adequate chronological control throughout the peat profile which is currently available for very few cores (Turney et al., 2016). However, several cores do have adequately constrained age-depth models and this study presents data on carbon density for a substantial number of samples. In order to use these data to make preliminary inferences about change in apparent carbon accumulation we adopted the empirically-based framework of Ratcliffe et al. (2018) whereby age-depth models are constructed for all available sites, levels are assigned carbon density values of an appropriate age through multiple iterations of random re-selection, results are aggregated across cores and weighted by age-depth model precision to produce an overall reconstruction. These results allow us to make some initial inferences about temporal variability in carbon accumulation across the study region.

## RESULTS AND DISCUSSION

### *Peatland initiation*

Basal peats in our study sites ranged in age from pre-Holocene (SWI) to late Holocene (WCR). Combining our ten new dates with other basal dates from the literature gives a total dataset of thirty peat initiation dates for the Falkland Islands. These suggest that peat formation began very early with six sites showing pre-Holocene peat initiation, and the oldest sample thus-far published dated at 13475 ± 50 BP (calibrated weighted mean: 16163 cal. BP) (Wilson et al., 2002). The oldest dates are from the Lake Sulivan area of West Falkland (Wilson et al., 2002), but this is also the most intensively-studied area and it is probable that similarly old peat is present in other locations. The cSPD plots show that Falkland Island peatlands developed markedly earlier than the global norm, but early peatland development is not unusual for South America (Fig. 3). While considerably older peatlands are present around the world (Treat et al., 2019), many of these are in the tropics and Falkland Islands peatlands are atypically old for the temperate/boreal realm. This may relate to the limited extent of late Quaternary glaciation, which appears to have been restricted to cirques and small mountain glaciers, particularly in West Falkland (Clapperton, 1971; Clapperton and Suggern, 1976; Roberts, 1984). The available stratigraphic evidence suggests that peat formation was dominated by primary development and paludification with hydroseral development rare. Rates of peat initiation appear to have been relatively consistent from the early Holocene to ~5 ka cal. BP but then slowed (Fig. 4). However, comparing the cores dated in this study to a larger peat depth dataset from East Falkland suggests a bias towards deeper peats (Supplementary Fig. 4). This may have skewed the sample towards older dates, although it is notable that even some sites with shallow peat have early initiation dates (e.g. HOP) and comparison with the depth dataset is complicated by definitional issues and the fact that some locations in the depth dataset exceeded the maximum measurable depth. However representative they may be, our results demonstrate that the Falkland Islands contain a surprising number of very old peatlands which stresses the importance of including such under-studied regions in global datasets. Considerable work remains to be done to assess the developmental history of South American peatlands and our combined dataset expands the current radiocarbon data resource by almost 50%, albeit with a focus on a single region.

*Peat properties*

The sedimentary properties of Falkland Islands peats differ from those of most global peatlands (Fig. 1; Fig. 2). Ash content in these samples was relatively high with only a small proportion of samples having loss on ignition greater than 95% (15.2%), much less than the global mean (46%)(Fig. 2). Ash content was highest in SWI with sediments barely classifiable as peat (mean loss on ignition: 34%). Inorganic contents were comparatively high even in clearly ombrotrophic sites (e.g. SSX), suggesting that mineral dust transport in the very windy Falkland Islands climate may be the dominant reason for this high ash content. The nature of the inorganic component has not been investigated in detail but is likely to derive from both local aeolian processes and further-travelled mineral dust, with tephra from South America also recorded as highly abundant in Falkland Islands peats (Holmes et al., 1999). Peat bulk density and carbon content were high relative to global norms (Fig. 2). In the case of carbon content this may relate to the comparative rarity of *Sphagnum* in Falkland Island peatlands as *Sphagnum* peats skew carbon content towards lower values in global data (Loisel et al., 2014). The relatively high bulk density may be due to a combination of this relative scarcity of *Sphagnum*, high ash content and the highly humified nature of many peats. The combination of high bulk density and high carbon content means that the carbon density of peat also tends towards the upper end of the global range. Collectively these data demonstrate the importance of region-specific datasets in understanding peatland carbon stocks and dynamics; global values would not be appropriate for Falkland Islands peats.

