Supplemental Materials

Materials and methods

Following upon previous analyses and results from Traustason and Snorrason (2008), a simplified vegetation model, considering pollen and macrofossils, associated temperature dependencies, and current species’ abundance enabled us to provide rough estimates of the possible extent of pre-settlement birch forest and woodland coverage (Fig. 1D). Modern vegetation coverage is based on an island-wide mapping of the natural species distribution (Fig. 1E). Woodland and forest cover refers to shrubs and trees less than or above two meters’ height (see Traustason and Snorrason, 2008 for details), respectively.

High-resolution ring width measurements (0.01 mm) of four individual birch trees were produced along undisturbed radii of carefully selected disc samples (containing at least 70-100 annual growth increments, and well preserved bark). After surface preparation using razor blades and a core microtome (Gärtnert and Nievergelt, 2010; Gärtnert al., 2015), as well as visual and statistical cross-dating by means of TSAP (Rinn, 2003) and COFECHA software (Holmes, 1983), the raw ring width measurement series reveal synchronized year-to-year and longer term growth variability, and a common date for their outermost rings (Fig. 2A).

State-of-the-art procedures using the compact MICADAS radiocarbon facility at ETH Zurich (Synal et al., 2007), a tandem accelerator mass spectrometer (AMS), were used for high-precision radiocarbon dating (Wacker et al., 2010). Each measurement sample contains 30-50
mg of wood material from a single ring of birch stem ID: 0DRUM01. All samples were cleaned by a base-acid-base-acid bleaching method for holocellulose extraction before graphitization (Němec et al., 2010). The combination of sample combustion with an elemental analyser, and the subsequent graphitization of the CO$_2$ with H$_2$ on iron powder, is widely used to prepare graphite targets for radiocarbon measurement by AMS. The total measurement time was 1-2 hours per sample, subdivided into groups containing 10 cycles of 30-second measurements. An OX-II standard typically yielded about 500’000 counts or more ($^{12}$C-ion currents of 50 μA) (Wacker et al., 2010; Güttler et al., 2013; Wacker et al., 2014; Güttler et al., 2015). Two blanks from radiocarbon-dead New Zealand Kauri and German brown coal wood, as well as a precisely dendro-dated historical reference sample from 1515 CE (Tegel et al., 2010), were utilized for normalization of our $^{14}$C measurements and quality control. The unique $^{14}$C signature within ring 48 allows for only one matching position when comparing to the $^{14}$C signature of absolutely dated tree-ring records from Scandinavia and Russia. A Pearson $\chi^2$-test was used to test the goodness of the fit for the years 773-777 CE (Fig. DR1). The single best matching position was found when the outermost ring was set to 822 CE ($\chi^2 = 3.1$, 95%-limit =12.6, n =6). This is robust statistical evidence that the subfossil birch tree ID: 0DRUM01 from Drumbabót forest in southern Iceland was buried during winter dormancy between late-822 and early-823 CE (see Table DR3 for all data).

After considering ice core evidence (Fig. 2), the absolutely dated birch ring width chronology was compared against a suite of state-of-the-art tree ring and multi-proxy based summer temperature reconstructions for Scandinavia (Helama et al., 2009; Büntgen et al., 2011a; Esper et al., 2014), Europe (Büntgen et al., 2006, 2011b; Luterbacher et al., 2016), and different parts of the Northern Hemisphere extra-tropics (Schneider et al., 2015; Hanhijarvi et al., 2013;
McKay and Kaufman, 2014; Wilson et al., 2016). The mean summer temperature response of the different spatial domains following the newly dated Katla eruption in 822/3 CE was compared against the response of the two famous tropical eruptions of Samalas and Tambora in 1257 and 1815 CE, respectively (Fig. DR2).

