Younger Dryas deglaciation of Scotland driven by warming summers

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The Younger Dryas Stadial (YDS; ~12,900–11,600 y ago) in the Northern Hemisphere is classically defined by abrupt cooling and renewed glaciation during the last glacial–interglacial transition. Although this event involved a global reorganization of atmospheric and oceanic circulation [Denton GH, Alley RB, Comer GC, Broecker WS (2005) *Quat Sci Rev* 24:1159–1182], the magnitude, seasonality, and geographical footprint of YDS cooling remain unresolved and pose a challenge to our understanding of abrupt climate change. Here, we present a deglacial chronology from Scotland, immediately downwind of the North Atlantic Ocean, indicating that the Scottish ice cap disintegrated during the first half of the YDS. We suggest that stratification of the North Atlantic Ocean resulted in amplified seasonality that, paradoxically, stimulated a severe wintertime climate while promoting warming summers through solar heating of the mixed layer. This latter process drove deglaciation of downwind landmasses to completion well before the end of the YDS.

Determining the causes of abrupt climate change remains an outstanding question of paleoclimatology, the answer to which involves resolving the timing, magnitude, and geographic extent of past abrupt climate events. The Younger Dryas Stadial (YDS) is widely considered the canonical example of abrupt climate change. Mean annual temperatures in the circum-North Atlantic returned to near-full glacial values for ~1,300 y before rising 5–10 °C within a few years to decades (1, 2). This dramatic cooling has been correlated with renewed glaciation throughout the Northern Hemisphere, particularly in the circum-North Atlantic. In Europe, for instance, the YDS has been assumed to be synonymous with the most extensive glacier advances of the late glacial (3–7). The extreme temperatures of the stadial have been attributed to stratification of the North Atlantic water column and shutdown of meridional overturning circulation (MOC) (8), in addition to the spread of wintertime sea ice and shifting westerly airflow (9). However, although the North Atlantic remains a key player in hypotheses for the YDS, recent developments are refining our view of the event's full manifestation. Mean annual temperatures recorded in the Greenland ice cores were skewed toward strong wintertime cooling, due to the effect of expanded North Atlantic winter sea ice (10). Conversely, summer atmospheric temperatures, which dominate glacier mass balance, probably were milder than previously thought (10, 11–13). Thus the North Atlantic may have exhibited the hallmarks of a "continental climate" during the YDS, which, if true, has important implications regarding the role of highly seasonal North Atlantic stadial events in facilitating, rather than stalling, recession of adjacent ice masses. We address this problem by presenting a chronology of glacial activity immediately downwind of the North Atlantic in Scotland.

Glaciers are sensitive to small changes in climate, particularly temperature and precipitation. In western Europe, where climate is dominated by the ameliorating effect of the North Atlantic Current, glaciers are highly responsive to upwind sea-surface temperatures (*SI Text*), and past glacier behavior would have been dominated by North Atlantic sea-surface conditions. Thus the Scottish glacial record is ideal for reconstructing late glacial variability in North Atlantic temperature (Fig. 1). The last glacier resurgence in Scotland—the "Loch Lomond Advance" (LLA)—culminated in a ~9,500-km^2 ice cap centered over Rannoch Moor (Fig. 2*A*) and surrounded by smaller ice fields and cirque glaciers. The ice cap was drained via calving tidewater glaciers along its western margin and land-terminating glaciers along its eastern margin. Well-preserved moraines indicate that subsequent deglaciation was characterized by progressive, active retreat rather than rapid downwasting (16, 17). In contrast to the wealth of information constraining the physical characteristics of the LLA, few data exist resolving the precise age of the event. and there remains considerable uncertainty as to when the advance began or when glaciers reached their maximum extent (18–20). Nevertheless, the LLA traditionally is correlated with the YDS and assumed to have culminated near the end of the stadial (5).

