

This is a repository copy of *Contemporary carbon fluxes do not reflect the long-term carbon balance for an Atlantic blanket bog*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/118472/>

Version: Accepted Version

Article:

Ratcliffe, Joshua, Andersen, roxane, Anderson, Russell et al. (4 more authors) (2018) Contemporary carbon fluxes do not reflect the long-term carbon balance for an Atlantic blanket bog. *The Holocene*. pp. 140-149. ISSN 0959-6836

<https://doi.org/10.1177/0959683617715689>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Contemporary carbon fluxes do not reflect the long-term carbon balance for an Atlantic blanket bog

Journal:	<i>The Holocene</i>
Manuscript ID	HOL-16-0171.R2
Manuscript Type:	Paper
Date Submitted by the Author:	07-May-2017
Complete List of Authors:	Ratcliffe, Joshua; University of Waikato, School of Science & Engineering, ; Environmental Research Institute, University of the Highlands and Islands Andersen, Roxane; Environmental Research Institute, University of the Highlands and Islands Anderson, Russell; Forest Research, Northern Research Station newton, anthony; University of Edinburgh, School of GeoSciences Campbell, Dave; University of Waikato, School of Science & Engineering, Mauquoy, Dmitri; University of Aberdeen, School of Geosciences Payne, Richard; University of York, Environment Department; Penza State University, Department of Zoology and Ecology
Keywords:	Flow Country, ITRAX, LORCA, peat, tephrochronology, Scotland, carbon accumulation, core scanning
Abstract:	Peatlands are one of the largest terrestrial stores of carbon. Carbon exchange in peatlands is often assessed solely by measurement of contemporary fluxes, however these fluxes frequently indicate a much stronger sink strength than that measured by the rate of C accumulation in the peat profile over longer timescales. Here we compare profile based measurements of C accumulation with the published net ecosystem C balance for the largest peatland area in Britain, the Flow Country of northern Scotland. We estimate the long-term rate of C accumulation to be 15.4 g C m ⁻² yr ⁻¹ for a site where a recent eddy covariance study has suggested contemporary C uptake more than six times greater (99.37 g C m ⁻² yr ⁻¹). Our estimate is supported by two further long-term C accumulation records from nearby sites which give comparable results. We demonstrate that a strong contemporary C sink strength may not equate to a strong long-term sink and explore reasons for this disparity. We recommend that contemporary C sequestration should be viewed in the context of the long-term ecological drivers, such as fires, eco-hydrological feedbacks, and the changing quality of litter inputs.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

1
2
3 **Contemporary carbon fluxes do not reflect the long-term carbon balance for an Atlantic**
4 **blanket bog**
5
6

7
8 Joshua Ratcliffe^{1,2}, Roxane Andersen², Russell Anderson³, Anthony Newton⁴, David
9 Campbell¹, Dmitri Mauquoy⁵ Richard Payne^{6,7}
10
11

12
13 ¹ School of Science & Engineering, University of Waikato, Private Bag 3105, Hamilton 3240,
14 New Zealand.
15
16

17
18 ² Environmental Research Institute, University of the Highlands and Islands, Thurso,
19 Caithness KW14 7JD, United Kingdom.
20
21

22
23 ³ Forest Research, Northern Research Station, Roslin, Midlothian EH25 9SY, United
24 Kingdom.
25
26

27
28 ⁴ School of GeoSciences, University of Edinburgh, Institute of Geography, Drummond
29 Street, Edinburgh EH8 9XP, United Kingdom.
30
31

32
33 ⁵ School of Geosciences, University of Aberdeen, Elphinstone Road, Aberdeen, AB24 3UF,
34 Scotland
35
36

37
38 ⁶ Environment Department, University of York, Heslington, York YO10 5DD, United
39 Kingdom.
40
41

42
43 ⁷ Department of Zoology and Ecology, Penza State University, Krasnaya str. 40, 440026
44 Penza, Russia.
45
46

47
48 Correspondence to: J. Ratcliffe (jlr34@students.waikato.ac.nz)
49
50

51
52 KEYWORDS: Flow Country, ITRAX, core-scanning, LORCA, peat, tephrochronology,
53 Scotland
54
55

Abstract

Peatlands are one of the largest terrestrial stores of carbon. Carbon exchange in peatlands is often assessed solely by measurement of contemporary fluxes, however these fluxes frequently indicate a much stronger sink strength than that measured by the rate of C accumulation in the peat profile over longer timescales. Here we compare profile based measurements of C accumulation with the published net ecosystem C balance for the largest peatland area in Britain, the Flow Country of northern Scotland. We estimate the long-term rate of C accumulation to be $15.4 \text{ g C m}^{-2} \text{ yr}^{-1}$ for a site where a recent eddy covariance study has suggested contemporary C uptake more than six times greater ($99.37 \text{ g C m}^{-2} \text{ yr}^{-1}$). Our estimate is supported by two further long-term C accumulation records from nearby sites which give comparable results. We demonstrate that a strong contemporary C sink strength may not equate to a strong long-term sink and explore reasons for this disparity. We recommend that contemporary C sequestration should be viewed in the context of the long-term ecological drivers, such as fires, eco-hydrological feedbacks, and the changing quality of litter inputs.

A Introduction

1
2
3 Peatlands store more carbon (C) in a given area than any other terrestrial biome (Dise and
4 Phoenix, 2011). They cover only 2-3% of the global land area, but are estimated to store 612
5 GtC (Yu, 2011); equivalent to greater than half the CO₂ currently stored in the atmosphere
6 (Dise, 2009). On a global scale, peatlands have been a persistent sink for atmospheric CO₂
7 throughout the Holocene (Yu, 2011), resulting in a net climatic cooling effect for all but the
8 first few centuries of their initiation (Frolking and Roulet, 2007).
9

10
11 Peatlands are unusual in that they can store C over geological timescales, yet this C is located
12 close to the surface, and is vulnerable to climatic and anthropogenic disturbances (Frolking et
13 al., 2011). Globally, degraded peatlands are thought to be emitting more than 1400 Mt tonnes
14 of CO₂ annually (Joosten, 2009), more than international aviation and marine transport
15 combined (Cames et al., 2015). In Scotland, our study area, degraded peatlands could be
16 responsible for as much as 15% of national greenhouse gas emissions (Smith et al., 2009) and
17 it is estimated that restoration of peatlands could provide up to 2.7 Mt CO₂-eq savings per
18 year (Chapman et al., 2012). The capacity of restored peatlands to halt losses and to store and
19 sequester C in the future has been recognised as a key criterion when prioritising areas for
20 restoration (Artz et al. 2013, Artz et al. 2014). However, for many peatlands there are no
21 reliable baseline C accumulation rates against which to assess losses and gains. These
22 uncertainties are even more acute at the regional scale and for certain peatland types, such as
23 blanket bogs (Lindsay, 2010). As a consequence, peatland C is rarely included in global
24 climate models, despite the potential for strong climatic feedbacks (Limpen et al., 2008).
25

26
27 The two most widely used approaches to assessing C sequestration in peatlands involve
28 measuring contemporary C fluxes to quantify the net ecosystem C budget (NECB), and
29 determining the C accumulated over time in peat profiles. Flux studies focus on quantifying
30 the key inputs and outputs of C from the system. Studies typically involve chamber or eddy
31 covariance (EC) measurements of net CO₂ and CH₄ emission or uptake, combined with
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 measurements of aquatic C fluxes. Such studies have the advantage of quantifying the
4
5 different components of the C budget, with their differing greenhouse warming potentials.
6
7 Eddy covariance towers allow the recording of fluxes from a relatively large footprint, but
8
9 have the important disadvantage of being highly resource-intensive. Therefore such records
10
11 are relatively rare, only span the recent past and frequently omit some elements of the C
12
13 budget such as methane or aquatic C. The longest published flux record for any peatland, the
14
15 Canadian raised bog Mer Bleue, only spans the last 15 years (Humphreys et al., 2014) and,
16
17 Auchencorth Moss, the longest record in the UK, only covers 11 years (Helfter et al., 2015) .
18
19
20
21 To place these relatively short-term NECB records into their long-term context, it is
22
23 necessary to consider the long-term accumulation of C in peatlands. Carbon accumulation
24
25 studies combine analyses of the C content of the peat with a chronology of peat accumulation
26
27 to quantify how much C a peatland has accumulated over time. Such studies have the
28
29 advantage of longer temporal reach, but there are also disadvantages, in that they cannot
30
31 distinguish amongst C fluxes and can only assess the C which is accumulated by the peatland
32
33 and *retained* in the peat. As such, net loss of C will always appear as a slowdown in
34
35 accumulation, or a hiatus in peat growth; negative values are not possible. The latter is an
36
37 important caveat, as factors such as fire or drought may cause peatlands to abruptly lose C
38
39 which had previously been retained for hundreds of years (Frolking et al., 2014). Actuo and
40
41 palaeo C flux/sequestration methods are seldom used in combination (Roulet et al., 2007),
42
43 and when they are, they have not been in agreement (Table I)
44
45
46
47

48
49 **INSERT TABLE I HERE**
50
51
52
53
54
55
56
57
58
59
60

1
2
3 While C accumulation profiles are globally quite numerous (Charman et al., 2013; Korhola et
4 al., 2010; Turunen and Turunen, 2003; van Bellen et al., 2011; Yu, 2011, 2006a), they are
5 relatively rare in some otherwise well-studied regions such as the UK (Lindsay, 2010). Many
6 published profile records have been dated at low resolution, sometimes with only a single
7 dating point (Lindsay 2010). Without a robust chronology, profile studies reveal relatively
8 little about the processes driving C dynamics. In Scotland, three published high-resolution
9 (with four or more evenly spaced dates) C accumulation profiles are available, which span
10 the entire period of bog development (Anderson 2002). Several short profiles do exist for
11 other sites (Billett et al., 2010; Yang et al., 2001), but these have mostly been for the
12 relatively undecomposed acrotelm peat close to the surface, and as such are not representative
13 of either long-term relative C accumulation (LORCA), or indeed the contemporary NECB
14 which includes C exchange across the whole profile, not just the acrotelm.

15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30 Theoretically, measurements of NECB and LORCA should converge as NECB is measured
31 over longer time scales (Frolking and Roulet, 2007; Frolking et al., 2014; Yu, 2012), yet the
32 timescale over which this will occur is relatively unknown (Yu, 2012). A convergence of
33 rates was seemingly apparent in the long record from Mer Bleue (Roulet et al 2007), however
34 recent updates to the NECB record now suggest a contemporary C sequestration rate more
35 than double that implied by peat cores (Roulet et al., 2016).

36
37
38
39
40
41
42
43
44
45
46
47 A six year EC record of C exchange has recently been published for a site in the Flow
48 Country of Scotland, Cross Lochs (Levy & Gray, 2015), making it the third longest published
49 record for C flux over Atlantic blanket bog (Artz et al., 2015) and arguably the only
50 published EC record from a near pristine site (Levy and Gray, 2015). Incorporated in the C
51 balance are measurements of CO₂, CH₄ and DOC. Non CO₂ losses of C accounted for 13% of
52
53
54
55
56
57
58
59
60

1
2
3 the total NECB and were mainly through DOC export. The site was presented as a strong and
4
5 consistent sink for C over the six years, with a reported average NECB of $-99.37 \text{ g C m}^{-2} \text{ yr}^{-1}$.
6
7

8 Using either the contemporary flux or the profile approach in isolation provides an
9
10 incomplete picture of the processes driving C dynamics. In this study, we produced three C
11
12 accumulation profiles to complement C exchange measurements for the Flow Country of
13
14 Caithness and Sutherland. We then used a detailed chronology to assess whether the
15
16 contemporary NECB at the Cross Lochs eddy covariance site is representative of long-term C
17
18 accumulation. Finally, we discuss the factors driving C exchange over different timescales.
19
20
21
22
23
24
25
26
27

28 A Site description

29
30
31
32

33 INSERT FIGURE 1 HERE

34
35

36 We collected and dated cores from three sites in the Flow Country peatlands of Caithness and
37
38 Sutherland (Figure 1). Our key site was Cross Lochs (OS National Grid reference: NC 85095
39
40 44154), which is the site of the eddy covariance tower considered by Levy & Grey (2015).
41
42

43 This site is located within the RSPB Forsinard Flows National Nature Reserve, north west of
44
45 one of the pool systems which are characteristic of the Flow Country (Lindsay et al., 1988).
46
47

48 The coring site was on a gentle slope with vegetation dominated by *Sphagnum spp.* (incl. *S.*
49
50 *cuspidatum*, *S. papillosum* and *S. fallax*), *Calluna vulgaris*, *Trichophorum germanicum* and
51
52 *Eriophorum angustifolium* and a peat depth of 3.68 m. The peat was dominated by *Sphagnum*
53
54 *spp.* and sedge remains with birch macrofossils towards the base. Humification varied down
55
56 core below the acrotelm alternating between H4 and H8 on the von post scale.
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17 To assess the variability of LORCA across the Flow Country blanket bogs, we also sampled
18 two other sites further to the east.