Screening for tephra shards was performed on the northwest Greenland ice core NEEM-2011-S1 (268.94-273.36 m; 814-837 CE), following the Desert Research Institute’s (Reno, USA) protocols (Jensen et al., 2014; Sun et al., 2014). A total of 20 individual samples were cut by band saw from the outer part (cross sectional area of 16 cm$^2$; 300 g per sample) of the archived NEEM-2011-S1 ice core sections with a constant, approximately annual, resolution of 22 cm. The meltwater was evaporated on frosted microprobe slides in a laminar flow cupboard at Queen’s University Belfast (Northern Ireland), and the dry residues were covered with Buehler EpoxiCure resin (Coulter et al., 2012). Although sample volumes were comparably large, only two shards were visually identified in samples dating to circa 815 and 822 CE (QUB-1835 and QUB-1841). The isolated shard in QUB-1841 was very pale brown and cuspate, and measured 26 $\mu$m by 11 $\mu$m. It proved too small for successful electron microprobe analysis. Shard surface was exposed by 12 $\mu$m alumina grinding and up to 1 $\mu$m diamond paste polishing. The slide QUB-1841 was carbon coated and volcanic glass composition analysed using the JEOL FEG-SEM microprobe at Queen’s University Belfast (Northern Ireland).

**Documentary evidence**

The historical sources from Europe and the Mediterranean region contain the following information from *Annales Colonienses* (AC), *Annales Regni Francorum* (ARF), *Annales Sancti Benigni Divionensis* (ASBD), *Annales Sancti Emmerammi Ratisponensis Maiores* (ASER),
817 CE: Aig anaiccenta & sngchta már ro batar o Notlaic Stellgeo h-Init. Imtecht Boinde cosaib tirmaibh & ala n-aile n-aband. fon oin-cumai ind lochg. Ete & fianlaighi iar Loch Echoch. Oiss allti do thofunn. Solaich dauurthigeiarmg o chete iar Lochaibh Eirne a tirib Connacht h-i Tir h-Ua Craumtain; aliaque incognita per gelu & grandinem in hoc anno facta. Unprecedented frost and great snow from Epiphany to Shrovetide. The Boyne and other rivers were traversed with dry feet and the lakes in like manner. Herds and multitudes [went] upon Loch-Echach, and wild deer were hunted. The roofing of an oratory was afterwards [brought] by carriage-way across the lakes of Erne, from the lands of Connaught to the land of Ui-Cremthainn; and other unprecedented things were done this year through frost and hail (AU, p. 309). [Best understood as winter 817-18.]

820 CE: Hoc anno propter iuges pluvias et aerem nimio humore resolutum magna incommoda contigerunt. Nam et hominum et boum pestilentia tam inmane longe lateque grassata est, ut vix una pars totius regni Francorum ab hac peste inmunis atque intacta posset inveriri. Frumenta quoque et legumina imbrium adsiduiitate corrupta vel colligi non poterant vel collecta conputrescebant. Vinum etiam, cuius parvus prventus eodem anno fuit, propter caloris inopiam acerbum et insuave fiebat. In quibusdam vero locis de inundatione fluminum aquis in plano stagnantibus autumnalis satio ita impedita est, ut penitus nihil frugum ante verni temperiem seminaretur. In this year, great troubles occurred because of continual rains and air being softened with too much moisture. In fact, a pestilence of people and oxen spread far and wide to such a great extent that scarcely any part of the entire Frankish kingdom could be found immune...
from the plague or untouched by it. Grain and also vegetables, spoiled by the constant rain, either could not be gathered or were rotted when collected. Also, the wine, little of which was produced this year, was bitter and sour because of the lack of warm weather. In some places autumn sowing was so impeded by stagnant waters on level ground following the flooding of rivers that utterly no crop was sown before the temperateness of spring. (ARF, p. 154).