To derive an independent chronology of glacier recession downwind of the North Atlantic, we mapped and dated glacial deposits in the western sector of Rannoch Moor (56.636°N, 4.7732°W), located at the former center of the LLA ice cap, to reconstruct the final stages of ice-cap retreat. End moraines of up to 5 m relief define the northward recession of an active ice front across the moor (~300 m elevation), whereas chaotic mounds located on broad uplands (~400 m elevation) near the moor's center indicate final stagnation of remnant ice (Fig. 2*B*). Previous investigations into the deglacial chronology of the site invoked ice-free conditions at Rannoch Moor—and consequently throughout Scotland—as early as 12,400 ± 330 calendar years (cal yr) [sample SRR-1074 (21) (Dataset S1)] and no later than

Significance

Resolving the full manifestation of past abrupt climate change is key to understanding the processes driving and propagating these events. As a principal component of global heat transport, the North Atlantic Ocean also is susceptible to rapid disruptions of meridional overturning circulation and thus widely invoked as a cause of abrupt climate variability in the Northern Hemisphere. We assess the impact of one such North Atlantic cold event—the Younger Dryas Stadial—on an adjacent ice mass and show that, rather than instigating a return to glacial conditions, this abrupt climate event was characterized by deglaciation. We suggest this pattern indicates summertime warming during the Younger Dryas, potentially as a function of enhanced seasonality in the North Atlantic.

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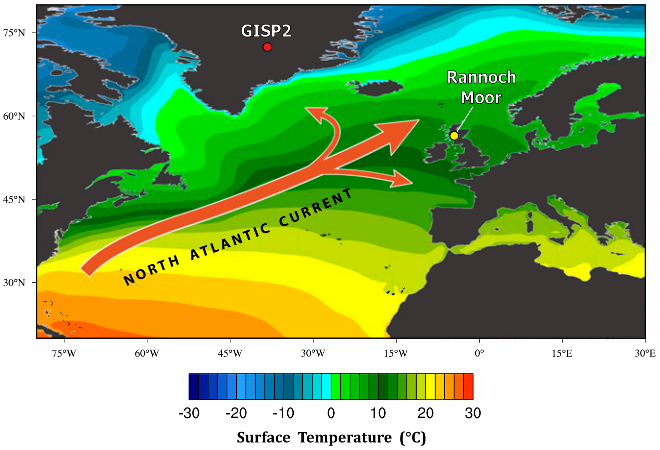

Fig. 1. Surface temperature and heat transport in the North Atlantic Ocean. The relatively mild European climate is sustained by warm sea-surface temperatures and prevailing southwesterly airflow in the North Atlantic Ocean (NAO), with this ameliorating effect being strongest in maritime regions such as Scotland. Mean annual temperature (1979 to present) at 2 m above surface (image obtained using University of Maine Climate Reanalyzer, www.cci-reanalyzer.org). Locations of Rannoch Moor and the GISP2 ice core are indicated.

12,150 ± 300 cal yr [sample BIRM-858 (21) (Dataset S1)]. This scenario conflicts with the canonical view that glaciers in Scotland collapsed in response to rapid warming at the end of the YDS (as reviewed in ref. 20), suggesting instead that deglaciation was underway early in the stadial.

To address this discrepancy, we collected 13 sediment cores from moraine-dammed bogs on Rannoch Moor (Fig. 2*B* and Figs. S1–S3) and extracted organic material for ^{14}C dating from sediments immediately overlying the LLA till. Our independent radiocarbon-based chronology is underpinned by 20 basal ages derived from these water-lain postglacial sediments. Samples consisted primarily of terrestrial plant macrofossils (*Materials and Methods* and Fig. S4) that most likely were dislodged from adjacent land surfaces (e.g., by slope processes, wind, rain, etc.) and incorporated into nearby drainage, before being deposited along with reworked minerogenic sediments in topographic basins. Thus, terrestrial plant remains in these earliest postglacial deposits typically do not reflect growth position. There is no evidence (e.g., till, disturbance of sediments) in our cores for ice overriding subsequent to deposition of the LLA till. Moreover, the near-perfect preservation of the plant remains (Fig. S4) argues against these macrofossils having been glacially reworked from the pre-LLA landscape. Thus the earliest organics in our cores represent the onset of postglacial plant colonization of Rannoch Moor and provide a minimum limit on the age of complete deglaciation of the LLA ice cap.