21
22 Catanach (OS National Grid reference: ND 00605 48769) is also located within the RSPB
23 Forsinard Flows National Nature Reserve, approximately 16 km north east of Cross Lochs.
24 The vegetation community was similar to Cross Lochs including *Sphagnum spp.*, along with
25 *Calluna vulgaris*, *Betula nana* and *Arctostaphylos uva-ursi*, the peat was shallower (1.76 m)
26 and the stratigraphy showed a mixture of *Sphagnum* and sedge peat which was more
27 humified than at the other sites, typically H7 or above in the catotelm peat.
28
29

30
31
32
33
34
35
36 Bad a' Cheo (OS National Grid reference: ND 16500 50174) is the easternmost sampling
37 site, located in an area which has been enclosed from grazing, except by deer, since 1968,
38 close to the A9 road. The vegetation is dominated by *Sphagnum spp.*, with *Calluna*
39 *vulgaris* and *Eriophorum spp.* present, but less abundant than in the other sites. The peat
40 depth at this site was 4.46 m. *Sphagnum spp.* remains were more abundant in the core
41 stratigraphy compared to the previous sites; however, layers of sedge peat were also
42 present. Birch wood was found in the bottom section of the core and humification was
43 low, H4-H6, in the catotelm peat and the vegetation composition was disenable even
44 close to the base of the core.
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6 A Methods
7
8
9
10

11
12
13
14 B Coring strategy
15
16
17
18
19
20
21
22

23 Cores were taken in October 2013 using a 7 cm diameter, 1 m long Russian peat corer
24 (Belokopytov & Beresnevich 1955 in: Jowsey 1966). Sampling was carried out from the
25 midpoint between hummock and hollow microforms down to the mineral substrate, using the
26 twin borehole method with 10 cm overlaps in order to minimise the risk of core compression,
27 as outlined by De Vleeschouwer et al. (2010). The two boreholes were no more than 0.3 m
28 apart. In the Cross Lochs site the coring point was selected to be towards the centre of the EC
29 tower footprint. Cores were transported and stored horizontally to avoid compression and
30 refrigerated until analysis.
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

47 B Bulk density, loss on ignition and carbon content analysis
48
49

50 Bulk density (ρ) measurements were carried out at 1 cm resolution for the Cross Lochs core
51 and at 5 cm resolution for the other cores. Only a single sample was analysed for the
52 uppermost 5 cm of the Cross Lochs core, due to the fibrous nature of the peat. Sample
53 volume was determined using the water displacement method (Chambers et al., 2011). Wet
54
55
56
57
58
59
60

1
2
3 peat samples, approximately 10-20 cm³ in size, were carefully removed from the cores and
4
5 placed into a volumetric cylinder and water volume displaced recorded. Samples were dried
6
7 overnight at 105°C, and ground sub-samples incinerated at 550°C for 4 hours. The difference
8
9 in weight before and after incineration was used to calculate loss on ignition.
10

11
12 C and N content was determined using an elemental analyser (Caro Erba 1108, University of
13
14 Stirling), calibrated for each run using rice flour standards with standard checks every 10 to
15
16 12 samples. Loss on ignition and C content was measured at 5 cm resolution and values for a
17
18 small number of missing segments (for instance due to low sample size in low density peat)
19
20 were interpolated.
21
22

23 24 25 26 27 B Tephrochronology

28
29
30
31
32
33
34
35
36 Cryptotephrochronology offers the potential for high-precision dating, but at the expense of
37
38 the time-consuming process of locating tephra shards (Gehrels et al., 2008). However,
39
40 advances in multi-sensor core scanning offers the opportunity to speed up this process. The
41
42 use of an 'ITRAX' scanner, which combines X-ray fluorescence (XRF) and X-radiography,
43
44 has been shown to be effective for locating cryptotephra in lake sediments (Kylander et al.,
45
46 2011). X-radiography has previously shown good potential for locating larger cryptotephra
47
48 layers in the north of Scotland (Dugmore and Newton, 1992)
49

50
51
52 Multi-sensor core scanning was carried out using the ITRAX core scanner (Cox Analytical
53
54 Systems) at the University of Aberystwyth. High-resolution (0.2 mm) X-radiographs were
55
56 produced for all cores. XRF elemental profiles were produced at 0.2 mm resolution for Cross
57
58
59
60

1
2
3 Lochs and 2 mm for the other sites. Tephra layers were identified by: 1) visible black bands
4 in the X-radiographs; 2) peaks in key elements such as Fe, Ca, Ti and Mn in the XRF-
5 profiles, and 3) distinct troughs in the loss on ignition data. Where at least one of these
6 features was apparent, 1 cm thick samples spanning the zone of interest were sub-sampled.
7
8 Samples were incinerated in a muffle furnace at 550°C for 4 hours, when necessary they were
9 soaked in 10% HCl to remove coloration from the ash and mounted on a slide for analysis as
10 described by Pilcher and Hall (1992). These samples were examined microscopically at ×400
11 magnification and tephra shards identified by their distinctive morphology.
12
13

14
15
16 A total of four tephra layers were found which contained quantities of shards sufficient for
17 geochemical analysis. In order to link these tephra deposits to eruptions of known age they
18 were geochemically analysed by electron probe microanalysis (EPMA). Peat samples
19 containing tephra from the relevant horizons were acid digested following Dugmore et al.
20 (1992), and thin sections were prepared by mounting the shards in resin, grinding to a
21 thickness of 75 µm and polishing until smooth using 6 µm and 1 µm diamond pastes
22 (Dugmore et al. 1995).
23
24
25
26
27
28
29
30
31
32
33
34
35
36

37 Shards were analysed using Wavelength Dispersive Spectrometry (WDS) on a Cameca
38 SX100 electron microprobe at the School of Geosciences, University of Edinburgh (see
39 supplementary data). The microprobe was set to an accelerating voltage of 15 kV, with a
40 beam current of 2 nA (Na, Mg, Al, Si, Ca, Fe, and K) and 80 nA (Ti, Mn and P). A beam
41 diameter of 5 µm was used to prevent mobilisation of sodium. Standards of basaltic (USGS
42 BCR2g) and rhyolitic (Lipari obsidian) glasses were measured alongside the tephra to assess
43 analytical performance. Full details of the settings are presented in Hayward (2012).
44
45
46
47
48
49
50
51
52

53 Tephra layers were linked to known eruptions through comparison with published elemental
54 data from TephraBase (Newton et al., 2007) with a particular focus on the Hekla-4 and Glen
55
56
57
58
59
60

1
2
3 Garry tephtras which were both expected to be found in our sites (Newton et al., 2007). Based
4
5 on the recommendations in Dugmore et al. (1995), distinctive oxide ratios of FeO and TiO₂
6
7 were primarily used in the identification of Hekla 4 while CaO and MgO ratios were used for
8
9 Glen Garry.
10

11
12
13
14
15
16
17
18 B Radiocarbon dating
19
20
21
22
23
24
25
26

27 Macrofossils of above-ground and near surface material were located within the peat core and
28
29 cleaned in preparation for radiocarbon analysis. Samples selected for ¹⁴C dating comprised
30
31 *Sphagnum austinii* leaves, *Molinia caerulea* rhizomes, woody twigs of *Betula spp.*, stems of
32
33 unidentified brown mosses and charcoal fragments. Eleven samples were dated from the full
34
35 length of the Cross Lochs core and one sample each from the base of each of the Catanach
36
37 and Bad a' Cheo cores (Table II). Samples were dated at the Poznan Radiocarbon Laboratory
38
39 (Poznan, Poland) and DirectAMS (Washington, USA).
40
41
42
43
44
45
46
47
48

49 B Age-depth models and carbon accumulation
50
51
52
53
54
55
56
57
58
59
60

1
2
3 Age-depth models were constructed using the Bayesian modelling package BACON (Blaauw
4 and Christen, 2011), using a combination of tephra and AMS radiocarbon dates. The
5
6 calibrated age of the Hekla 4 eruption had a much lower chronological error associated with
7
8 the calendar age and was therefore particularly useful in constraining the model. BACON
9
10 uses prior information such as plausible accumulation rates and the law of superposition to
11
12 A reduce uncertainty and produce a more realistic model (Blaauw and Christen, 2011). Priors
13
14 for accumulation mean, accumulation shape and memory mean were set at default values
15
16 based on the compilation of Goring (2012). Data on bulk density and C content were
17
18 combined with the BACON age-depth models to produce reconstructions of C accumulation
19
20 which incorporate temporal uncertainty.
21
22
23
24

25 RESULTS

26 B Tephrochronology

27
28
29
30
31
32 Four identifiable tephra layers were found. Two in the Bad a' Cheo core, BADO 134.3 and
33
34 BADO 200.1, and one each in Catanach and Cross Lochs cores, CATO 116.7 and CRSLO
35
36 165.6 respectively. Geochemical analyses produced results which strongly correlated with the
37
38 Hekla 4 eruption (c. 4287 ± 58 cal. BP; Pilcher et al. (1996)) for three of the tephra layers:
39
40 BADO 200.1, CATO116.7 and CRSLO 165.6 (Figure 2), and the Glen Garry eruption (c.
41
42 2176 ± 244 cal. BP; Barber et al., (2008)) for the remaining layer: BADO 134.3 (Figure 3;
43
44 Supplementary material). These four tephra layers were used in the age/depth models. An
45
46 additional tephra layer with geochemistry strongly matching that of the Lairg A eruption was
47
48 also found in analysable quantities at 2.28 m depth, in a core taken 200 m away from Bad a'
49
50 Cheo within a conifer plantation (Ratcliffe, 2015). Three more potential tephra layers were
51
52 detected in the Cross Lochs core, but due to the low density of shards we were unable to
53
54
55
56
57
58
59
60

1
2
3 correlate them to an eruption using EPMA. More details of these can be found in (Ratcliffe,
4
5 2015).
6
7

8 **INSERT FIGURE 2 HERE**
9

10
11
12
13 **INSERT FIGURE 3 HERE**
14
15
16
17

18
19
20 B Radiocarbon dating
21
22
23
24
25
26
27

28 Radiocarbon dates ranged from 1885 ± 30 to 9287 ± 32 BP (Table II) and generally had low
29 error, with a mean uncertainty of ± 127 years in the 1σ calibrated age. All dates conformed to
30 the law of superposition, with one exception. Poz-62766 was much younger than expected,
31 and this date is suspected of being inaccurate. The radiocarbon lab noted that Poz-62766
32 contained less than the minimum advisable weight of C. It was included in the age-depth
33 modelling; but the preferred model does not pass through it. Radiocarbon dating suggests
34 peat initiation at 9491-9558 1σ cal BP for Cross Lochs, 5745-5910 1σ cal. BP. for Catanach,
35 and 8455-8855 1σ cal. BP. for Bad a' Cheo (Table II).
36
37
38
39
40
41
42
43
44
45

46 **INSERT TABLE II HERE**
47
48
49
50
51
52
53
54
55
56
57

58 B Age-depth models
59
60

1
2
3
4
5
6 An age-depth model was produced for each site (Figure 4) to show the estimated uncertainty
7
8 in the age of peat throughout the profile. The Cross Lochs core is better constrained, with less
9
10 uncertainty for peat age at a given depth compared to Bad a' Cheo and Catanach. The time
11
12 period from 2 ka to 4 ka cal. BP. is perhaps the best constrained, whereas uncertainty is
13
14 higher for both the last 2 ka and for the early Holocene.
15
16

17
18 **INSERT FIGURE 4 HERE**
19
20
21
22
23
24
25
26
27
28
29
30
31

32 **B Carbon accumulation**
33
34
35
36

37 Peat has accumulated throughout the Holocene, with no evidence for any hiatuses (Figure 5).
38
39 Accumulation rates varied between 8 and 32 g C m⁻² yr⁻¹. Cross Lochs had an average C
40
41 accumulation rate of 15.43 ± 5.06 g C m⁻² yr⁻¹ while for Catanach it was 16.47 ± 4.20 g C m⁻²
42
43 yr⁻¹. The average C accumulation rate for the Bad a' Cheo profile was 17.43 ± 4.90 g C m⁻²
44
45 yr⁻¹.
46
47

48
49 At Cross Lochs, the C accumulation rate was generally slightly higher than average in the
50
51 early Holocene, and decreased rapidly at c. 6030 cal. BP. Carbon accumulation began to
52
53 increase again just before c. 4570 cal. BP. and peaked around c. 2890 ka cal. BP. before
54
55
56
57
58
59
60

1
2
3 decreasing rapidly. There was then a slow increase in C accumulation up to the boundary
4
5 with the acrotelm (Figure 5).
6
7

8 Results for the Catanach site imply that carbon accumulation was most rapid in the first 2560
9
10 years after initiation, with rates in the region of 16-20 g C m⁻² yr⁻¹, followed by a decrease
11
12 down to 12-15 g C m⁻² yr⁻¹ which persisted until c. 940 cal BP (Figure 5) and the transition
13
14 zone to acrotelm peat.
15
16

17
18
19
20
21 **INSERT FIGURE 5 HERE**
22
23
24
25
26
27
28

29 Bad a' Cheo also had relatively higher carbon accumulation rates during the early Holocene,
30
31 with a decrease around 6520 cal BP. Carbon accumulation was fairly stable until just before c
32
33 4 ka cal. BP. when it declined and remained low until around 2 ka cal. BP. There was then a
34
35 rapid increase in the average rate of carbon accumulation similar to levels recorded between
36
37 c. 6-4 ka cal. BP. (Figure 5).
38
39