821 CE: Autumnalis satio iugitate pluviarum in quibusdam locis impedita est. Cui hiems in tantum prolixa successit et aspera, ut non solum minores rivi ac mediocres fluvii, verum ipsi maximi ac famosissimi amnes, Rhenus videlicet ac Danubius Albisque ac Sequana caeteraque per Galliam atque Germaniam oceanum petentia flumina, adeo solida glacie stringentur, ut tricenis vel eo amplius diebus plaustra huc atque illuc commeantia velut pontibus iuncta sustinerent; cuius resolutio non modicum villis iuxta Rheni fluenta constitutis damnun intulit. Autumn sowing was impeded in some places by constant raining. So long and harsh a winter [821-22] followed that not only small streams and mid-sized rivers, but also the greatest and most famous rivers, namely the Rhine, Danube, Elbe and Seine, and other rivers in Gallia and Germania [roughly Frankish Europe west and east of the Rhine] making for the ocean, were so bound by solid ice that for thirty days or more they held wagons travelling here and there as though connected by bridges; after melting the current brought damage on not a few villas set up next to the Rhine (ARF, 157).

821 CE: Hiemps erat valde dura. The winter [likely that of 821-22] was very hard (AX, p. 6).

821 CE: Aigh anaicenta; ru-reset inna muire & inna locha & inna aibni co ruchta graige & eti & fedman iarmaibh. Unusual frost; and the seas, and lakes, and rivers were frozen, so that droves, and cattle, and burdens, could be conveyed over them (AU, p. 315). [Best understood as winter 821-22.]

822 CE: Fames ualida. Great food shortage (ASN, p. 40). [Most likely a reference to dearth in Carolingian Europe, not Anglo-Saxon England. The ASN often addressed continental history and made use of continental sources.]


822-823 CE: That same year [207 AH] Spain was desolated by a terrible famine which killed many people. In some provinces, a mudd [a measure of volume, here of grain] sold for thirty dinars (KT, p. 198).

823 CE: Hiemps magnus, similiter siccitas grandis et famis valida. Great winter, likewise large drought and strong famine (ASER, p. 93) [It is possible this winter is that of 823-24 CE].

823 CE: Hoc anno prodigia quaedam extitisse narrantur…et in multis regionibus fruges grandinis vastatione deletae atque in quibusdam locis simul cum ipsa grandine veri lapides atque ingentis ponderis decidere visi; domus quoque de caelo tactae hominesque ac caetera animalia passim fulminum ictu praeter solitum crebro exanimata dicuntur. Secuta est ingens pestilentia atque hominum mortalitas, quae per totam Franciam inmaniter usquequaque grassata est et innumeram hominum multitudinem diversi sexus et aetatis gravissime seviendo consumpsit. In this year certain omens are reported to have happened…and in many regions the crops were destroyed by the ravages of hail and in some places, along with the hail, real stones of enormous weight were seen to fall; also houses are said to have been touched by the sky, and everywhere people and other animals were killed by strikes of lightning more often than usual. There followed an enormous pestilence and mortality of people, which spread savagely throughout all the Frankish
kingdom, very grievously consuming with rage an untold multitude of people of different sex
and age (ARF, pp. 163-164).

ca.820-823 CE: Eo tempore quedam prodigiosa signa apparentia animum imperatoris
sollicitabant...crebra et inusitata fulgura, lapidum cum grandine casus, pestilentia hominum et
animalium. Propter quae singula piissimus imperator crebro fieri ieunia, orationumque instantia
atque elemosinarum divitionibus divinitatem per sacerdotium monebat offitium placandam,
certissime dicens, per haec portendi magnam humano generi futuram cladem. At that time,
portentous signs appeared rousing the emperor’s spirit...frequent though unusual lightning,
stones falling with hail, and a pestilence of people and animals. On account of these signs, the
most pious emperor advised that frequent fasts, constant prayers and generous alms be offered
through the priesthood to appease God, saying assuredly that by means of these things a great
disaster would befall humankind (Astronomer, XXXVII, pp. 420, 422). [The Astronomer made
use of the ARF.]