Results and Discussion

Radiocarbon ages are shown in Fig. 3 and are given in Dataset S1. Ages from the lowermost macrofossils in each core range from 9,140 ± 180 to 10,550 ± 65 ^{14}C y, corresponding to 10,320 ± 270 to 12,480 ± 100 cal yr (Dataset S1). This nonnormal distribution is characteristic of minimum-limiting datasets and confirms that the basal ages do not represent a single event (deglaciation) but a process: the progressive postglacial colonization by plants of Rannoch Moor. Initial sparse vegetation is succeeded over time by more extensive and continuous cover, a nonuniform process which may have been complicated by the presence of buried ice (*SI Text*). Thus the distribution of basal dates will be skewed toward younger ages, whereas those more closely representing the onset of plant colonization will be relatively few (*SI Text*). For this reason, because we want to examine the very first occurrence of plant growth on Rannoch Moor—and thereby provide a close minimum-limiting age for deglaciation—we focus on the oldest basal dates.

When did postglacial plant colonization of Rannoch Moor begin? Here, we use several statistical approaches to establish the basal radiocarbon age(s) most representative of that event. First, following geologic convention (e.g., 22), we take the single oldest age in our dataset as the closest constraint on deglaciation. Sample OS-99685 (10,550 ± 65 ^{14}C y; Dataset S1), from the basal section of core RM-12–3A, gives a weighted-mean calibrated age

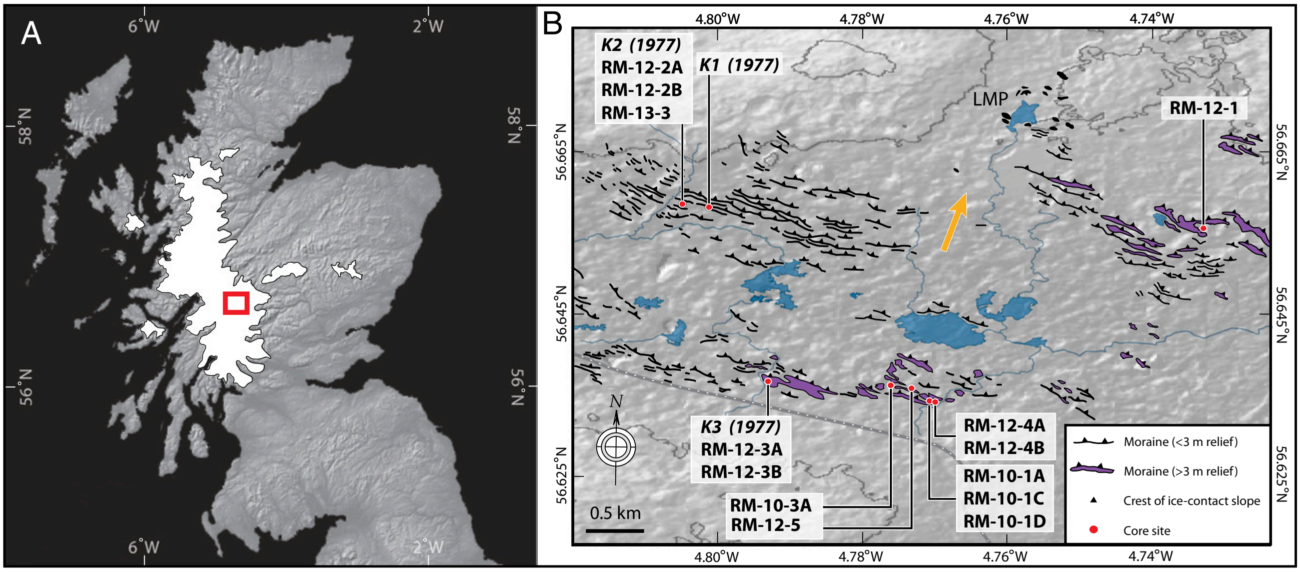

Fig. 2. Extent of the LLA ice cap in Scotland and glacial geomorphology of western Rannoch Moor. (*A*) Maximum extent of the ~9,500 km^2 LLA ice cap and larger satellite ice masses, indicating the central location of Rannoch Moor. Nunataks are not shown. (*B*) Glacial-geomorphic map of western Rannoch Moor. Distinct moraine ridges mark the northward active retreat of the glacier margin (indicated by arrow) across this sector of the moor, whereas chaotic moraines near Lochan Meall a' Phuill (LMP) mark final stagnation of ice. Core sites are shown, including those (K1–K3) of previous investigations (14, 15).