*Carbon accumulation rate*

Long-term rates of carbon accumulation were highly variable between sites with $LARCA_{FC}$ ranging from 2.6 to 32 g C $m^{-2}$ $yr^{-1}$. Rates were lowest in the valley and Whitegrass dominated sites, higher in the Diddle Dee sites and highest in the Tussac site: Cape Dolphin. However, for the Tussac peatland on Beauchene Island investigated by Smith and Clymo (1984) we calculated an exceptionally high $LARCA_{FC}$ of 139 g C $m^{-2}$ $yr^{-1}$. This is more than six times the global mean accumulation rate (Loisel et al., 2014) and more than 50% higher than the highest published LARCA figure of which we are aware (88.6 g C $m^{-2}$ $yr^{-1}$: Tolonen and Turunen (1996)). Carbon accumulation in this site appears to be the highest documented in any global peatland and was justifiably termed 'extraordinary' by the original authors. While the peat accumulation rate and depth of this site are towards the upper end of the global distribution, the high rate of carbon accumulation is primarily attributable to the extremely high bulk density of the peat. Older data often needs to be treated with caution but in this case the original authors went to considerable efforts to validate their bulk density measurements and the chronology is plausible; there is currently little reason not to accept this as a valid result, although further work would clearly be desirable.

Falkland Islands peats appear to encompass a very large range of accumulation rates. In the majority of sites $LARCA_{FC}$ was low to very low. Our data do not allow us to assess whether this is because of low initial carbon accumulation or subsequent carbon loss, but active peat erosion is clearly a feature of the Falklands peatlands landscape. Erosion features are widely visible and in two cores from West Falkland, Wilson et al. (2002) dated the upper surface of eroding peats to 13040 ± 50 BP and 13080 ± 60 BP respectively. It is also clear that fire has had a long-term role in Falkland peatland carbon dynamics with macrofossil charcoal highly abundant in peat cores (Mauquoy, unpublished data). It is likely that factors such as natural and anthropogenic burning, overgrazing and aeolian erosion are at least part of the reason for the low rates observed in many sites.

The reasons for the extremely rapid carbon accumulation rates in the Tussac sites are similarly unclear. The Falklands are at the edge of the climatic envelope for global peatlands being relatively dry for their mild temperature, with mean annual precipitation a little over 600mm and mean annual temperature of around 6°C (Supplementary Fig. 5). The climate regime has a high degree of seasonal consistency in precipitation and relatively mild, relatively consistent temperature which may allow for a long growing season (Supplementary Fig. 6). This is similar to Patagonia where high carbon accumulation has been attributed to similar climatic conditions in – otherwise quite different – peatlands (Loisel and Yu, 2013). However, all Falkland Island peatlands experience a broadly similar climate and the distinguishing feature of Tussac sites is their coastal location. In these locations marine birds and mammals are likely to be a significant vector for nutrients as they shelter on or amongst the large grass tussocks. Nutrient inputs through faeces and carcases may promote high rates of both primary production and decomposition, ultimately leading to the formation of very carbon-dense peat. The biogeochemistry of these highly unusual sites would clearly repay further detailed study.

*Variability in apparent carbon accumulation*

Two features are apparent in our carbon accumulation simulations (Fig. 4): an increase in peat and carbon accumulation in the late Holocene (last ~2ka) and, less clearly, an increase in carbon accumulation between 7.5 and 9.5ka cal. BP. The latter is based on a relatively limited number of cores and samples but is interesting as it parallels previous reconstructions from cores around the world and often attributed to the Holocene Thermal Maximum (HTM)(Loisel et al., 2014; Ratcliffe et al., 2018). The only previously published peatland carbon accumulation reconstruction does not extend back sufficiently far to address changes in this period (Turney et al., 2016). The Falklands climate is dominated by Westerly winds (Jones et al., 2016) and reduced wind speeds in the Southern Westerly belt have been reconstructed for the HTM (Saunders et al., 2018). Due to the position of the Falkland Islands in the lee of the Andean mountain chain, this may have led to enhanced precipitation on the Falkland Islands during this time interval given the negative correlation between 850-hPa zonal wind speed strength and precipitation in eastern Patagonia (Garreaud et al., 2013). In a previous Falkland Islands study Turney et al. (2016) attributed an increase in carbon accumulation at the top of their cores, similar to that we reconstruct, to recent climate change. However, this conclusion is unsafe because cores will inevitably show an increase in *apparent* carbon accumulation simply due to the transition to acrotelm peat which has not yet had the opportunity to decompose. This 'near-surface uptick' is widely reported and can be expected in all peat cores (Loisel et al., 2014). The result here should be considered an artefact pending compelling evidence to the contrary.