40 Carbon accumulation rates in the Cross Lochs and Bad a'Cheo cores during the early to mid-
41
42 Holocene were consistently above the long-term averages for these sites and both decreased
43
44 around 6.5-6 ka cal. BP. At that time, the younger Catanach peatland commenced peat
45
46 formation. Changes in C accumulation rates for the late Holocene are more contradictory,
47
48 with the period of c. 4-2.5 ka cal. BP. representing the highest accumulation rates for the
49
50 Cross Lochs core, the lowest for Bad a' Cheo, and intermediate values for Catanach. Carbon
51
52 accumulation rates between 2 ka – 750 cal. BP. years for Bad a' Cheo and Catanach were
53
54 close to the long-term mean, while at Cross Lochs accumulation rates were amongst the
55
56
57
58
59
60

1
2
3 lowest seen since bog development was initiated. However, interpretation of the Bad a'Cheo
4
5 and Catanach records is limited by the available dating points.
6
7
8
9
10

11
12
13
14 A Discussion
15
16
17
18
19
20

21
22 B Carbon accumulation and climate in peatlands of northern Scotland
23
24
25
26
27
28
29
30

31 LORCA for the three sites in our study was $16.44 \text{ g C m}^{-2} \text{ yr}^{-1}$, slightly lower than the value
32
33 of $21.3 \text{ g C m}^{-2} \text{ yr}^{-1}$ reported for three sites in the North West Highlands by Anderson (2002)
34
35 However, these rates are very similar to the mean rate of $18.6 \text{ g C m}^{-2} \text{ yr}^{-1}$ estimated for
36
37 northern peatlands globally (Yu, 2011). Our values include C stored across the whole profile
38
39 including the acrotelm, as do the majority of published values for LORCA. However, long-
40
41 term peat accumulation depends on the transfer of organic material from the acrotelm to the
42
43 catotelm (Wieder, 2001) and the proportion of primary production which actually reaches the
44
45 catotelm is highly variable (Yu et al., 2001). This proportion depends on factors such as litter
46
47 quality, litter turnover and acrotelm (water table) depth (Bauer, 2004). Thus, the inclusion of
48
49 the acrotelm will overestimate the long term C accumulation rate as younger peats have
50
51 undergone relatively less decomposition than older peats (Clymo et al., 1998) . It is difficult
52
53 to predict what proportion of organic matter in the acrotelm will be transferred to the
54
55 catotelm. For example, the recent rate of C accumulation (RERCA) for Scottish peats has
56
57
58
59
60

1
2
3 been found to be 35-209 g C m⁻² yr⁻¹ over the last 150 years (Billett et al., 2010), which for
4
5 our cores would represent approximately the top 0.1 m of the profile, or the upper half of the
6
7 acrotelm. It is difficult to say how much of this RERCA will be *retained* in the peat over a
8
9 given time period without considering the individual ecohydrological properties of the
10
11 peatland. In a review of several thousand peat profile measurements, RERCA was found to
12
13 be poorly correlated to LORCA (Turunen, 2003).
14
15

16
17 Initiation of peat development was not uniform across sites. Peat formation at Cross Lochs
18
19 and Bad a' Cheo commenced in the early Holocene, which was a period of both rapid lateral
20
21 expansion and C accumulation for northern peatlands globally (Yu et al., 2009). Whilst at
22
23 Catanach peat accumulation did not occur until the mid-Holocene at 5.7-5.9 ka cal. BP, and
24
25 coincided with a decline in tree cover and an increase in *Calluna* pollen at the regional scale
26
27 between 6.8 and 4.6 ka cal. BP (dates published in Charman., (1994) and calibrated here for
28
29 comparative purposes using Oxcal) which may be linked to bog expansion (Charman, 1994,
30
31 1992). At all three sites in this study, the peat was directly underlain by bedrock or glacial till
32
33 and no evidence of lake mud was found, indicating that paludification, rather than
34
35 terrestrialisation was the dominant process in peatland initiation.
36
37

38
39 Perhaps the most dramatic change in Holocene C accumulation rates (Figure 5) occurred at
40
41 approximately 4.4 ka cal. BP. During this time, *Pinus sylvestris* colonised a large area of
42
43 Scottish blanket bog in response a drying of the climate, which may have been induced by a
44
45 migration of the jet stream northwards (Gear and Huntley, 1991). About four centuries later,
46
47 the regional climate became wetter and colder (Anderson et al., 1998), triggering the regional
48
49 extinction of *P. sylvestris* located on blanket bog (Gear and Huntley, 1991). In a nearby
50
51 pollen core, the pollen assemblage shows a rise in *Empetrum nigrum* immediately prior to the
52
53 sudden and short-lived peak in *P. sylvestris*, supporting the hypothesis of drier regional
54
55 conditions at this time (Charman, 1990).
56
57
58
59
60

1
2
3 Only the core chronology for Cross Lochs is detailed enough at this point in the stratigraphy
4
5 (Table 2) to interpret sub-millennial changes, which may explain the differing response in C
6
7 accumulation seen for Catanach and Bad a' Cheo. There was a moderate increase in C
8
9 accumulation at Cross Lochs during the dry period between 4.3-3.9 ka cal. BP followed by a
10
11 much greater increase in the wet period from 3.9 - 3.3 ka cal. BP. Carbon assimilated as leaf
12
13 litter is particularly sensitive to climate for a period of decades to centuries after fixation,
14
15 while it is stored in the aerobic acrotelm (Frolking et al., 2014). Therefore it is important to
16
17 note that the better preservation conditions of the wet period may have resulted in better
18
19 preservation of the C fixed during the preceding dry period.
20
21

22
23 These findings are in agreement with those for the same time period published in Anderson
24
25 (2002), but are somewhat contradictory to when compared to other findings from later time
26
27 periods. Changes in solar activity and the length of growing season have been found to be the
28
29 dominant drivers of C accumulation at the centennial scale during the late Holocene
30
31 (Charman et al., 2013; Mauquoy et al., 2008, 2002). However, as the response of peatland C
32
33 to changes in climate and hydrology is often non-linear (Laiho, 2006; Swindles et al., 2012),
34
35 fair comparisons cannot be made unless the same time period, and therefore the same
36
37 climatic drivers, are being compared. Our results and those of Anderson (2002) indicate some
38
39 of the most dramatic changes in Holocene peatland C accumulation have occurred in the mid-
40
41 Holocene, around the time of the temporary expansion of *P. sylvestris* on to blanket bog.
42
43 Therefore, we suggest this may be one of the most interesting periods to study environmental
44
45 drivers of peatland C accumulation.
46
47
48
49
50

51
52
53
54 B The potential utility of core scanning
55
56
57
58
59
60

1
2
3
4
5
6 A major limitation to producing more records of Holocene C accumulation is the cost of
7
8 dating date peat cores at high resolution (Payne et al., 2016). Tephrochronology offers the
9
10 potential for precise dates, but at the expense of time-consuming analyses. We found that
11
12 core scanning was capable of rapidly locating cryptotephra. Denser layers, such as
13
14 CRSLO165.6, were immediately obvious, showing up as dark bands on the X-radiograph,
15
16 similar to those reported by Dugmore & Newton (1992) and producing distinguishable peaks
17
18 across a range of elements. However, these were not found to be representative of the more
19
20 detailed geochemistry recorded in Figures 2 & 3. Smaller layers such as BADO134.3 induced
21
22 a more subtle response, with no visible band on the X-radiograph and element peaks barely
23
24 visible above background levels. All peaks in the elemental data needed to be verified for the
25
26 presence of tephra using optical microscopy and many false positives were found, but the
27
28 reduction in labour was still considerable. We therefore believe that wider adoption of core
29
30 scanning may encourage the greater use of tephrochronology in peatland palaeoecological
31
32 research. The core scanner also revealed several distinct cryptotephra layers in the Cross
33
34 Lochs core which had shard concentrations too low to be successfully analysed. However,
35
36 chronostratigraphic matching indicates that the layer located at 1.383 m might have
37
38 originated from the Hekla-S/Kebister eruption, and the layer at 2.520 m from Lairg A. The
39
40 presence of at least 14 identifiable cryptotephra layers in Scotland (Swindles et al., 2011)
41
42 demonstrates the potential of tephrochronology for contributing to the chronology of future
43
44 profile-based estimates of C accumulation.
45
46
47
48
49
50
51
52
53
54
55

56
57 B Comparison of core-based and EC flux-based carbon accumulation rate estimates
58
59
60

1
2
3
4
5
6
7
8
9 The LORCA calculated for Cross Lochs, $15.43 \text{ g C m}^{-2} \text{ yr}^{-1}$, is much lower than that of the
10
11 NECB of $99.37 \text{ g C m}^{-2} \text{ yr}^{-1}$ published in Levy & Grey (2015). Such differences between
12
13 LORCA and contemporary NECB seem to be the norm rather than the exception (Table I),
14
15 although the number of sites for which both data are available is admittedly small. Lac la
16
17 Biche, Moanatuatua and Moor House (Table I), show particularly large differences in C
18
19 accumulation derived from the two approaches, with NECB approximately three to six times
20
21 greater than LORCA. This is despite having inter-annual flux datasets and allowing for
22
23 measured, or realistic estimates, of non-CO₂ fluxes. For example C losses through CH₄
24
25 emissions from bogs, which constitute all sites in Table 1 with the exclusion of Lac la Biche,
26
27 typically do not exceed 8 g C yr^{-1} (Roulet et al., 2007). For fens, of which Lac la Biche is an
28
29 example, CH₄ emissions may be higher but would not typically exceed 35 g C yr^{-1}
30
31 (Bäckstrand et al., 2009). The export of DOC from intact peatlands is typically $10\text{-}20 \text{ g C m}^{-2}$
32
33 yr^{-1} (Baird et al., 2009) but may be as high as $25\text{-}40 \text{ g C m}^{-2} \text{ yr}^{-1}$ for drained peatlands (Billett
34
35 et al., 2004; Dinsmore et al., 2010; Strack and Zuback, 2013). Consequently, non-CO₂ fluxes
36
37 would need to be unrealistically high to explain the discrepancy between contemporary and
38
39 long-term C balance for the three sites in Table 1 which do not include DOC and CH₄. As
40
41 such contemporary C accumulation is clearly greater than long-term C accumulation at a
42
43 range of sites across the world, despite the slowdown in C accumulation which might be
44
45 expected as peatland ecosystems mature (Clymo et al., 1998). Possible explanations for this
46
47 may be found in the operational time scales of different drivers of peatland C dynamics (Yu,
48
49 2006b). The drivers of C accumulation over centennial to millennial timescales should not be
50
51 expected to be the same as those driving inter-annual variation (Frolking et al., 2014).
52
53
54
55
56
57
58
59
60

1
2
3 For example, the flux density of photosynthetically available radiation (PAR) usually drives
4
5 fluxes at daily or shorter timescales, through the impact on plant photosynthesis. While PAR
6
7 is highly variable from day to day and also century to century (Mauquoy et al., 2008), inter-
8
9 annual variability in PAR can be quite low (Strachan et al., 2016). As such, at the inter-
10
11 annual scale precipitation and temperature may be better predictors of C dynamics (Peichl et
12
13 al., 2014; Strachan et al., 2016). This is not because precipitation and temperature are
14
15 fundamentally more important to peatland C balance, but because they tend to show greater
16
17 variance than PAR over that interval. Similarly variance in other drivers of peatland C
18
19 accumulation, such as vegetation type, fire and low-frequency changes in climate (Frolking et
20
21 al., 2014; Turetsky et al., 2002) will be close to zero over the intervals eddy covariance can
22
23 practically measure, but could become a significant, or even dominant, source of variance
24
25 over longer intervals. The environmental drivers of C dynamics in peatlands, over a given
26
27 time period, will be strongly influenced by the variance in drivers that occurs over that
28
29 period. Lack of variance over the timescales measured means some important drivers of the C
30
31 balance simply cannot be accounted for.
32
33
34
35

36
37 Fire is known to be a particularly important component of long term C dynamics (Pitkanen et
38
39 al., 1999) and plays a prominent role in the functioning of the majority of northern peatlands
40
41 (Turetsky et al., 2015). However, including fires in the contemporary peatland C balance is
42
43 impractical as they occur only intermittently. At Cross Lochs, fire has been common since the
44
45 early Holocene (Charman, 1992; Robinson, 1987) and charred *Calluna* remains have been
46
47 found in the surface peat not far from the EC site (Charman 1990). A single fire event may
48
49 release C accumulated over a century or more (e.g. 140 years; Pitkanen et al., 1999), and
50
51 may reduce C uptake in peatlands by as much as 85% over their developmental history
52
53 (Turetsky et al., 2002). This lost C, and associated peat depth, will cause an apparent slowing
54
55 of the long-term C accumulation rate. Contemporary C sink strength can then be increased
56
57
58
59
60

1
2
3 for up to 75 years following a fire as vegetation recovers (Harden et al., 1997; Trumbore and
4
5 Harden, 1997; Ward et al., 2007; Wieder et al., 2009). Depending on the timing of
6
7 measurements, this may result in a situation where C losses from fire are not recorded in the
8
9 contemporary C balance, but increased C sequestration after the fire is recorded. If this occurs
10
11 then the contemporary C sink would be expected to be greater than the long term C
12
13 accumulation rate.
14
15