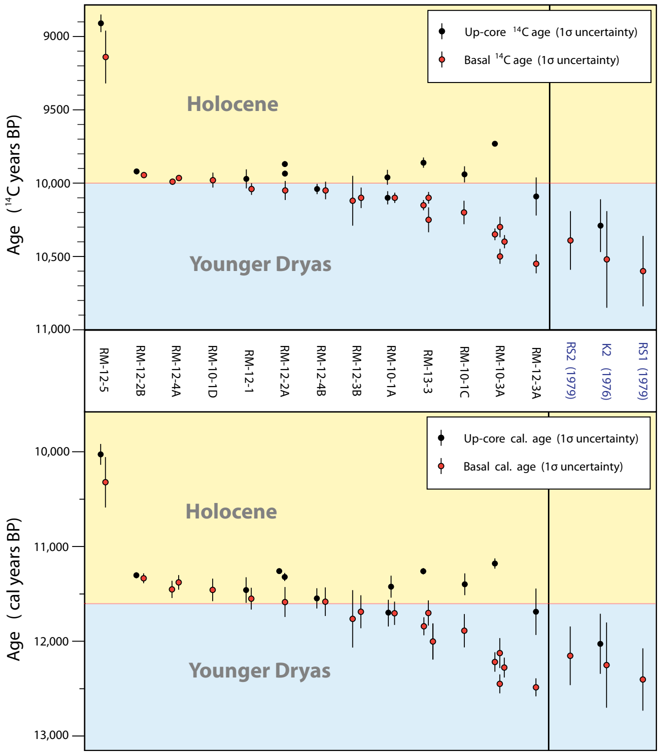

Fig. 3. Relative distribution of Rannoch Moor radiocarbon dates. Ages are shown for all thirteen cores (this study), as well as the relative distributions of previously published ages (19, 21, 22). Basal ^{14}C ages are highlighted in red. The ^{14}C ages from higher stratigraphic levels are shown in black.

of 12,480 ± 100 cal yr, whereas the earliest probable (defined here as the 90% confidence interval) age of that sample is 12,580 cal yr (Table 1, Fig. 4*A*, and Fig. S5). However, this widely used approach raises the possibility of basing paleoclimatic interpretations on a potentially "old" outlier sample. A second and more conservative method is to use the oldest replicable dates as a minimum age for deglaciation. Using χ^2 statistics, we identified the oldest replicable basal ^{14}C ages in our dataset as samples OS-99977, OS-99978, OS-89841, and OS-89842, all from the basal 4 cm of core RM-10–3A (*SI Text*, Fig. S1, and Dataset S1). This statistically indistinguishable grouping [$\chi^2 = (3, n = 4) = 7.6$, $P = 7.8$] has an error-weighted mean calibrated age of 12,262 ± 85 cal yr, which we take as a conservative date for the onset of plant colonization (Fig. 4*B* and Fig. S6). However, at 90% confidence, the earliest probable age for the first plants on Rannoch Moor based on these ages is 12,493 cal yr (Fig. S6).

A third and broader-scale approach assesses the cumulative probability of all eighteen basal ages. Because the nonnormal distribution of this dataset precludes taking the mean as a close minimum age for plant colonization (*SI Text*), we use the 90% confidence interval to identify the earliest probable age represented by this dataset as 12,371 cal yr (Table 1 and Fig. S7). Furthermore, although 40% of the cumulative-probability curve lies <11.6 ka, this distribution reflects the inclusion of basal ages that are considerably younger than the onset of plant growth. Thus we argue that for this analysis of all basal data the 90% value constrains most closely the age of deglaciation.