824 CE: Hiemps aspera valdeque prolixa facta est, quae non solum caetera animalia, verum
etiam homines quosdam inmanitate frigoris extinxit...imperator vero ite...propter famem, quae adhuc praevalida erat, usque ad initium autumni adgredi
distuli...Hoc anno paucis ante solstitium aestivale diebus in territorio Augustodunense aere in
tempestatem subita mutatone converso ingens fragmentum ex glacie simul cum grandine
decidisse narratur, cuius longitudo quindecim, latitudo septem, crassitudo duos pedes habuisse
dicitur. There was a harsh and very drawn-out winter [that of 823/24] that killed not only other
animals but also some people with the fierceness of its cold...[emperor Louis the Pious] deferred
the march that he was prepared to make into Brittany until the beginning of autumn on account
of a food shortage, which was still very strong...In this year, a few days before the summer
solstice it is reported that in the Autunois region, after a sudden change of air caused a storm, a huge fragment of ice fell simultaneously with hail, which is reported to have been fifteen feet long, seven wide and two thick (ARF, pp. 164-167).

824 CE: Magna pestilentia in Hibernia insola senioribus & pueris & infirmis; magna fames & defectio panis. A great pestilence in the island of Ireland among the old, children, and the infirm; a great famine and failure of bread (AU, p. 321) [Best dated to 825].

c.820-825 CE: But famine and plunder began to reappear at Alexandria; and the patriarch [James, 819-830] could not find that which he was wont to give to the churches, for nothing was left to him. And the visits of the faithful from all parts to the church of the martyr Saint Mennas at Maryût [Abu Mena] were interrupted; and with them the patriarch used to trade. The cause of all this was the fighting that took place between the Egyptians and the Madlajites and Spaniards (TB, XIX, p. 451). [Whether volcanic eruptions c.817-825 CE contributed to this dearth is uncertain. Note that the 822/3 Katla eruption does not appear to have suppressed significantly the Nile’s flow (data kindly provided by D. Kondrashov), as did the 939/40 Eldgjá and 1783-84 Laki eruptions (Popper, 1951; Kondrashov 2005; Oman et al., 2006)].

The historical written sources from China contain the following information from Xin Tangshu (XTS), Jiu Tangshu (JTS) and Tang huiyao (THY):

821 CE: 長慶元年六月己丑，白虹貫日。 三年二月庚戌，白虹貫日 On 27 July 821 a white rainbow crossed the sun. On 9 April 823, a white rainbow crossed the sky (XTS 32, p. 833).

822 CE: 當冬十月頻雪，其後恆燠，水不冰凍，草木萌發，如正二月之後 In the same winter, in the tenth month (October-November 822) there were repeated snowfalls, after that it
was constantly warm, water did not freeze, plants sprouted as if (it was) right after the second month March-April (JTS 16, p. 502).

822 CE: 穆宗長慶元年二月，海州海水冰 821, second month (February-March 822) the sea water froze in Haizhou district (XTS 36, 936).

822-23 CE: (長慶二年) 其年十一月頻雪後恆燠水不冰凍草木萌發如正二月. In the same year, eleventh month (December 822 to January 823), after repeated snowfalls it was constantly warm and water did not freeze, and plants and trees spouted as if they were right in the second month March-April (THY 44, 14/2).

823-24 CE: 穆宗長慶三年十一月雨木冰 敬宗寶曆元年十一月雨木冰. In December-January 824 it was excessively cold; In December 823 to January 826 it was excessively cold (THY repeats XTS).

824 CE: 長慶三年十一月丁丑，雨木冰 On 1 January 824, it was excessively cold (XTS, 34, 875).

824 CE: 長慶四年六月庚寅，京師雨雹如彌丸 On 12 July 824 in the capital the hailstones rained like bullets and pellets (XTS 36, p. 945).

825 CE: 寶曆元年十二月乙酉夜，西北有霧起，須臾遍天，霧止，有赤氣，或淺或深，久而乃散 On the night of the yiyou day of the 12th month of the first year of the Baoli reign (825) in the northwest a fog arose that rapidly filled the sky; when the fog stopped, there was a reddish vapor, now light, now dense, it lasted a long time and then dispersed (XTS 34, 894).