16
17 The relationship between environmental variables and C dynamics becomes increasingly
18
19 complex over longer timescales and strong relationships recorded over inter-annual
20
21 timescales cannot always be assumed to stand up over longer time periods. The indirect
22
23 effects of environmental drivers on peatland C dynamics will be moderated through
24
25 ecohydrological feedbacks operating over many decades (Laiho, 2006; Waddington et al.,
26
27 2015). These feedbacks can result in either an amplification, or a dampening, of the influence
28
29 of an environmental conditions on peatland C dynamics (Laiho, 2006; Swindles et al., 2012;
30
31 Waddington et al., 2015). For example, feedbacks between water table, decay and peat
32
33 hydraulic conductivity may cause decay rates to be relatively insensitive to changes in
34
35 precipitation over long periods of time (Swindles et al., 2012; Waddington et al., 2015). Yet
36
37 alternatively, positive feedbacks may enhance the impact of changes in precipitation on C
38
39 balance through changes in vegetation, modification of transpiration rates and further
40
41 lowering of the water table (Waddington et al., 2015). Thus thresholds of peatland
42
43 ecohydrological response, i.e. whether negative or positive feedbacks will be dominant, and
44
45 over what timescale, are an important considerations to be made when assessing the
46
47 environmental drivers of peatland C balance (Limpens et al., 2008).
48
49
50
51

52
53 Carbon sequestration rates close to $100 \text{ g C m}^{-2} \text{ yr}^{-1}$ in ombrotrophic bogs are likely to be
54
55 unsustainable in the long-term, as values of C accumulation inferred from profile
56
57 measurements rarely come close to $100 \text{ g C m}^{-2} \text{ yr}^{-1}$ and have only ever been recorded for
58
59
60

1
2
3 peatlands in the early stages of initiation (Page et al., 2004; Pendea and Chmura, 2012) or for
4
5 fen peats in response to rapid changes in hydrology (Yu et al., 2003). Litter inputs into
6
7 peatlands typically undergo comparatively rapid decay in the acrotelm for a period of decades
8
9 to centuries (Malmer and Wallén, 2004) before passing into the relatively stable catotelm.
10
11 The portion of the photosynthetically-fixed C which reaches the catotelm will depend on the
12
13 amount of decay this material undergoes. This is controlled by factors such as mean position
14
15 and variability of the water table depth, along with temperature and the properties of the litter
16
17 inputs (Bauer, 2004; Clymo et al., 1998). Short-term increases in C accumulation can actually
18
19 represent changes in acrotelm thickness, rather than any change in input to the relatively
20
21 stable catotelm (Belyea and Clymo, 2001). This could be expected in bogs where vascular
22
23 plant cover is increasing, resulting in higher, but more easily decomposable, litter inputs
24
25 (Malmer et al., 2005; Waddington et al., 2015). For example, the primary production in
26
27 sedge-dominated fens is usually much higher than in *Sphagnum* bogs, yet C accumulation is
28
29 on average lower for fen peats due to differences in litter quality (Rydin et al., 2006;
30
31 Turunen, 2003). The stability of C added to the acrotelm, and the portion of it which
32
33 ultimately reaches the long-term store in the catotelm, should be considered when assessing
34
35 the sink strength of a peatland based on the contemporary NECB.
36
37
38
39
40
41
42
43

44 It has been hypothesised that environmental change has caused an increase in NECB, relative
45
46 to Holocene C accumulation rates, across northern peatlands (Yu, 2012) and this could be the
47
48 case at Cross Lochs. The specific drivers of this change could include lengthening of the
49
50 growing season, increased nitrogen deposition, and CO₂ enrichment, all of which have been
51
52 predicted to cause an increase in peatland C accumulation rates (Charman et al. 2013).

53 Nitrogen deposition for Forsinard has been estimated at 6.3 kg N ha⁻¹ yr⁻¹, a value which is
54
55 lower than much of the UK, but is high enough to impact on many peatland vegetation
56
57
58
59
60

1
2
3 communities (Payne, 2014). The growing season has increased by more than five weeks
4
5 relative to 1961 (Sniffer, 2014). CO₂ enrichment has been demonstrated to increase primary
6
7 production in forests by as much as 25% (DeLucia et al., 1999). While the effects of CO₂
8
9 enrichment on nutrient poor peatlands appear to be small (Hoosbeek et al., 2001). However
10
11 the combined effects of increased N deposition and CO₂ enrichment have seldom been
12
13 explored (Siegenthaler et al., 2010). Modelling of peatland C processes is required to ‘bridge
14
15 the gap’ between NECB and LORCA (Bauer, 2004) and can be used to forecast the fate of
16
17 recently fixed C. This has proved to be challenging thus far because of the numerous
18
19 interacting processes and feedbacks involved in peatland ecohydrology (Waddington et al.,
20
21 2015) and the lack of good palaeo and contemporary data on C accumulation and ecological
22
23 parameters at the site level, such as decay and productivity rates. Locating palaeoecological
24
25 work at flux sites, and conversely locating new flux sites in peatlands with a well studied
26
27 palaeoecology, such as those outlined in Payne et al., (2016) may facilitate better modelling
28
29 in the future.
30
31
32
33
34
35
36
37
38
39
40

41 A Conclusion

42
43 Large discrepancies exist between contemporary and long-term C accumulation rates across a
44
45 number of peatlands globally, including in our blanket bog site, Cross Lochs, in the north of
46
47 Scotland. Long term C accumulation rates provide a measure for C which has been *retained*
48
49 in the deeper catotelm peat but provide a poor measure of current C accumulation rates.

50
51
52 NECB provides a measure of a peatlands current C balance, however we argue that when
53
54 considered in isolation NECB may provide a poor indicator of peatland ecosystem C
55
56 dynamics over intermediate and longer time scales. The context provided by long-term C
57
58
59
60

1
2
3 accumulation rates, published here and in other studies, would suggest that contemporary C
4
5 accumulation rates at or greater than 100 g C yr^{-1} are not sustainable in the medium to long-
6
7 term in ombrotrophic bogs. While productivity dominates the variance in peatland C
8
9 accumulation over short time scales, this becomes progressively less so over longer time
10
11 periods. C fixed through primary production will be most vulnerable to fire and microbial
12
13 decay over the following period of acrotelm residence time, typically a period of decades to
14
15 centuries. Thus decay and disturbance become more important when considering
16
17 progressively longer timescales.
18
19

20
21 Changes in vegetation communities over the period of acrotelm residence preceding flux
22
23 measurements may result in contemporary CO_2 fluxes which compare the primary production
24
25 of the contemporary vegetation community with the heterotrophic respiration of litter
26
27 dominated by former communities. For instance, a peatland which has seen a recent shift
28
29 from *Sphagnum* towards vascular species may have higher rates of primary productivity
30
31 associated with vascular plants. However, low rates of heterotrophic respiration associated
32
33 with *Sphagnum* litter, which may still be the dominant source of heterotrophic respiration,
34
35 may be retained. Such a site would show strong C sink activity for a temporary period, until
36
37 the acrotelm litter composition changes to become representative of the current community.
38
39

40
41 Thus when NECB is used as an assessment of C balance, and especially when extrapolating
42
43 to the regional scale, peatland C flux measurements should be considered together with how
44
45 representative the current vegetation community is of the down core acrotelm litter. Equally
46
47 important when extrapolating data over longer time scales, is the amount of decay that
48
49 recently fixed C is likely to undergo before it reaches the relatively stable catotelm. While
50
51 site productivity derived from contemporary fluxes is relatively straightforward to interpret,
52
53 heterotrophic respiration will be strongly influenced by the palaeoecology of the individual
54
55 site, therefore we recommend that future studies of peatland C balance should combine
56
57
58
59
60

1
2
3 contemporary and palaeo approaches. This would have the advantage of producing data with
4
5 which to parameterise and validate site level models of C accumulation, which are ultimately
6
7 needed to better predict future peatland C dynamics.
8
9

10 11 12 13 A Acknowledgements 14 15 16 17 18 19 20

21 This work was primarily funded by the Carnegie Trust for the Universities of Scotland (grant
22 LG13STIR007), the British Ecological Society and the Royal Society. RJP and RA
23
24 acknowledge support from the Leverhulme Trust (RPG-2015-162) and RJP was funded by
25
26 the Russian Scientific Fund (14-14-00891).
27
28
29

30
31 We would also like to thank the RSPB, Patrick Sinclair, and the Forestry Commission for
32
33 granting access to the field sites and for help in retrieving the peat cores. Angela Creevy and
34
35 David Braidwood and volunteers from Forsinard Flows NNR helped with the core collection
36
37 while Prof. Stuart Gibb, Dr Chris Hayward and Norrie Russell provided valuable advice and
38
39 assistance.
40
41
42
43
44
45
46
47
48

49 A References 50 51 52 53 54 55 56 57 58 59 60

- 1
2
3 Anderson, D.E., 2002. Carbon Accumulation and C/N Ratios of Peat Bogs in North-west Scotland.
4 Scottish Geographical Journal 118, 323–341.
5
- 6 Artz, R., Saunders, M., Yeluripati, J., Chapman, S., Moxley, J., Malcolm, H., Couwenberg, J., 2015.
7 Implications for longer-term policy and implementation into the AFOLU Inventory of the IPCC
8 2013. Supplement to the 2006 Guidelines: Wetlands. ClimateXChange Scotland, The James
9 Hutton Institute, Aberdeen.
10
- 11 Artz, R.R.E., Donnelly, D., Aitkenhead, M., Balana, B., Chapman, S., 2013. A decision support tool for
12 peatland restoration in Scotland. ClimateXChange Scotland, The James Hutton Institute,
13 Aberdeen.
14
- 15 Artz, R.R.E., Donnelly, D., Andersen, R., Mitchell, R., S.J., C., Smith, J., Smith, P., R, C., Balana, B.,
16 Cuthbert, A., 2014. Managing and restoring blanket bog to benefit biodiversity and carbon
17 balance – a scoping study. Scottish Natural Heritage Commissioned Report No. 562.
18
- 19 Bäckstrand, K., Crill, P.M., Jackowicz-Korczyński, M., Mastepanov, M., Christensen, T.R., Bastviken, D.,
20 2009. Annual carbon gas budget for a subarctic peatland, northern Sweden. Meddelanden fran
21 Lunds Universitets Geografiska Institutioner, Avhandlingar 53–65.
22
- 23 Baird, A.J., Belyea, L.R., Comas, X., Reeve, A., Slater, L., 2009. Hydrology and Landscape Spatial
24 Heterogeneity. In: Carbon Cycling in Northern Peatlands.
25
- 26 Barber, K., Langdon, P., Blundell, A., 2008. Dating the Glen Garry tephra: a widespread late-Holocene
27 marker horizon in the peatlands of northern Britain. The Holocene 18, 31–43.
28
- 29 Bauer, I.E., 2004. Modelling effects of litter quality and environment on peat accumulation over
30 different time-scales. Journal of Ecology 92, 661–674.
31
- 32 Belyea, L.R., Clymo, R.S., 2001. Feedback control of the rate of peat formation. Proceedings.
33 Biological sciences / The Royal Society 268, 1315–1321.
34
- 35 Billett, M., Charman, D., Clark, J., Evans, C., Evans, M., Ostle, N., Worrall, F., Burden, a, Dinsmore, K.,
36 Jones, T., McNamara, N., Parry, L., Rowson, J., Rose, R., 2010. Carbon balance of UK peatlands:
37 current state of knowledge and future research challenges. Climate Research 45, 13–29.
38
- 39 Billett, M.F., Palmer, S.M., Hope, D., Deacon, C., Storeton-West, R., Hargreaves, K.J., Flechard, C.,
40 Fowler, D., 2004. Linking land-atmosphere-stream carbon fluxes in a lowland peatland system.
41 Global Biogeochemical Cycles 18, 1–12.
42
- 43 Blaauw, M., Christen, A., 2011. Flexible Paleoclimate Age-Depth Models Using an Autoregressive
44 Gamma Process. Bayesian Analysis 6, 457–474.
45
- 46 Cames, M., Graichen, J., Siemons, A., Cook, V., 2015. Emission Reduction Targets for International
47 Aviation and Shipping, Study for the ENVI Committee. European Union.
48
- 49 Campbell, D.I., Smith, J., Goodrich, J.P., Wall, A.M., Schipper, L.A., 2014. Year-round growing
50 conditions explains large CO₂ sink strength in a New Zealand raised peat bog. Agricultural and
51 Forest Meteorology 192-193, 59–68.
52
- 53 Chambers, F.M., Beilman, D.W., Yu, Z., 2011. Methods for determining peat humification and for
54 quantifying peat bulk density , organic matter and carbon content for palaeostudies of climate
55 and peatland carbon dynamics. Mires and Peat 7, 1–10.
56
57
58
59
60