Although there are several ways to establish the most representative age for deglaciation using a minimum-limiting dataset such as ours, we note that, regardless of approach, the outcome does not change our conclusions. As shown in Table 1, the difference between the earliest probable age (12,580 cal yr) and our most conservative estimate (12,262 ± 85 cal yr) is <400 y, reflecting the consistency among our oldest basal ages. Furthermore, because these ages represent the first vegetation to colonize Rannoch Moor following deglaciation, they constitute a minimum-limiting age for final disappearance of the LLA ice cap. Our chronology indicates that deglaciation of Rannoch Moor was complete as early as ∼12,580 cal yr, but no later than ∼12,200 cal yr (Fig. 4). This interpretation is reinforced by the tight agreement between our data and existing minimum-limiting ages from Rannoch Moor (14, 15, 21) (Fig. 3 and Dataset S1).

Both "earliest" and "conservative" scenarios indicate that Rannoch Moor was deglaciated by mid-YDS time (Fig. 4) and therefore that the extensive ∼9,500-km^2 LLA ice cap was gone from the landscape at least 500 y before the end of the stadial. These findings conflict with the prevailing view that glaciers in Scotland advanced and maintained maximum positions throughout much of the YDS, posing the question: What drove deglaciation during a period of apparently severe North Atlantic cold? Furthermore, if the YDS was characterized by deglaciation, then when did the LLA itself occur?

We consider two possible resolutions to the paradox of deglaciation during the YDS. First, declining precipitation over Scotland due to gradually increasing North Atlantic sea-ice extent has been invoked to explain the reported shrinkage of glaciers in the latter half of the YDS (18). However, this course of events conflicts with recent data depicting rapid, widespread imposition of winter sea-ice cover at the onset of the YDS (9), rather than progressive expansion throughout the stadial. Furthermore, considering the gradual active retreat of LLA glaciers indicated by the geomorphic record, our chronology suggests that deglaciation began considerably earlier than the mid-YDS, when precipitation reportedly began to decline (18). Finally, our cores contain lacustrine sediments deposited throughout the latter part of the YDS, indicating that the water table was not substantially different from that of today. Indeed, some reconstructions suggest enhanced YDS precipitation in Scotland (24, 25), which is inconsistent with the explanation that precipitation starvation drove deglaciation (26).

We prefer an alternative scenario in which glacier recession was driven by summertime warming and snowline rise. We suggest that amplified seasonality, driven by greatly expanded winter sea ice, resulted in a relatively continental YDS climate for western Europe, both in winter and in summer. Although sea-ice formation prevented ocean–atmosphere heat transfer during the

Table 1. Radiocarbon and calibrated age determinations for the minimum deglaciation-age scenarios

Scenario	Age (^{14}C y)	Mean calibrated age (cal yr)	Earliest probable age at 90% confidence (cal yr)
Single oldest age: OS-99685	10,550 ± 65	12,481 ± 95	12,580
Oldest replicable ages (n = 4): OS-99978, OS-89842, OS-89841, OS-99977	10,394 ± 25	12,262 ± 85	12,493
All basal ages (n = 20)	—	—	12,371