825 CE: September-October 825 敬宗寶歷元年八月，邠州霜殺稼 825 frost caused crop failure in Binzhou district (XTS 36, 943).
826 CE: 寶曆元年十一月丙申，雨木冰 On 9 Jan 826, it was excessively cold (Source XTS 34, 875).

REFERENCES CITED


264, p. 948–952.

Zielinski, G.A., Mayewski, P.A., Meeker, L.D., Grönvold, K., Germani, M.S., Whitlow, S.,
Twickler, M.S., and Taylo, K., 1997, Volcanic aerosol records and tephrochronology of the
26640.

Table DR1. Ice core-based estimates of stratospheric sulfate injection (SSI) from Icelandic
eruptions (Sigl et al., 2015; Toohey and Sigl, 2016; Toohey et al., 2016) (a according to NS1-
2011 ice (Sigl et al., 2015); b no tephra confirmation from ice cores; c Global Volcanism
Downloaded 06 Sep 2016. http://dx.doi.org/10.5479/si.GVP.VOTW4-2013).

<table>
<thead>
<tr>
<th>Start Year</th>
<th>End Year</th>
<th>SSI (Tg S)</th>
<th>Volcano</th>
<th>Eruption date</th>
</tr>
</thead>
<tbody>
<tr>
<td>817</td>
<td>820</td>
<td>9.3</td>
<td>possibly Katla b</td>
<td>Unknown</td>
</tr>
<tr>
<td>822/3</td>
<td>825</td>
<td>5.6</td>
<td>Katla b</td>
<td>Fall 822 – Spring 823</td>
</tr>
<tr>
<td>876</td>
<td>880</td>
<td>7.3</td>
<td>Veðivötn (Landnám)</td>
<td>Unknown</td>
</tr>
<tr>
<td>939/40</td>
<td>940</td>
<td>16.2</td>
<td>Katla (Eldgjá)</td>
<td>Unknown</td>
</tr>
<tr>
<td>1477</td>
<td>1477</td>
<td>5.1</td>
<td>Bárðarbunga b</td>
<td>1477 Feb (?) c</td>
</tr>
<tr>
<td>1721</td>
<td>1721</td>
<td>1.4</td>
<td>Katla b</td>
<td>1721 May 11 – Oct 15 (± 45 days) c</td>
</tr>
<tr>
<td>1755</td>
<td>1756</td>
<td>1.5</td>
<td>Katla b</td>
<td>1755 Oct 17 – 1756 Feb 13</td>
</tr>
<tr>
<td>1783</td>
<td>1784</td>
<td>20.8</td>
<td>Lakagígar (Laki)</td>
<td>1783 Jun 8 – 1784 Feb 7</td>
</tr>
<tr>
<td>1875</td>
<td>1875</td>
<td>1.0</td>
<td>Askja b</td>
<td>1875 Jan 1 – 1875 Oct 17</td>
</tr>
</tbody>
</table>
Table DR2. Sections of Greenland ice cores in the 9th century, in which tephra layers were previously recorded (a according to NS1-2011 ice (Sigl et al., 2015); b also recorded in GRIP; c glass shard was too small to perform microprobe analysis).