- 1
2
3 Chapman, S., Artz, R., Donnelly, D., James, T., 2012. Carbon Savings from Peat Restoration. *Climate*
4 *Exchange* 1–17.
5
6 Charman, D.J., 1990. Origins and development of the Flow Country blanket mire, Northern Scotland,
7 with particular reference to patterned fens. Unpublished PhD thesis. University of
8 Southampton.
9
10 Charman, D.J., 1992. Blanket mire formation at the Cross Lochs, Sutherland, northern Scotland.
11 *Boreas* 21, 53–72.
12
13 Charman, D.J., 1994. Late-glacial and Holocene vegetation history of the Flow Country, northern
14 Scotland. *New Phytologist* 127, 155–168.
15
16 Charman, D.J., Beilman, D.W., Blaauw, M., Booth, R.K., Brewer, S., Chambers, F.M., Christen, J.A.,
17 Gallego-Sala, A., Harrison, S.P., Hughes, P.D.M., Jackson, S.T., Korhola, A., Mauquoy, D.,
18 Mitchell, F.J.G., Prentice, I.C., van der Linden, M., De Vleeschouwer, F., Yu, Z.C., Alm, J., Bauer,
19 I.E., Corish, Y.M.C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J.,
20 Moschen, R., Nichols, J.E., Nieminen, T.M., MacDonald, G.M., Phadtare, N.R., Rausch, N.,
21 Sillasoo, Ü., Swindles, G.T., Tuittila, E.-S., Ukonmaanaho, L., Väliranta, M., van Bellen, S., van
22 Geel, B., Vitt, D.H., Zhao, Y., 2013. Climate-related changes in peatland carbon accumulation
23 during the last millennium. *Biogeosciences* 10, 929–944.
24
25
26 Clymo, R.S., Turunen, J., Tolonen, K., Mar, N., 1998. Carbon accumulation in peatland. *OIKOS* 81,
27 368–388.
28
29 De Vleeschouwer, F., Chambers, F.M., Swindles, G.T., 2010. Coring and sub-sampling of peatlands for
30 palaeoenvironmental research. *Mires and Peat* 7, 1–10.
31
32 DeLucia, E.H., Hamilton, J.G., Naidu, S.L., Thomas, R.B., A, A.J., Finzi, A., Lavine, M., Matamala, R.,
33 Mohan, E., Hendrey, G.R., Schlesinger, W.H., 1999. Net primary production of a forest
34 ecosystem with experimental CO₂ enrichment. *Science* 284, 1177–1179.
35
36 Dinsmore, K.J., Billett, M.F., Skiba, U.M., Rees, R.M., Drewer, J., Helfter, C., 2010. Role of the aquatic
37 pathway in the carbon and greenhouse gas budgets of a peatland catchment. *Global Change*
38 *Biology* 16, 2750–2762.
39
40 Dise, N.B., 2009. Environmental science. Peatland response to global change. *Science* 326, 810–811.
41
42 Dise, N.B., Phoenix, G.K., 2011. Peatlands in a changing world. *The New Phytologist* 191, 309–11.
43
44 Dugmore, A.J., Larsen, G.R.N., J., A., 1995. Seven tephra isochrones in Scotland. *The Holocene* 5,
45 257–266.
46
47 Dugmore, A.J., Newton, A.J., 1992. Thin tephra layers in peat revealed by X-radiography. *Journal of*
48 *Archaeological Science* 19, 163–170.
49
50 Dugmore, A.J., Newton, A.J., Sugden, D.E., Larsen, G., 1992. Geochemical stability of fine-grained
51 silicic Holocene tephra in Iceland and Scotland. *JQS. Journal of quaternary science* 7, 173–183.
52
53 Flanagan, L.B., Syed, K.H., 2011. Stimulation of both photosynthesis and respiration in response to
54 warmer and drier conditions in a boreal peatland ecosystem. *Global Change Biology* 17, 2271–
55 2287.
56
57
58
59
60

- 1
2
3 Frolking, S., Roulet, N.T., 2007. Holocene radiative forcing impact of northern peatland carbon
4 accumulation and methane emissions. *Global Change Biology* 13, 1079–1088.
5
6 Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.-S., Roulet, N., 2011.
7 Peatlands in the Earth's 21st century climate system. *Environmental Reviews* 19, 371–396.
8
9 Frolking, S., Talbot, J., Subin, Z.M., 2014. Exploring the relationship between peatland net carbon
10 balance and apparent carbon accumulation rate at century to millennial time scales. *The*
11 *Holocene* 24, 1167–1173.
12
13 Garnett, B.M.H., 1998. Carbon storage in Pennine moorland and response to change. Newcastle
14 University. Unpublished PhD thesis.
15
16 Gehrels, M.J., Newnham, R.M., Lowe, D.J., Wynne, S., Hazell, Z.J., Caseldine, C., 2008. Towards rapid
17 assay of cryptotephra in peat cores: Review and evaluation of various methods. *Quaternary*
18 *International* 178, 68–84.
19
20 Goring, S., Williams, J.W., Blois, J.L., Jackson, S.T., Paciorek, C.J., Booth, R.K., Marlon, J.R., Blaauw, M.,
21 Christen, J. a., 2012. Deposition times in the northeastern United States during the Holocene:
22 Establishing valid priors for Bayesian age models. *Quaternary Science Reviews* 48, 54–60.
23
24 Harden, J.W., O'Neill, K.P., Trumbore, S.E., Veldhuis, H., Stocks, B., 1997. Moss and soil contributions
25 to the annual net carbon flux of a maturing boreal forest. *Journal of Geophysical Research* 102,
26 805–816.
27
28 Hayward, C., 2012. High spatial resolution electron probe microanalysis of tephtras and melt
29 inclusions without beam-induced chemical modification. *The Holocene* 22, 119–125.
30
31 Helfter, C., Campbell, C., Dinsmore, K.J., Drewer, J., Coyle, M., Anderson, M., Skiba, U., Nemitz, E.,
32 Billett, M.F., Sutton, M. a., 2015. Drivers of long-term variability in CO₂ net ecosystem
33 exchange in a temperate peatland. *Biogeosciences* 12, 1799–1811.
34
35 Hoosbeek, M.R., Van Breemen, N., Berendse, F., Grosvernier, P., Vasander, H., Wallén, B., 2001.
36 Limited effect of increased atmospheric CO₂ concentration on ombrotrophic bog vegetation.
37 *New Phytologist* 150, 459–463.
38
39 Humphreys, E.R., Charron, C., Brown, M., Jones, R., 2014. Two Bogs in the Canadian Hudson Bay
40 Lowlands and a Temperate Bog Reveal Similar Annual Net Ecosystem Exchange of CO₂. *Arctic,*
41 *Antarctic, and Alpine Research* 46, 103–113.
42
43 Joosten, H., 2009. The Global Peatland CO₂ Picture Peatland status and emissions in all countries of
44 the world. *Wetlands International*.
45
46 Jowsey, P.C., 1966. An improved peat sampler. *New phytologist* 65, 245–248.
47
48 Korhola, A., Ruppel, M., Seppä, H., Väliranta, M., Virtanen, T., Weckström, J., 2010. The importance
49 of northern peatland expansion to the late-Holocene rise of atmospheric methane. *Quaternary*
50 *Science Reviews* 29, 611–617.
51
52 Kylander, M.E., Lind, E.M., Wastegard, S., Lowemark, L., 2011. Recommendations for using XRF core
53 scanning as a tool in tephrochronology. *The Holocene* 22, 371–375.
54
55 Laiho, R., 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the
56 impacts of lowered water levels. *Soil Biology and Biochemistry* 38, 2011–2024.
57
58
59
60

- 1
2
3 Levy, P.E., Gray, a, 2015. Greenhouse gas balance of a semi-natural peatbog in northern Scotland.
4 Environmental Research Letters 10, 094019.
5
- 6 Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H.,
7 2008. Peatlands and the carbon cycle : from local processes to global implications – a synthesis.
8 Biogeosciences 5, 1475–1491.
9
- 10 Lindsay, R., 2010. Peatbogs and Carbon a critical synthesis to inform policy development in oceanic
11 peat bog conservation and restoration in the context of climate change, RSPB Scotland.
12
- 13 Lindsay, R.A., Charman, D.J., Everingham, F., Reilly, R.M.O., 1988. The Flow Country The peatlands of
14 Caithness and Sutherland, Peterborough: Nature Conservancy Council. Interpretive Services
15 Branch.
16
- 17 Lloyd, A.R., 2010. Carbon fluxes at an upland blanket bog in the north Pennines. University of
18 Durham. Unpublished PhD thesis.
19
- 20 Malmer, N., Johansson, T., Olsrud, M., Christensen, T.R., 2005. Vegetation, climatic changes and net
21 carbon sequestration in a North-Scandinavian subarctic mire over 30 years. Global Change
22 Biology 11, 1895–1909.
23
- 24 Malmer, N., Wallén, B., 2004. Input rates, decay losses and accumulation rates of carbon in bogs
25 during the last millennium: internal processes and environmental changes. The Holocene 14,
26 111–117.
27
- 28 Mauquoy, D., Engelkes, T., Groot, M.H., H.M., Markesteijn, F., Oudejans, M.G., van der Plicht, J., van
29 Geel, B., 2002. High-resolution records of late-Holocene climate change and carbon
30 accumulation in two north-west European ombrotrophic peat bogs. Palaeogeography,
31 Palaeoclimatology, Palaeoecology 186, 275–310.
32
- 33 Mauquoy, D., Yeloff, D., Van Geel, B., Charman, D.J., Blundell, A., 2008. Two decadal resolved
34 records from north-west European peat bogs show rapid climate changes associated with solar
35 variability during the mid-late Holocene. Journal of Quaternary Science 23, 745–763.
36
- 37 Newton, A.J., Dugmore, A.J., Gittings, B.M., 2007. Tephrobase : tephrochronology and the
38 development of a centralised European database. Journal of Quaternary Science 22, 737–743.
39
- 40 Page, S.E., Wüst, R. a. J., Weiss, D., Rieley, J.O., Shotyk, W., Limin, S.H., 2004. A record of Late
41 Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat
42 bog(Kalimantan, Indonesia): implications for past, present and future carbon dynamics. Journal
43 of Quaternary Science 19, 625–635.
44
- 45 Payne, R.J., 2014. The exposure of British peatlands to nitrogen deposition, 1900 – 2030. Mires and
46 Peat 14, 1–9.
47
- 48 Payne, R.J., Ratcliffe, J., Andersen, R., Flitcroft, C.E., 2016. A meta-database of peatland
49 palaeoecology in great Britain. Palaeogeography, Palaeoclimatology, Palaeoecology 457, 389–
50 395.
51
- 52 Peichl, M., Öquist, M., Ottosson Löfvenius, M., Ilstedt, U., Sagerfors, J., Grelle, A., Lindroth, A.,
53 Nilsson, M.B., 2014. A 12-year record reveals pre-growing season temperature and water table
54 level threshold effects on the net carbon dioxide exchange in a boreal fen. Environmental
55 Research Letters 9, 055006.
56
57
58
59
60