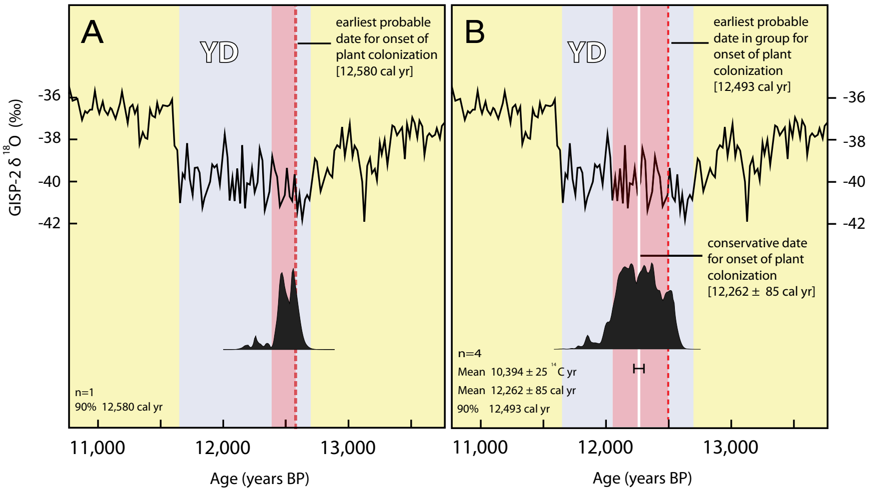

Fig. 4. Minimum-limiting ages for the final collapse of the LLA ice cap compared with the Greenland temperature record. (*A*) Sum-probability curve for the single oldest basal age, shown in black, with 90% confidence interval (pink shading) and maximum probable age for plant colonization (red dashed line). This age suggests Rannoch Moor was ice-free by 12,580 cal yr. (*B*) Sum-probability curve for the oldest replicable basal ages, showing both the oldest probable age for plant colonization and the error-weighted mean (white line) with 2σ uncertainty (black bar). This calibrated mean age represents our conservative estimate for the final collapse of the LLA ice cap and indicates that Rannoch Moor was deglaciated no later than ~12,200 cal yr. For comparison, the GISP2 $\delta^{18}O$ record (23) and YDS (blue shading) are shown.

winter months (10), summertime melting of sea ice would have imposed an extensive freshwater cap on the ocean surface (27), resulting in a buoyancy-stratified North Atlantic. In the absence of deep vertical mixing, summertime heating would be concentrated at the ocean surface, thereby increasing both North Atlantic summer sea-surface temperatures (SSTs) and downwind air temperatures. Such a scenario is analogous to modern conditions in the Sea of Okhotsk (28) and the North Pacific Ocean (29), where buoyancy stratification maintains considerable seasonal contrasts in SSTs. Indeed, Haug et al. (30) reported higher summer SSTs in the North Pacific following the onset of stratification than previously under destratified conditions, despite the growing presence of northern ice sheets and an overall reduction in annual SST. A similar pattern is evident in a new SST record from the northeastern North Atlantic, which shows higher summer temperatures during stadial periods (e.g., Heinrich stadials 1 and 2) than during interstadials on account of amplified seasonality (30).

The effects of stratification-driven summertime warming may have been exacerbated by amplified seasonal shifts of the boreal westerlies. Although the jet stream likely was stronger and more zonal across the North Atlantic during YDS winters on account of expanded sea-ice (9), retreat of the sea-ice edge during spring and summer to a position north of Norway (31) could have facilitated a more meridional trajectory of the summertime jet, resulting in incursions of warmer subtropical air masses to Scotland. Additionally, YDS warming of the midlatitude North Atlantic that arose as a consequence of curtailed MOC (32) would have enhanced warming of subtropical air masses, potentially stimulating summertime melting of downwind European glaciers. Concurrently, increasing radiative heating due to maximum summer insolation, combined with rising atmospheric CO_2 concentrations (33), could have dominated seasonal warming and glacier recession during the YDS.

Regarding the timing of the LLA, our chronology provides a firm minimum constraint for the event and shows deglaciation of Rannoch Moor—and thus Scotland—was complete by at least ~12,200 y ago. Although this scenario is supported by earlier radiocarbon studies (14, 15, 21, 34), it is difficult to reconcile with the paradigm of the LLA being driven by YDS cooling, because that would require the accumulation and collapse of a major ice cap within as little as 400 y. Indeed, one recent assessment places the onset of the YDS closer to 12.7 ka (9), further shortening the window of time available for a stadial-driven advance. Such rapid build-up and decay of the ice cap is inconsistent, however, with the abundance of geomorphic data indicating deglaciation was dominated by gradual active retreat rather than sudden stagnation (16, 17) and with recent modeled reconstructions of the ice cap's evolution forced by Greenland temperature data (20). Thus in the context of our chronology we suggest the LLA represents either (*i*) a relatively minor expansion during the earliest YDS of a preexisting ice mass or (*ii*) a glacial advance predating the YDS chronozone. The latter scenario is consistent with an earlier interpretation of the Scottish record suggesting an Allerød age for the LLA (34) and with the pre-YDS advance of outlet glaciers in western Norway toward their maximum late glacial positions (35).