*Carbon stock*

There is currently no established peat map for the Falkland Islands, which makes it impossible to accurately calculate the total carbon stock. A recent assessment by Evans et al. (2019) combined the peat depth survey described in this study with previous superficial deposit mapping by the British Geological Survey (Aldiss and Edwards, 1999) to produce an indicative estimate that 2820 $km^2$ ha of the Falkand Islands (around one quarter of the total land area) is peat covered, noting that this estimate is highly uncertain. If we combine this estimate with the measured carbon densities obtained from our cores plus those of Smith and Prince (1985) (mean= 0.073 g C $cm^{-3}$), and take our depth dataset as representative of peat depth (mean= 76cm), the total C stock would be 156 MtC. This approximate figure may be conservative (for example because peat depths > 2.5 m were not captured in the survey) but is, for instance, equivalent to more than 12,000 times the emissions associated with all annual energy consumption on the islands (2009 data: (iMC Worldwide, 2012)) and considerably greater than a published assessment of the peatland carbon stock of Wales (~121 MtC)(ECOSSE, 2007). Mapping of Falkland Islands peats is now underway which should allow this estimate to be better-constrained in the future.

**ACKNOWLEDGEMENTS**

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Author contributions: RJP secured funding. RJP, GR and CE conducted fieldwork. FR-H, DM, RJP and TS conducted laboratory work. FR-H and RJP conducted data compilation and RJP conducted data analysis. RJP wrote the first draft of the manuscript, to which all authors contributed with comments and interpretation.

**FIGURES AND TABLES**

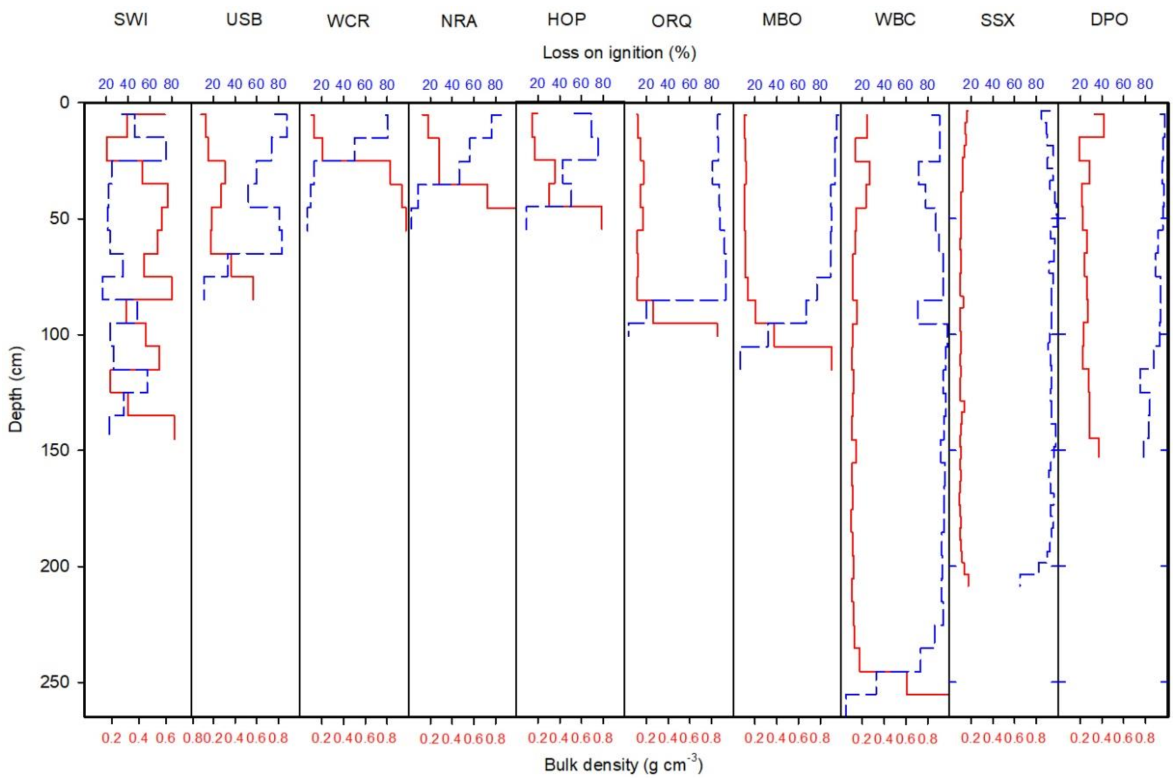



Figure 1. Bulk density (red, solid line) and loss on ignition (blue, dashed line) profiles for the ten peat cores presented in this study.