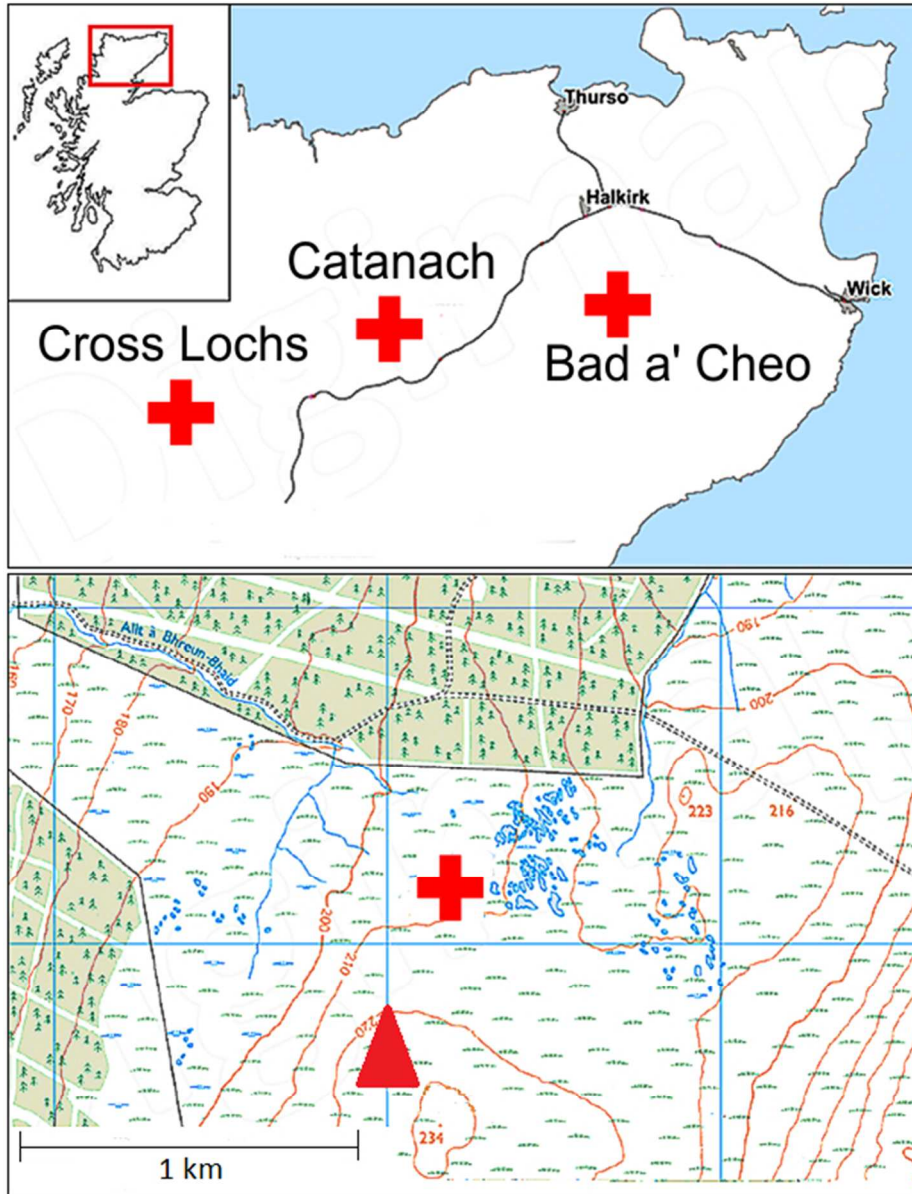
- 1
2
3 Pendea, I.F., Chmura, G.L., 2012. A high-resolution record of carbon accumulation rates during
4 boreal peatland initiation. *Biogeosciences* 9, 2711–2717.
5
6 Pilcher, J.R., Hall, V.A., 1992. Towards a tephrochronology for the Holocene of the north of Ireland.
7 *The Holocene* 2, 255–259.
8
9 Pilcher, J.R., Hall, V.A., 1996. Tephrochronological studies in northern England. *The Holocene* 100–
10 105.
11
12 Pitkanen, K., Turunen, J., Tolonen, K., 1999. The role of fire in the carbon dynamics of a mire, eastern
13 Finland. *The Holocene* 9, 453–462.
14
15 Ratcliffe, J., 2015. Carbon Accumulation Rates Over the Holocene in Flow Country Peatlands and the
16 Direct Comparison of Open and Afforested Peatland Carbon Stocks Using Tephrochronology.
17 University of Aberdeen. Unpublished MSc thesis.
18
19 Robinson, D., 1987. Investigations into the Aukhorn Peat Mounds, Keiss, Caithness: Pollen, Plant
20 Macrofossil and Charcoal Analyses. *New Phytologist* 106, 185–200.
21
22 Roulet, N.T., Humphreys, E.R., Frolking, S., Talbot, J., Lafleur, P.M., Moore, T., 2016. Can continental
23 bogs with stand the pressure due to climate change ? In: EGU.
24
25 Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R., Bubier, J., 2007.
26 Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland.
27 *Global Change Biology* 13, 397–411.
28
29 Rydin, H., Jeglum, J.K., Jeglum, J.K., 2006. *The biology of peatlands*. Oxford university press.
30
31 Schipper, L.A., Mcleod, M., Scott, N., Clarkson, B., Smith, J., Campbell, D., 2002. Subsidence rates and
32 carbon loss in peat soils following conversion to pasture in the Waikato Region , New Zealand.
33 *Soil Use and Management* 18, 91–93.
34
35 Siegenthaler, A., Buttler, A., Bragazza, L., Heijden, E. Van Der, Grosvernier, P., Gobat, J.M., Mitchell, E.
36 a D., 2010. Litter- and ecosystem-driven decomposition under elevated CO₂ and enhanced N
37 deposition in a Sphagnum peatland. *Soil Biology and Biochemistry* 42, 968–977.
38
39 Smith, J.U., Chapman, S.J., Bell, J.S., Bellarby, J., Gottschalk, P., Hudson, G., Lilly, A., Smith, P., Towers,
40 W., 2009. Developing a methodology to improve soil C stock estimates for Scotland & use of
41 initial results from a resampling of the national soil inventory of Scotland to improve the
42 ECOSSE model., The Scottish Government.
43
44 Sniffer, 2014. Growing season length, Scotland's Climate Trends Handbook. Sniffer Project CC13.
45 http://www.environment.scotland.gov.uk/climate_trends_handbook. Accessed June 2016.
46
47 Strachan, I.B., Pelletier, L., Bonneville, M.-C.M.-C., 2016. Inter-annual variability in water table depth
48 controls net ecosystem carbon dioxide exchange in a boreal bog. *Biogeochemistry* 127, 99–111.
49
50 Strack, M., Zuback, Y.C. a, 2013. Annual carbon balance of a peatland 10 yr following restoration.
51 *Biogeosciences* 10, 2885–2896.
52
53 Swindles, G.T., Lawson, I.T., Savov, I.P., Connor, C.B., Plunkett, G., 2011. A 7000 yr perspective on
54 volcanic ash clouds affecting northern Europe. *Geology* 39, 887–890.
55
56 Swindles, G.T., Morris, P.J., Baird, A.J., Blaauw, M., Plunkett, G., 2012. Ecohydrological feedbacks
57 confound peat-based climate reconstructions. *Geophysical Research Letters* 39, 2–5.
58
59
60

- 1
2
3 Trumbore, S.E., Harden, J., 1997. Accumulation and turnover of carbon in organic and mineral soils
4 of the BOREAS northern study area. *Journal of Geophysical Research* 102, 817–830.
5
6 Turetsky, M., Wieder, K., Halsey, L., Vitt, D., 2002. Current disturbance and the diminishing peatland
7 carbon sink. *Geophysical Research Letters* 29, 7–10.
8
9 Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van der Werf, G.R., 2015. Global vulnerability of
10 peatlands to fire and carbon loss. *Nature Geoscience* 8, 11–14.
11
12 Turunen, C., Turunen, J., 2003. Development history and carbon accumulation of a slope bog in
13 oceanic British Columbia, Canada. *The Holocene* 13, 225–238.
14
15 Turunen, J., 2003. Past and present carbon accumulation in undisturbed boreal and subarctic mires:
16 A review. *Suo* 54, 15–28.
17
18 Van Bellen, S., Garneau, M., Booth, R.K., 2011. Holocene carbon accumulation rates from three
19 ombrotrophic peatlands in boreal Quebec, Canada: Impact of climate-driven ecohydrological
20 change. *The Holocene* 21, 1217–1231.
21
22 Waddington, J.M., Morris, P.J., Kettridge, N., Granath, G., Thompson, D.K., Moore, P. a., 2015.
23 Hydrological feedbacks in northern peatlands. *Ecohydrology* 8, 113–127.
24
25 Ward, S.E., Bardgett, R.D., McNamara, N.P., Adamson, J.K., Ostle, N.J., 2007. Long-term
26 consequences of grazing and burning on northern peatland carbon dynamics. *Ecosystems* 10,
27 1069–1083.
28
29 Wieder, R.K., 2001. Past, present, and future peatland carbon balance: An empirical model based on
30 Pb-210-dated cores. *Ecological Applications* 11, 327–342.
31
32 Wieder, R.K., Scott, K.D., Kamminga, K., Vile, M. a., Vitt, D.H., Bone, T., Xu, B., Benscoter, B.W., Bhatti,
33 J.S., 2009. Postfire carbon balance in boreal bogs of Alberta, Canada. *Global Change Biology* 15,
34 63–81.
35
36 Yang, H., Rose, N.L., Boyle, J.F., Battarbee, R.W., 2001. Storage and distribution of trace metals and
37 spheroidal carbonaceous particles (SCPs) from atmospheric deposition in the catchment peats
38 of Lochnagar , Scotland 115, 231–238.
39
40 Yu, Z., 2006a. Holocene carbon accumulation of fen peatlands in boreal western Canada: A complex
41 ecosystem response to climate variation and disturbance. *Ecosystems* 9, 1278–1288.
42
43 Yu, Z., 2006b. Power laws governing hydrology and carbon dynamics in northern peatlands. *Global*
44 *and Planetary Change* 53, 169–175.
45
46 Yu, Z., 2011. Holocene carbon flux histories of the world's peatlands: Global carbon-cycle
47 implications. *The Holocene* 21, 761–774.
48
49 Yu, Z., Campbell, I.D., Campbell, C., Vitt, D.H., Bond, G.C., Apps, M.J., 2003. Carbon sequestration in
50 western Canadian peat highly sensitive to Holocene wet-dry climate cycles at millennial
51 timescales. *The Holocene* 13, 801–808.
52
53 Yu, Z., Turetsky, M.R., Campbell, I.D., Vitt, D.H., 2001. Modelling long-term peatland dynamics. II.
54 Processes and rates as inferred from litter and peat-core data. *Ecological Modelling* 145, 159–
55 173.
56
57
58
59
60

1
2
3 Yu, Z.C., 2012. Northern peatland carbon stocks and dynamics: A review. Biogeosciences 9, 4071–
4 4085.
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

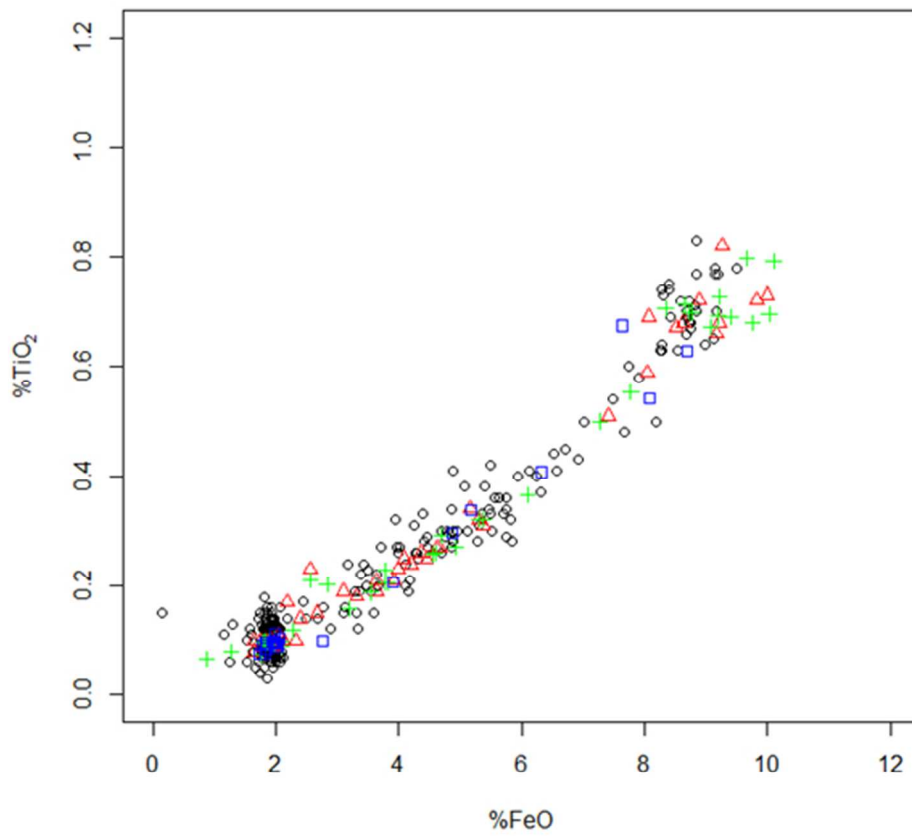
For Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



map of site locations in the north of Scotland marked by crosses b) detailed location of the Cross Lochs core, marked by a cross and the eddy covariance tower, marked as a triangle. © Crown Copyright and Database Right 2016 Ordnance Survey (Digimap Licence)

160x208mm (96 x 96 DPI)



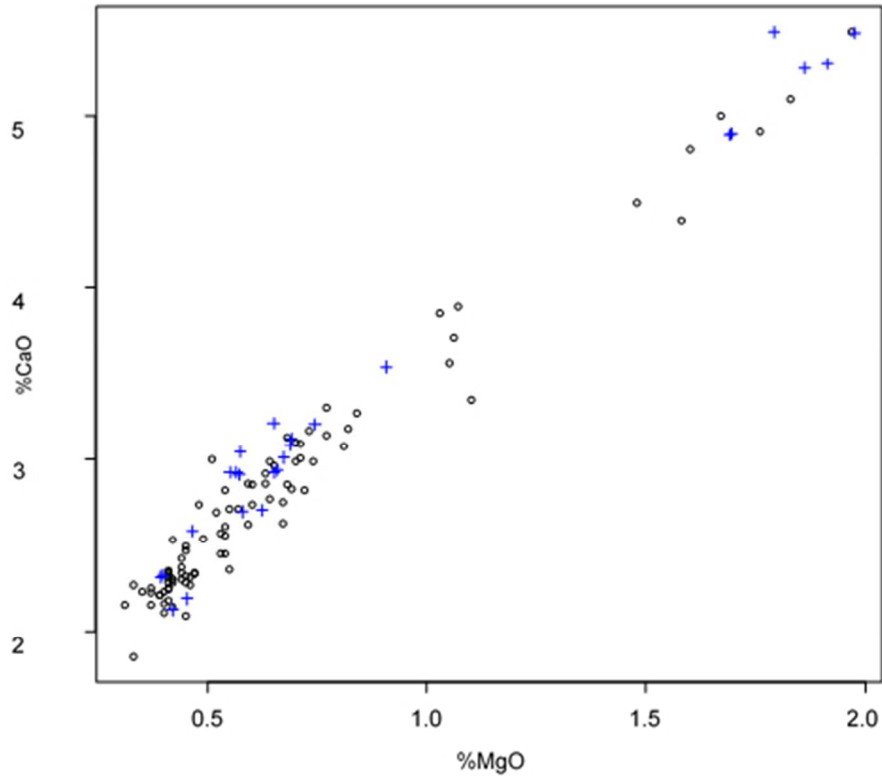
% TiO and FeO of reference Hekla 4 shards from Tephabase (Newton et al., 2007), displayed as black circles, Compared with shards from Cross Lochs, red triangles and Catanach, green crosses and Bad a' Cheo, blue squares.