<table>
<thead>
<tr>
<th>Ice Core</th>
<th>Depth (m)</th>
<th>Shards (N)</th>
<th>Age (CE)</th>
<th>Tephra (Lab Code)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GISP2</td>
<td>286.25-286.40</td>
<td>not reported</td>
<td>877.9-878.5</td>
<td>Landnám b (Zielinski et al., 1997)</td>
</tr>
<tr>
<td>NGRIP</td>
<td>235.05-235.25</td>
<td>&gt;1,000</td>
<td>851.6-852.7</td>
<td>White River Ash (Coulter et al., 2012)</td>
</tr>
<tr>
<td>NEEM-2011</td>
<td>265.65-266.12</td>
<td>130</td>
<td>852.7-855.3</td>
<td>White River Ash (Jensen et al., 2014)</td>
</tr>
<tr>
<td></td>
<td>271.83-272.03</td>
<td>1</td>
<td>822.0-823.0</td>
<td>N/A c (QUB-1835) This Study</td>
</tr>
<tr>
<td></td>
<td>273.14-273.36</td>
<td>1</td>
<td>814.6-815.9</td>
<td>Non-Icelandic (QUB-1841) This Study</td>
</tr>
</tbody>
</table>

Table DR3. Measured radiocarbon concentrations and ages for the measured annual tree-ring samples. The given year is determined by counting back from the outermost ring set to 822 CE.

<table>
<thead>
<tr>
<th>Year CE</th>
<th>Lab Code</th>
<th>F¹⁴C</th>
<th>Radiocarbon age [BP]</th>
<th>δ¹³C</th>
<th>measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>770</td>
<td>ETH-50901</td>
<td>0.8548 ± 0.0022</td>
<td>1260 ± 21</td>
<td>-25.1</td>
<td>1</td>
</tr>
<tr>
<td>771</td>
<td>ETH-50902</td>
<td>0.8502 ± 0.0022</td>
<td>1304 ± 21</td>
<td>-23.8</td>
<td>1</td>
</tr>
<tr>
<td>772</td>
<td>ETH-50163</td>
<td>0.8486 ± 0.0020</td>
<td>1319 ± 19</td>
<td>-26.4</td>
<td>1</td>
</tr>
<tr>
<td>773</td>
<td>ETH-50162</td>
<td>0.8516 ± 0.0021</td>
<td>1290 ± 19</td>
<td>-26.8</td>
<td>1</td>
</tr>
<tr>
<td>774</td>
<td>ETH-50161</td>
<td>0.8577 ± 0.0015</td>
<td>1233 ± 14</td>
<td>-26.8</td>
<td>1</td>
</tr>
<tr>
<td>775</td>
<td>ETH-50160</td>
<td>0.8655 ± 0.0012</td>
<td>1160 ± 12</td>
<td>-25.2</td>
<td>3</td>
</tr>
<tr>
<td>776</td>
<td>ETH-50159</td>
<td>0.8654 ± 0.0014</td>
<td>1161 ± 13</td>
<td>-23.4</td>
<td>2</td>
</tr>
<tr>
<td>777</td>
<td>ETH-50158</td>
<td>0.8642 ± 0.0017</td>
<td>1172 ± 17</td>
<td>-22.7</td>
<td>1</td>
</tr>
<tr>
<td>778</td>
<td>ETH-50157</td>
<td>0.8613 ± 0.0019</td>
<td>1199 ± 18</td>
<td>-23.9</td>
<td>1</td>
</tr>
<tr>
<td>779</td>
<td>ETH-50156</td>
<td>0.8634 ± 0.0021</td>
<td>1180 ± 20</td>
<td>-29.8</td>
<td>1</td>
</tr>
<tr>
<td>780</td>
<td>ETH-50155</td>
<td>0.8645 ± 0.0019</td>
<td>1169 ± 18</td>
<td>-22.6</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure DR1. \( \chi^2 \)-test of the measured \(^{14}\text{C} \) results are given for the most likely positions of the last ring, when matched to the mean of annually resolved tree-ring data from Japan and Europe. The orange line is the upper limit (\( \chi^2 = 12.6, n = 6 \)) of the 95% probability range for the six measured data points.
Figure DR2. Comparison of the mean response of Scandinavian, European and large-scale Northern Hemisphere warm-season temperatures following the a Katla, b Samalas and c Tambora eruptions in 822/3, 1257 and 1815 CE.