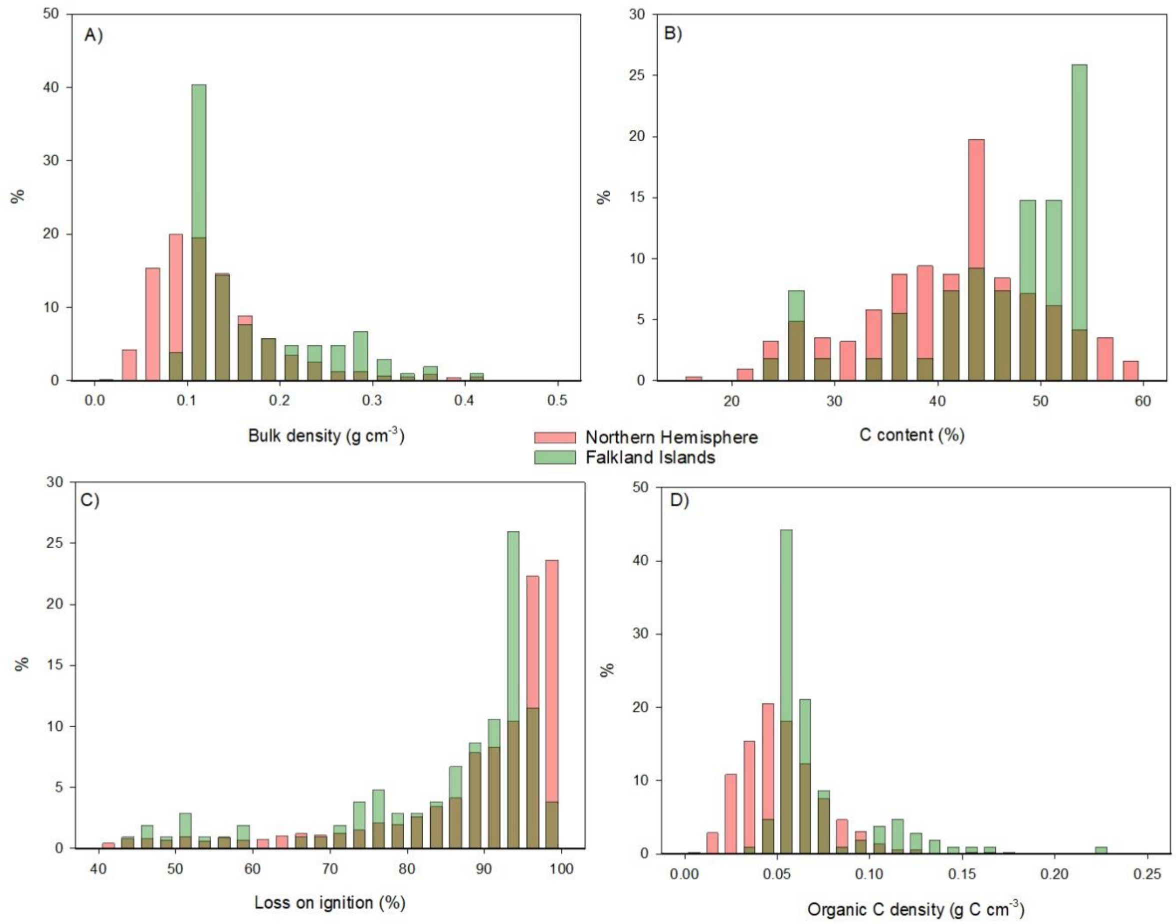



Figure 2. Comparison of peat properties from sites sampled here to the Northern Hemisphere dataset of Loisel et al. (2014). To avoid over-representing results from cores sampled at high resolution, all cores were reduced to 10cm increment means. Samples with LOI<40% or BD>0.5g $cm^{-3}$ were excluded.