164x144mm (96 x 96 DPI)



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

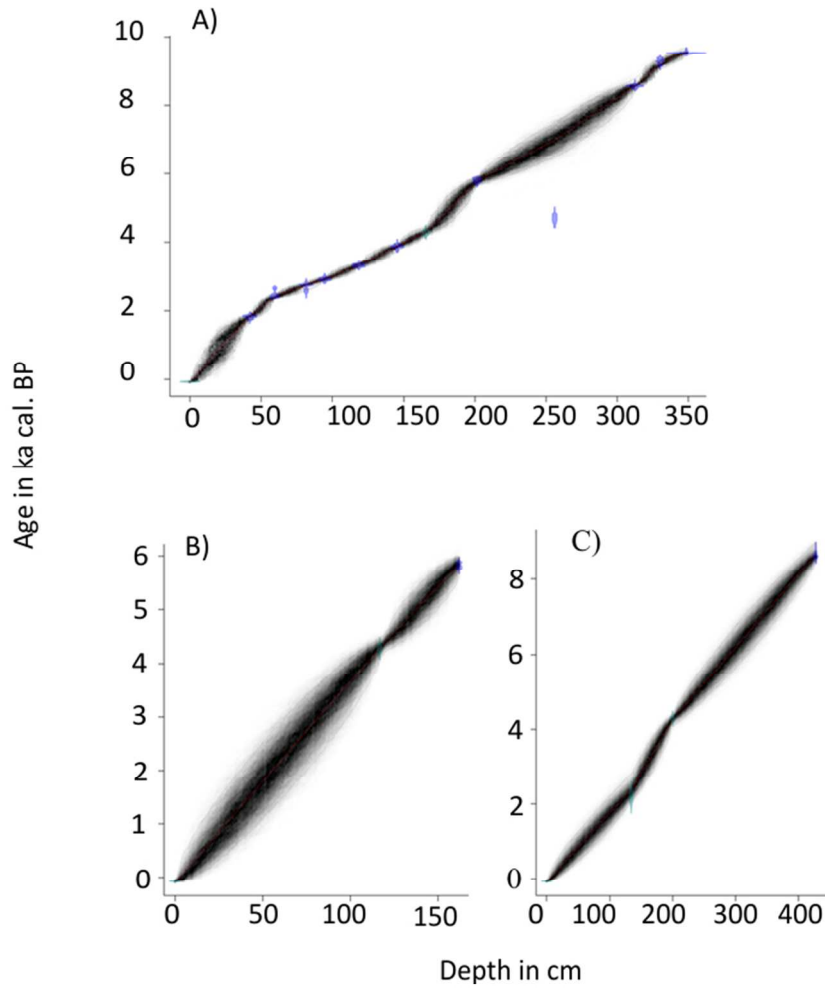


Calcium and magnesium oxide concentration of BADO134 shards, blue crosses, compared with reference material for the Glen Garry eruption obtained from Tephabase (Newton et al., 2007), black circles.

140x121mm (96 x 96 DPI)



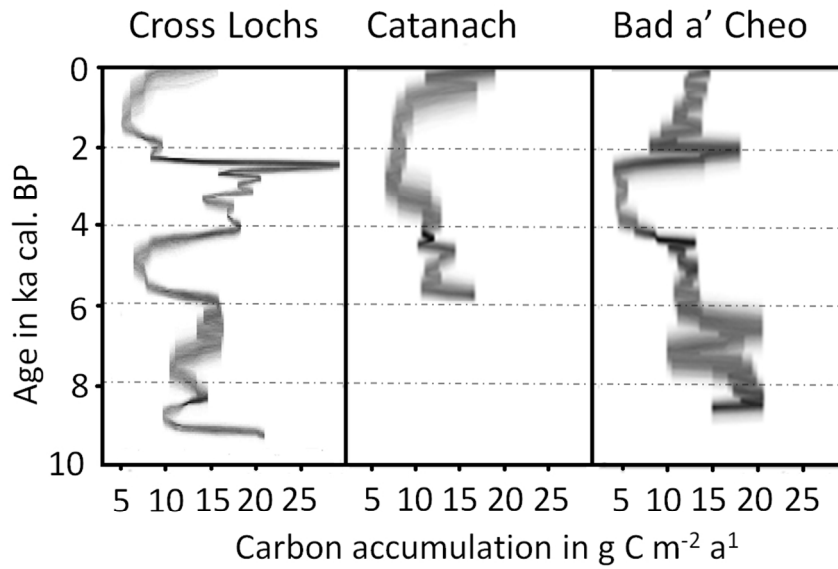
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



Age-depth models produced in BACON for a) Crosslochs b) Catanach and C) Bad a 'Cheo. Thickness of the plot represents the uncertainty in the age

220x250mm (96 x 96 DPI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



Long term carbon accumulation rates over time for Cross Lochs, Catanach and Bad a' Cheo. Thickness of the plot represents the uncertainty in age.

345x216mm (96 x 96 DPI)

Review

Site	Fluxes included In contemporary carbon balance	Contemporary carbon balance in $\text{g C m}^{-2} \text{yr}^{-1}$	Long term carbon accumulation in $\text{g C m}^{-2} \text{yr}^{-1}$	References
Mer Bleue, Canada	CO ₂ , CH ₄ , DOC,	32 ± 40.0	14-21.9	(Roulet et al., 2016, 2007)
‘Wesern peatland’ Lac la Biche, Canada	CO ₂	~189 ± 47	19-24	(Flanagan and Syed, 2011)
Moanatuatua, New Zealand	CO ₂	~234	34.2	(Campbell et al., 2014; Schipper et al., 2002)
Forsinard/Cross Lochs, Scotland	CO ₂ , CH ₄ , DOC	99.4 ± 9.5	15.4-17.5	(Levy and Gray, 2015); this publication
Moor House, Pennines, England	CO ₂ , DOC, POC, CH ₄	134.3 ± 32	27	(Garnett, 1998; Lloyd, 2010)
Lac Le Caron, Canada	CO ₂	~76	22.6	(Strachan et al., 2016; van Bellen et al., 2011)

Site:	Lab no.	Mid-point depth (cm)	Material selected for dating	Radiocarbon date (BP)	Best estimate (cal BP)	1 σ Calibrated age range (cal.BP)
Cross Lochs	Poz-62862	42	Charcoal	1885 \pm 30	1834	1731-1890
Cross Lochs	Poz-62861	59.5	Charcoal	2405 \pm 30	2426	2349-2682
Cross Lochs	Poz-62858	81.5	<i>Sphagnum austinii</i> leaves	2600 \pm 50	2735	2495-2844
Cross Lochs	Poz-62863	94.5	Charcoal	2805 \pm 30	2907	2804-2995
Cross Lochs	D-AMS 006128	118.5	<i>Molinia caerulea</i> rhizome	3092 \pm 25	3296	3234-3370
Cross Lochs	Poz-62864	145.5	Charcoal	3580 \pm 30	3882	3777-3977
Cross Lochs	Poz-62860	201.5	<i>Molinia caerulea</i> Rhizome	5040 \pm 35	5815	5664-5902
Cross Lochs	Poz-62766	256	<i>Molinia caerulea</i> rhizome	4170 \pm 80	4694	4446-4862
Cross Lochs	D-AMS 006126	330	<i>Molinia caerulea</i> rhizome	8279 \pm 32	9287	9136-9405
Cross Lochs	D-AMS 006127	312.5	<i>Molinia caerulea</i> rhizome	7787 \pm 32	8568	8460-8632
Cross Lochs	D-AMS 006125	348.5	<i>Betula</i> stem	8567 \pm 33	9535	9491-9558
Bad a' Cheo	Poz-62859	427.5	Brown moss stems	7830 \pm 50	8614	8455-8855
Catanach	Poz-62866	162	Charcoal	5080 \pm 35	5816	5745-5910

1
2
3
4
5
6
7 Table I:

8 Sites for which with published long-term and contemporary rates of C accumulation. Sites which do
9 not have multiple years of eddy covariance data and those with only long term or contemporary
10 measurements have been excluded. Contemporary C accumulation rates are listed as approximate
11 for those sites where the carbon balance is missing either DOC or CH₄. DOC is an abbreviation of
12 dissolved organic carbon and POC is particulate organic carbon.
13
14

15 Table II:

16 Radiocarbonage, depth, calibrated age and 1 σ Calibrated age range for the AMS radiocarbon dates
17 used in the age depth models
18
19

20
21 Figure 1: map of site locations in the north of Scotland marked by crosses b) detailed location of the
22 Cross Lochs core, marked by a cross and the eddy covariance tower, marked as a triangle. © Crown
23 Copyright and Database Right 2016 Ordnance Survey (Digimap Licence)
24
25

26 Figure 2:

27 % TiO and FeO of reference Hekla 4 shards from Tephabase (Newton et al., 2007), displayed as
28 black circles, Compared with shards from Cross Lochs, red triangles and Catanach, green crosses and
29 Bad a' Cheo, blue squares.
30
31

32 Figure 3:

33 Calcium and magnesium oxide concentration of BADO134 shards, blue crosses, compared with
34 reference material for the Glen Garry eruption obtained from Tephabase (Newton et al., 2007),
35 black circles.
36
37

38 Figure 4:

39 Age-depth models produced in BACON for a) Crosslochs b) Catanach and c) Bad a' Cheo. Thickness
40 of the plot represents the uncertainty in the age
41
42

43 Figure 5:

44 Long term carbon accumulation rates over time for Cross Lochs, Catanach and Bad a' Cheo.
45 Thickness of the plot represents the uncertainty in age
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

SUPPLEMENTARY MATERIAL

Geochemistry from electronprobe microanalysis of tephra shards at 164cm in the Cross Lochs core, Identified as

Hekla 4

Shard	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
1	70.74	0.23	14.96	3.99	0.16	0.04	2.22	4.90	2.51	0.01	99.75
2	62.47	0.73	14.65	10.00	0.29	0.77	4.59	4.61	1.67	0.23	100.01
3	63.58	0.72	14.40	8.90	0.28	0.56	4.31	4.80	1.68	0.21	99.43
4	61.98	0.82	14.33	9.26	0.29	0.87	4.59	4.34	1.66	0.25	98.40
5	63.45	0.68	14.21	8.63	0.31	0.65	4.67	4.32	1.78	0.23	98.93
6	64.27	0.51	14.18	7.42	0.26	0.31	3.94	5.09	1.90	0.11	97.99
7	68.56	0.27	14.16	4.67	0.19	0.09	2.72	5.26	2.27	0.03	98.21
8	62.52	0.66	14.06	9.18	0.29	0.62	4.29	4.84	1.76	0.21	98.44
9	62.48	0.72	14.01	9.82	0.32	0.74	4.58	4.45	1.66	0.24	99.04
10	64.84	0.69	13.97	8.07	0.28	0.54	4.07	4.71	1.82	0.19	99.17
11	71.07	0.21	13.90	3.64	0.14	0.04	2.34	4.48	2.46	0.01	98.29
12	68.06	0.34	13.88	5.17	0.20	0.13	2.95	4.87	2.20	0.06	97.86
13	62.95	0.68	13.86	9.22	0.32	0.66	4.56	4.35	1.63	0.20	98.44
14	69.55	0.25	13.57	4.45	0.17	0.07	2.57	4.98	2.37	0.03	98.01
15	62.10	0.67	13.54	8.51	0.29	0.60	4.32	4.75	1.81	0.19	96.80
16	68.24	0.32	13.51	5.31	0.21	0.12	3.09	4.98	2.26	0.03	98.07
17	71.73	0.19	13.42	3.10	0.14	0.02	2.20	5.17	2.56	0.01	98.55
18	68.95	0.25	13.31	4.08	0.17	0.06	2.68	4.73	2.47	0.02	96.74
19	67.98	0.31	13.29	5.38	0.21	0.09	2.96	4.85	2.10	0.04	97.21
20	63.85	0.59	13.19	8.05	0.28	0.48	3.70	4.70	1.86	0.17	96.87
21	70.03	0.21	13.16	3.93	0.16	0.04	2.21	4.75	2.43	0.01	96.93
22	72.19	0.18	13.15	3.32	0.15	0.00	2.15	5.08	2.54	0.02	98.79
23	69.15	0.24	13.04	4.20	0.17	0.10	2.69	4.86	2.36	0.02	96.82
24	73.74	0.10	13.01	2.33	0.08	0.02	1.29	3.51	3.45	0.00	97.55
25	69.63	0.26	12.97	4.36	0.15	0.10	2.61	4.48	2.35	0.04	96.96
26	71.21	0.19	12.73	3.64	0.13	0.04	2.10	4.83	2.55	0.02	97.45
27	73.84	0.09	12.72	1.99	0.08	0.03	1.30	5.13	2.87	0.01	98.06
28	73.10	0.17	12.69	2.19	0.08	0.12	1.37	4.83	2.85	0.00	97.39
29	72.46	0.11	12.67	2.04	0.07	0.00	1.27	4.86	2.78	0.01	96.26
30	71.65	0.15	12.60	2.67	0.11	0.02	1.70	4.80	2.64	0.01	96.35
31	72.27	0.14	12.52	2.39	0.07	0.10	1.68	5.16	2.44	0.00	96.78
32	75.02	0.08	12.48	1.64	0.07	0.04	1.38	3.93	2.79	0.01	97.42
33	73.88	0.10	12.43	1.65	0.09	0.02	1.32	4.58	2.85	0.02	96.94
34	74.10	0.09	12.38	1.91	0.08	0.02	1.22	4.77	2.93	0.00	97.50
35	73.47	0.09	12.29	1.94	0.08	0.01	1.31	4.70	2.99	0.01	96.89
36	72.95	0.10	12.28	2.13	0.08	0.03	1.27	4.63	2.94	0.00	96.41
37	73.90	0.09	12.27	1.93	0.08	-0.01	1.38	4.67	2.90	0.01	97.22
38	73.34	0.09	12.26	1.94	0.08	0.04	1.49	4.99	2.82	0.01	97.06
39	73.38	0.10	12.26	1.94	0.09	0.03	1.32	4.48	2.95	0.01	96.58
40	72.22	0.23	12.16	2.56	0.12	0.04	0.58	4.96	4.21	0.00	97.07
41	68.01	0.27	12.05	4.62	0.18	0.10	2.66	4.99	2.16	0.04	95.07
42	72.69	0.10	12.05	1.75	0.08	0.03	1.37	4.49	2.83	0.00	95.38