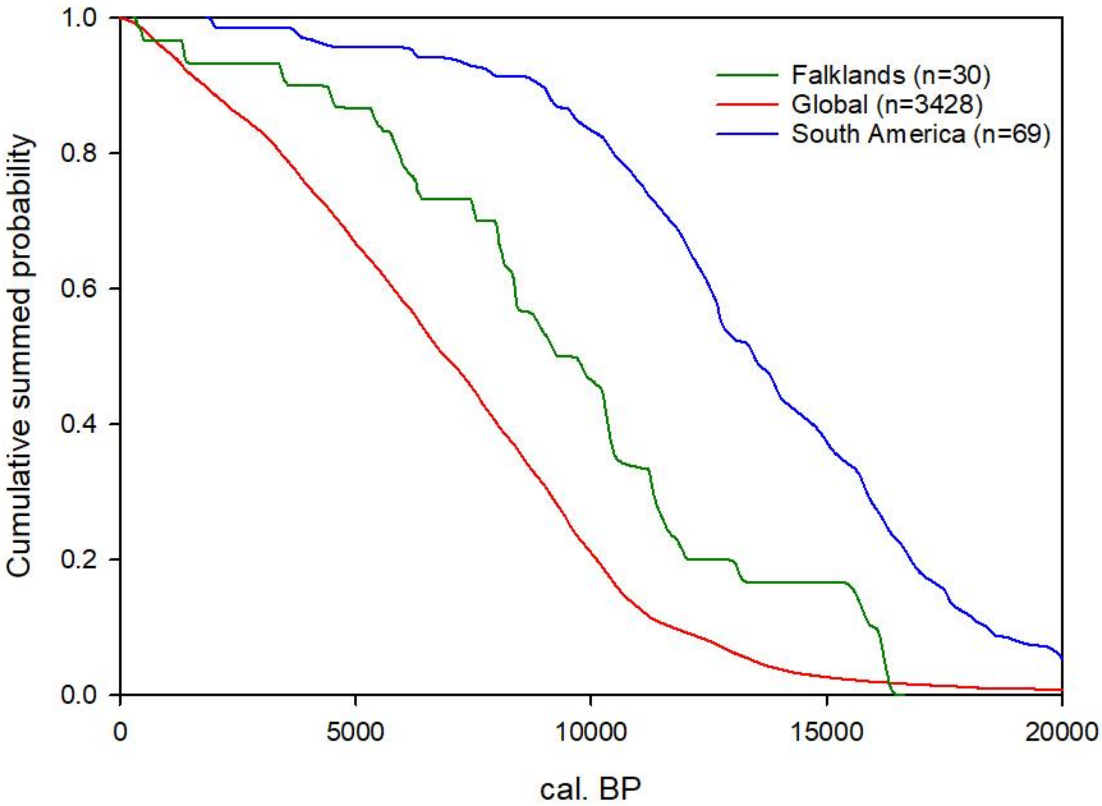



Figure 3. Cumulative summed probability distribution plot of peat initiation $^{14}C$ dates for Falkland Island peatlands (this study) compared to previously-presented datasets for global peat and extra-tropical South America (Treat et al., 2017).

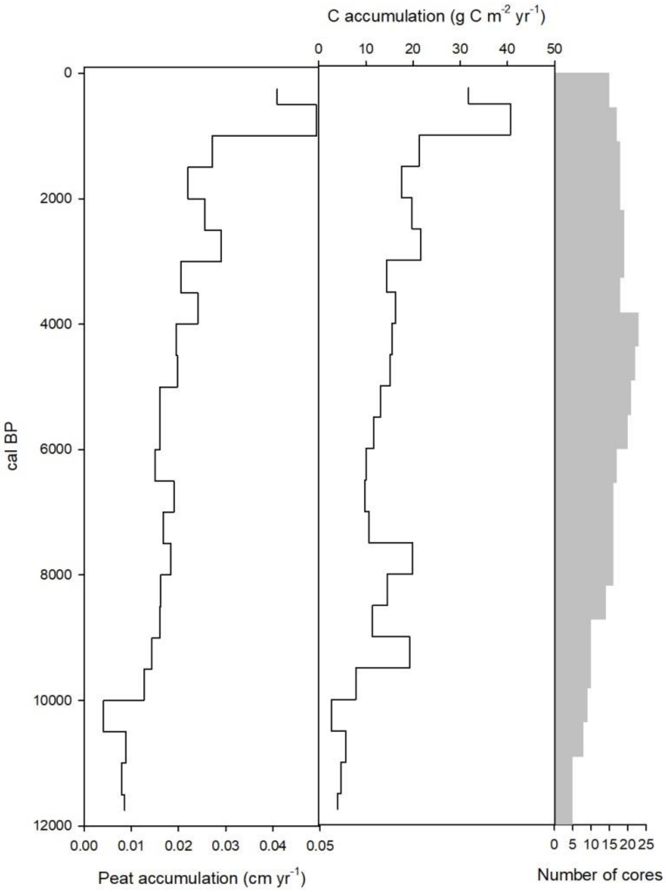


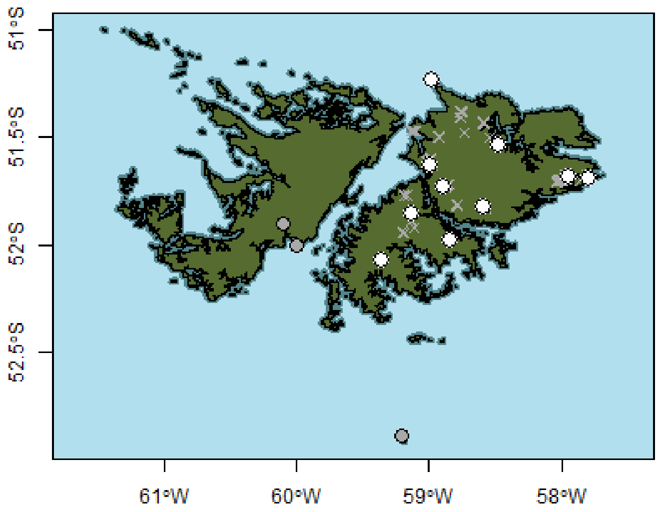

Figure 4. Inferred peat and carbon accumulation in Falkland Island peatlands, based on available data: a) aggregated peat accumulation rate across all sites; b) simulated carbon accumulation; c) number of dated core records contributing to the results.

Table 1. Details of sites, basal dates, peat depth and (full-core) long-term apparent rate of carbon accumulation ($LARCA_{FC}$) for sites in this study.

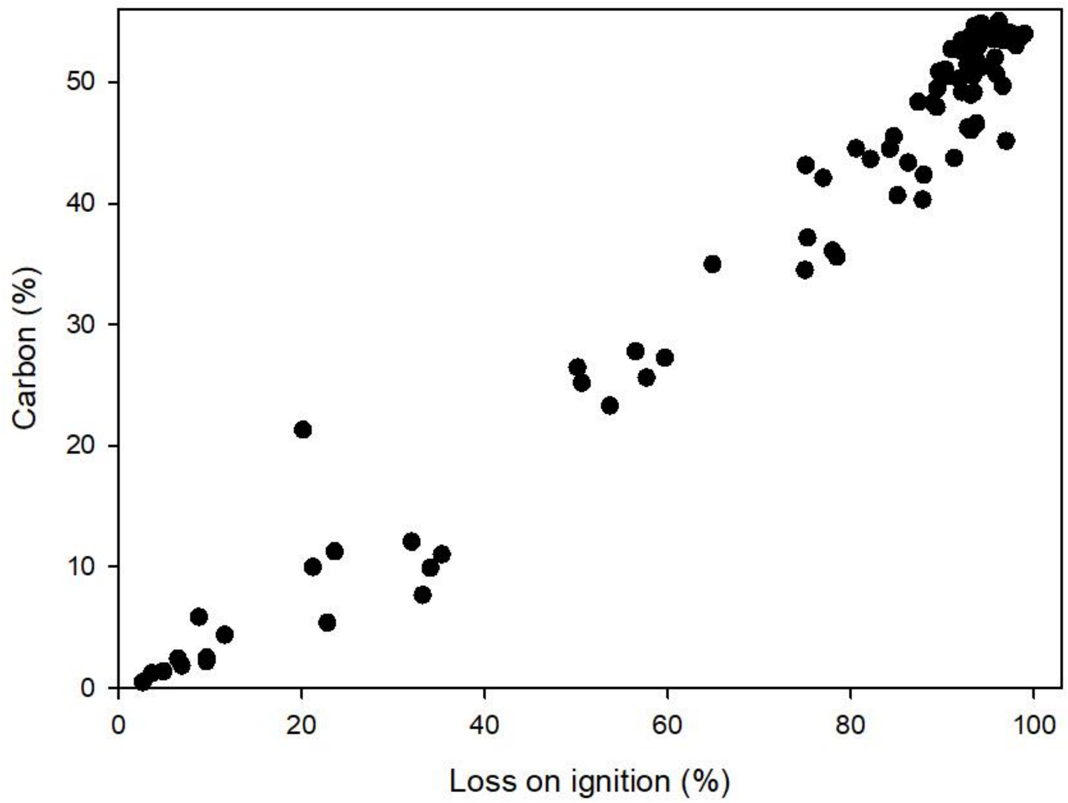
| **Site details** | | | | **Basal $^{14}$C date** | | | **Depth (cm)** | **$LARCA_{FC}$ (g C $m^{-2}$ $yr^{-1}$)** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Name** | **Code** | **S** | **W** | **Code** | **BP** | **Error** | | **Mean** | **5$^{th}$** | **95$^{th}$** |
| *Valley fen* | | | | | | | | | | |
| Swan Inlet | SWI | -51.82 | -58.59 | D-AMS-029687 | 13516 | 60 | 145 | 5.21 | 5.18 | 5.25 |
| *Whitegrass* | | | | | | | | | | |
| Mt. Usborne | USB | -51.73 | -58.89 | D-AMS-030520 | 10002 | 47 | 70 | 4.07 | 4 | 4.11 |
| Walker Creek | WCR | -51.98 | -58.84 | D-AMS-030519 | 1520 | 34 | 34 | 12.08 | 11.62 | 12.48 |
| North Arm | NRA | -52.07 | -59.36 | D-AMS-030518 | 6657 | 42 | 47 | 4.02 | 3.99 | 4.06 |
| Hope Cottage | HOP | -51.54 | -58.48 | D-AMS-030521 | 9924 | 47 | 50 | 2.65 | 2.62 | 2.66 |
| Orqueta | ORQ | -51.85 | -59.13 | D-AMS-029690 | 4740 | 42 | 97 | 10.8 | 10.54 | 11 |
| *Diddle dee* | | | | | | | | | | |
| Moody Brook | MBO | -51.69 | -57.95 | D-AMS-030516 | 7277 | 38 | 105 | 7.13 | 7.05 | 7.2 |
| Whalebone Cove | WBC | -51.69 | -57.80 | D-AMS-030517 | 8041 | 46 | 255 | 19 | 18.73 | 19.34 |
| Sussex Mountains | SSX | -51.63 | -59.00 | D-AMS-029686 | 10089 | 42 | 210 | 10.67 | 10.51 | 10.83 |
| *Tussac* | | | | | | | | | | |
| Cape Dolphin | DPO | -51.24 | -58.99 | D-AMS-029694 | 5542 | 45 | 156 | 32.18 | 31.76 | 32.6 |