43	76.80	0.09	11.98	1.77	0.09	0.01	1.14	4.32	3.00	0.00	99.20
44	73.60	0.09	11.79	1.75	0.07	0.04	1.33	4.60	2.92	0.01	96.20
45	74.98	0.09	11.78	1.92	0.09	0.03	0.92	3.42	3.29	0.00	96.54
46	73.04	0.09	11.58	1.76	0.07	0.00	1.18	4.77	2.84	0.00	95.33
47	74.74	0.10	11.54	1.84	0.09	0.04	0.91	3.79	3.48	0.01	96.52

Geochemistry from electronprobe microanalysis of tephra shards found in the Bad a' Cheo core at 200.1cm, Identified as Hekla 4

Shard	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
1	71.41	0.09	12.63	2.04	0.08	0.02	1.27	4.93	2.75	0.01	95.24
2	72.41	0.09	12.66	2.00	0.09	0.05	1.35	4.83	2.72	0.01	96.20
3	64.69	0.41	13.76	6.33	0.24	0.21	3.38	5.20	2.07	0.09	96.37
4	72.57	0.08	12.61	1.85	0.09	0.02	1.27	5.00	2.91	0.01	96.42
5	72.68	0.11	13.08	1.98	0.08	0.02	1.37	4.74	2.72	0.01	96.79
6	73.20	0.10	12.71	1.84	0.09	0.01	1.28	4.97	2.85	0.00	97.04
7	73.64	0.10	13.33	1.97	0.08	0.01	1.43	4.71	2.84	0.01	98.12
8	73.53	0.09	13.24	2.03	0.08	0.04	1.36	4.96	2.88	0.01	98.21
9	73.40	0.09	13.52	1.79	0.08	0.04	1.33	5.13	2.83	0.01	98.23
10	67.59	0.34	14.77	5.18	0.20	0.19	3.02	5.03	2.08	0.06	98.45
11	74.66	0.09	13.04	1.96	0.08	0.01	1.41	4.91	2.68	0.02	98.87
12	74.11	0.10	13.41	1.82	0.08	0.02	1.33	5.19	2.87	0.00	98.93
13	74.20	0.09	13.15	2.03	0.08	0.00	1.40	5.45	2.86	0.01	99.27
14	74.93	0.10	13.30	1.97	0.07	0.01	1.39	4.78	2.98	0.01	99.55
15	74.30	0.09	13.62	1.82	0.08	0.02	1.45	5.49	2.78	0.01	99.65
16	74.16	0.09	13.61	2.03	0.08	0.00	1.46	5.31	2.90	0.01	99.66
17	73.11	0.10	13.85	2.76	0.10	0.06	1.85	5.66	2.32	0.01	99.81
18	68.97	0.30	15.29	4.88	0.20	0.09	2.84	5.18	2.11	0.04	99.90
19	70.80	0.21	14.60	3.92	0.15	0.04	2.31	5.47	2.38	0.01	99.90
20	64.96	0.54	14.53	8.08	0.30	0.39	3.95	5.20	1.91	0.13	99.99
21	74.83	0.10	13.58	1.94	0.07	0.00	1.44	5.40	2.78	0.01	100.15
22	76.12	0.08	13.05	1.82	0.08	0.05	1.34	4.87	2.92	0.01	100.32
23	64.28	0.63	14.46	8.69	0.29	0.50	4.41	5.09	1.80	0.16	100.33
24	74.92	0.10	13.79	2.05	0.07	0.00	1.41	5.28	2.85	0.02	100.49
25	66.00	0.67	15.22	7.64	0.24	0.49	3.79	5.48	1.94	0.21	101.68
26	76.40	0.08	14.28	1.74	0.08	0.03	1.37	5.04	2.85	0.01	101.87

Geochemistry from electronprobe microanalysis of tephra shards found in the Catanach core at 116cm, Identified as Hekla 4

Shard	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
1	61.19	0.79	13.73	10.10	0.30	0.83	4.44	4.45	1.68	0.32	97.83
2	61.44	0.67	14.34	9.07	0.30	0.67	4.14	4.92	1.78	0.24	97.56
3	62.08	0.80	15.04	9.67	0.31	0.97	4.43	4.74	1.66	0.29	99.98
4	62.10	0.73	14.05	9.22	0.29	0.72	4.44	4.21	1.65	0.25	97.67
5	62.20	0.68	14.44	9.76	0.29	0.67	4.51	4.36	1.65	0.23	98.78
6	62.50	0.70	14.79	10.03	0.29	0.62	4.33	4.62	1.80	0.21	99.89

HOLOCENE

	7	62.59	0.69	14.31	9.20	0.28	0.71	4.34	4.56	1.75	0.22	98.66
1	8	62.78	0.69	14.03	9.41	0.30	0.71	4.62	4.55	1.67	0.21	98.98
2	9	62.90	0.70	14.96	8.72	0.28	0.69	4.26	4.49	1.79	0.23	99.01
3												
4	10	62.95	0.70	14.02	8.77	0.30	0.60	4.23	4.59	1.73	0.23	98.12
5	11	63.19	0.55	12.98	7.78	0.28	0.39	3.85	4.80	1.82	0.15	95.79
6	12	63.75	0.71	13.87	8.66	0.27	0.69	4.05	4.65	1.71	0.23	98.60
7	13	64.01	0.71	14.05	8.34	0.30	0.56	4.00	4.57	1.71	0.22	98.47
8												
9	14	65.92	0.50	14.15	7.27	0.24	0.32	3.49	4.96	1.98	0.11	98.94
10	15	66.65	0.37	13.24	6.10	0.23	0.16	3.03	4.80	2.13	0.07	96.77
11	16	67.54	0.27	13.18	4.93	0.15	0.07	2.58	4.75	2.24	0.03	95.74
12	17	67.85	0.26	14.46	4.60	0.18	0.07	2.68	5.04	2.35	0.04	97.51
13	18	67.89	0.32	13.51	5.30	0.19	0.12	2.91	4.75	2.24	0.05	97.29
14	19	68.33	0.29	13.38	4.70	0.18	0.11	2.82	4.93	2.27	0.04	97.07
15	20	68.48	0.32	13.46	5.38	0.20	0.14	2.93	5.12	2.16	0.05	98.25
16	21	69.16	0.21	12.94	3.79	0.15	0.06	2.22	4.73	2.40	0.02	95.67
17	22	69.49	0.21	13.69	2.56	0.15	0.10	3.19	5.48	1.71	0.03	96.61
18	23	69.73	0.26	14.65	4.55	0.16	0.27	2.78	5.42	1.47	0.06	99.36
19	24	70.40	0.23	13.67	3.79	0.14	0.06	2.28	4.79	2.43	0.02	97.81
20	25	70.47	0.16	11.90	3.20	0.12	0.02	1.96	4.66	2.63	0.01	95.13
21	26	70.97	0.21	12.90	3.83	0.15	0.02	2.29	4.85	2.44	0.03	97.68
22	27	71.02	0.20	12.02	2.83	0.13	0.04	1.87	4.75	2.63	0.03	95.52
23	28	71.26	0.19	13.17	3.54	0.13	0.03	2.12	4.50	2.55	0.01	97.52
24	29	72.37	0.12	13.38	2.28	0.10	0.03	1.44	4.85	2.60	0.02	97.18
25	30	72.53	0.10	13.14	1.97	0.08	-0.01	1.30	4.86	2.77	0.01	96.76
26	31	72.54	0.10	12.18	1.84	0.08	0.00	1.25	4.71	2.75	0.01	95.45
27	32	72.97	0.10	13.02	1.82	0.08	0.01	1.28	5.05	2.77	0.00	97.09
28	33	73.03	0.10	12.68	2.08	0.08	-0.01	1.28	4.84	2.80	0.00	96.87
29	34	73.04	0.09	12.15	2.10	0.09	0.02	1.29	4.87	2.74	0.00	96.40
30	35	73.19	0.08	12.67	1.75	0.09	0.01	1.21	4.40	2.83	0.01	96.24
31	36	73.20	0.10	12.23	1.79	0.07	0.02	1.28	4.59	2.86	0.01	96.14
32	37	73.35	0.07	11.06	0.88	0.06	0.01	0.65	3.82	5.28	0.01	95.20
33	38	73.56	0.09	12.65	1.98	0.08	0.04	1.29	4.65	2.82	0.01	97.16
34	39	73.97	0.10	11.84	1.99	0.09	0.01	1.37	4.78	2.81	0.01	96.96
35	40	74.42	0.10	12.85	1.88	0.07	0.00	1.29	5.12	2.60	0.00	98.33
36	41	74.90	0.08	12.55	1.76	0.07	0.02	1.33	4.39	2.85	0.02	97.95
37	42	75.41	0.08	12.76	1.28	0.07	0.03	1.41	4.18	2.78	0.01	98.01

Geochemistry from electronprobe microanalysis of tephra shards from Bad a' Cheo at 124cm, Identified as Glen Garry:

Shard	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
1	71.84	0.69	13.50	5.04	0.12	0.66	2.94	4.46	1.88	0.15	101.27
2	64.61	1.30	14.05	7.09	0.16	1.70	4.90	4.24	1.40	0.45	99.91
3	72.64	0.65	13.65	4.65	0.11	0.57	2.93	4.52	1.94	0.14	101.80
4	74.38	0.59	13.95	3.72	0.10	0.46	2.58	4.39	1.99	0.14	102.31
5	64.80	1.29	13.18	6.90	0.14	1.69	4.89	4.57	1.46	0.37	99.30
6	71.86	0.69	13.11	4.59	0.11	0.65	2.93	4.85	1.92	0.15	100.86
7	64.29	1.11	13.40	7.01	0.15	2.25	5.34	4.20	1.42	0.24	99.41
8	70.51	0.72	12.63	5.16	0.13	0.57	3.01	4.93	1.76	0.16	99.69

	9	62.54	1.42	13.54	7.74	0.17	1.91	5.30	4.14	1.29	0.45	98.50
1	10	68.32	0.85	12.94	5.48	0.15	0.91	3.54	4.51	1.74	0.23	98.66
2	11	69.08	0.71	13.15	4.58	0.12	0.57	3.04	4.68	1.71	0.15	97.81
3	12	72.71	0.10	13.07	2.02	0.08	-0.01	1.38	5.32	2.74	0.02	97.44
4	13	73.94	0.07	13.03	1.49	0.07	0.01	0.73	4.32	5.21	0.00	98.87
5	14	73.24	0.64	12.69	4.50	0.12	0.62	2.71	4.48	1.93	0.11	101.05
6	15	63.05	1.28	12.39	7.47	0.17	2.50	5.93	4.01	1.31	0.28	98.40
7	16	64.98	1.40	14.65	8.18	0.17	1.79	5.49	4.15	1.33	0.40	102.52
8	17	70.59	0.68	13.05	4.71	0.13	0.65	3.21	4.53	1.82	0.13	99.49
9	18	70.19	0.73	13.23	5.01	0.15	0.69	3.12	4.33	1.79	0.12	99.36
10	19	60.15	1.31	14.21	8.27	0.18	3.97	7.35	3.54	0.96	0.21	100.14
11	20	71.93	0.65	13.68	4.30	0.10	0.55	2.93	4.76	1.92	0.11	100.92
12	21	72.17	0.68	13.88	4.47	0.13	0.57	2.91	4.05	1.82	0.13	100.81
13	22	63.71	1.43	14.39	7.76	0.18	1.86	5.28	4.00	1.34	0.40	100.35
14	23	72.93	0.50	12.84	3.73	0.09	0.39	2.32	4.65	2.11	0.06	99.62
15	24	59.67	1.38	13.82	8.66	0.18	3.77	7.29	3.80	1.00	0.21	99.78
16	25	70.68	0.51	12.74	3.49	0.09	0.45	2.19	4.50	1.91	0.07	96.63
17	26	70.39	0.65	12.58	4.46	0.13	0.58	2.70	4.35	1.88	0.10	97.81
18	27	62.69	1.55	13.85	8.31	0.18	1.98	5.48	3.94	1.17	0.43	99.56
19	28	73.66	0.52	12.35	3.85	0.10	0.40	2.33	4.62	1.95	0.08	99.84
20	29	71.87	0.72	13.34	5.20	0.12	0.69	3.09	4.62	1.78	0.14	101.56
21	30	74.03	0.56	12.90	4.12	0.10	0.42	2.12	4.41	2.23	0.09	100.98
22	31	71.61	0.76	13.57	5.01	0.14	0.74	3.21	4.66	1.85	0.16	101.71
23												
24												
25												
26												
27												
28												
29												
30												
31												
32												
33												
34												
35												
36												
37												
38												
39												
40												
41												
42												
43												
44												
45												
46												
47												
48												
49												
50												
51												
52												
53												
54												
55												
56												
57												
58												
59												
60												