## SUPPLEMENTARY FIGURES AND TABLES

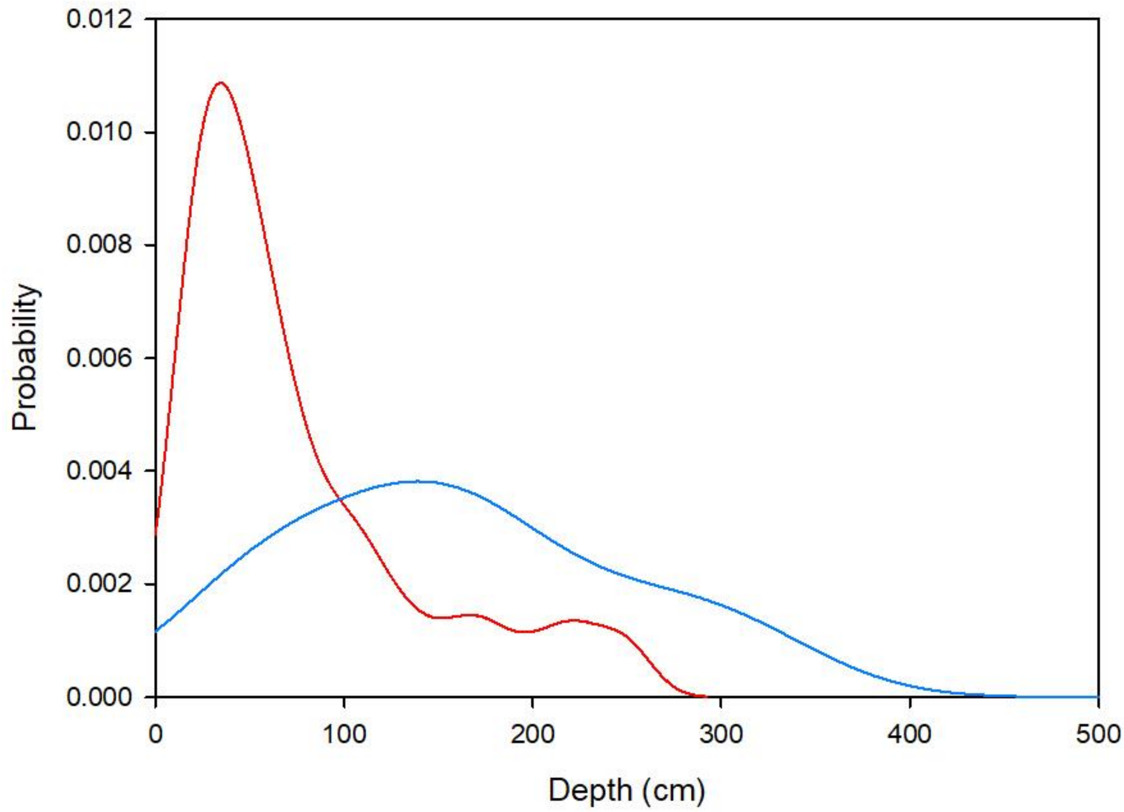

Supplementary Figure 1. Selected images of study sites, demonstrating different types of Falkland Island peatlands: A) Cape Dolphin (Tussac); B) Hope Cottage (Whitegrass); C) Whalebone Cove (Diddle Dee); D) Swan Inlet (Valley).



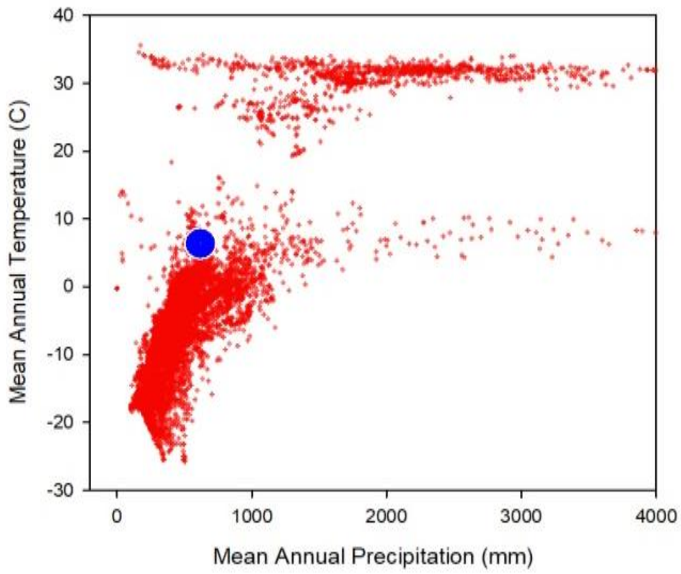

Supplementary Figure 2. Locations of sites considered in this study. Sites of new coring shown by white circles, previously studied coring sites shown by grey circles and sites of depth measurements shown by crosses.



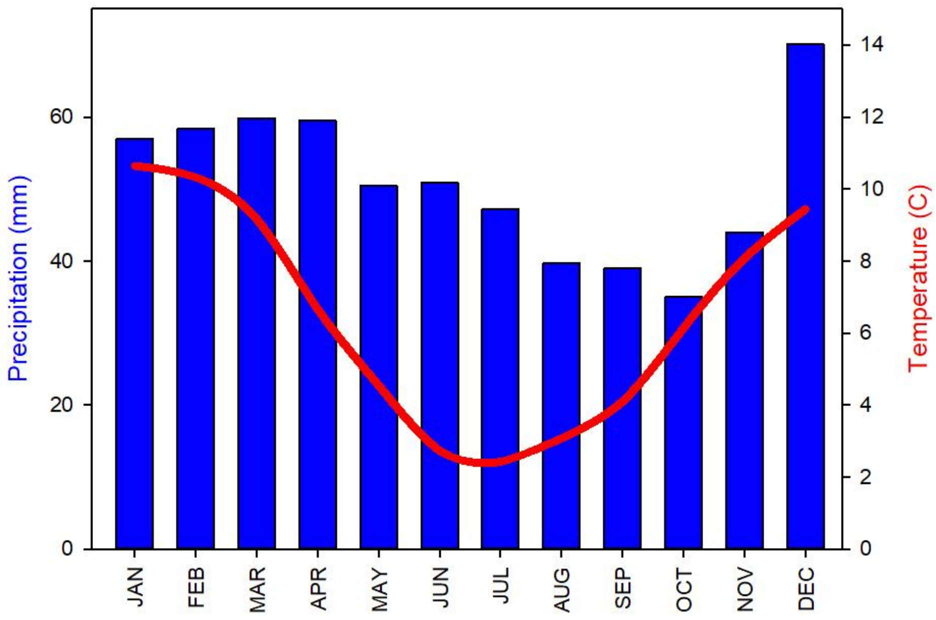

Supplementary Figure 3. Loss on ignition versus carbon content for Falkland Islands peat samples analysed in this study.




Supplementary Figure 4. Kernel density plot comparing total depths of dated cores (blue) to depths derived from a larger dataset of depth measurements from across East Falkland (red). See text for caveats on data quality and comparability.




Supplementary Figure 5. Climate space of global peatlands and the Falkland Islands. Red dots show 10,000 randomly positioned points on the global peat map of Yu et al. (2010) with mean annual temperature and precipitation data extracted from the database of Hijmans et al. (2005). Blue dot shows meteorological data for RAF Mountain Pleasant in central East Falkland (close to the SWI site) for the period 1985-2018. The bimodal temperature distribution of global peatlands represents the distinct climate spaces of tropical and temperate/high-latitude peatlands.




Supplementary Figure 6. Annual variability in precipitation and temperature (Station: RAF Mount Pleasant, 1985-2018).

**DATA AVAILABILITY**

Data underlying this study are available at: [URL to be added on acceptance]

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