Our interpretation of the Rannoch Moor data, involving the summer (winter) heating (cooling) effects of a shallow North Atlantic mixed layer, reconciles full stadial conditions in the North Atlantic with YDS deglaciation in Scotland. This scenario might also account for the absence of YDS-age moraines at several higher-latitude locations (12, 36–38) and for evidence of mild summer temperatures in southern Greenland (11). Crucially, our chronology challenges the traditional view of renewed glaciation in the Northern Hemisphere during the YDS, particularly in the circum-North Atlantic, and highlights our as yet incomplete understanding of abrupt climate change.

Materials and Methods

Macrofossils Used for ^{14}C Measurements. Radiocarbon analyses were performed primarily on plant material collected from basal sediments overlying glacial till with a 5-cm-diameter Livingstone corer. Basal sediments comprise finely laminated units of fine- and medium-grained sand and clay (Figs. S1–S3), occasionally separated by thin lenses of gyttja, and exhibit abrupt transitions into overlying organic-rich material. Overall concentrations of organics in the minerogenic material are low, reflecting the sparsely vegetated nature of recently deglaciated terrain, and increase with distance upcore. Macrofossils used in our analyses were dominated by terrestrial plant species such as *Rhacomitrium* sp., *Empetrum* sp., *Betula* sp., *Sphagnum* sp., *Pogonatum* sp., and *Vaccinium* sp. (Fig. S4 and Dataset S1). Additionally, species indicative of shallow aquatic environments include *Potamogeton* sp., *Chara* sp., and *Nitella* sp. One sample (OS-93723) consisted entirely of chitinous black beetle shell fragments. Sediments first were wet-sieved to remove the fine-grained fraction, then inspected under a microscope.

Macrofossils were extracted using tweezers and subsequently cleaned in deionized water in an ultrasonic bath to remove any fine-grained minerogenic residue that potentially could be a source of old carbon (39, 40). We note that contamination by dissolved old carbon (the hard-water effect) is unlikely to affect our samples due to the absence of carbonate lithologies in the surrounding area and our preferential selection of terrestrial species for radiocarbon analyses. Analyses were performed at the Keck–Carbon Cycle Accelerator Mass Spectrometry Laboratory, University of California, Irvine, and at National Ocean Sciences Accelerator Mass Spectrometry, Woods Hole Oceanographic Institute. Radiocarbon dates were calibrated to calendar years using OxCal v.4.2 (41, 42) and IntCal 09 (43).

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Supporting Information

Bromley et al. 10.1073/pnas.1321122111

SI Text

Sensitivity of Western European Glaciers to North Atlantic Sea-Surface Temperatures. Poleward transport of heat by the North Atlantic Current, in conjunction with the prevailing westerly airflow, has a pronounced ameliorating effect on the climate of Europe (1, 2) and maintains significantly higher average-air temperatures in western Europe than at comparable latitudes in North America. For example, average high temperatures in Oban (56.4°N), on the west coast of Scotland, for January and July are 7 and 18 °C, respectively. As a consequence of this strong oceanic–atmospheric effect, glaciers throughout Europe are directly influenced by changes in North Atlantic sea-surface temperature (3).

As passive indicators of climate, glaciers constitute highly visible thermometers, advancing and retreating in response to small changes in air temperature. Although other climatic and hypsometric parameters (e.g., precipitation, humidity, and aspect) also affect mass balance, in general, temperature is the dominant influence, as indicated by the almost uniform recession of glaciers today in response to anthropogenic warming (4). In Europe, where atmospheric temperature is dominated by the North Atlantic Ocean, the close association between glaciers and sea-surface temperature is demonstrated by the clear anticorrelation between glacier-mass balance in the Alps and the Atlantic Meridional Oscillation (AMO), with low AMO corresponding to positive glacier mass balance and vice versa (5).

As under modern conditions, Late Quaternary climate fluctuations—and therefore glacier behavior—in Europe also will have been dictated in large part by North Atlantic SSTs (e.g., 3, 6). Moreover, this oceanic influence will have been strongest in maritime regions, such as Scotland, located immediately downwind of the North Atlantic. Therefore the paleoclimate record from Scotland most closely reflects changes in the configuration of ocean circulation and heat transfer and thus is particularly valuable to our understanding of the mechanisms driving abrupt late glacial climate events such as the YDS.

Geologic Setting of Rannoch Moor and Implications of Minimum-Limiting Radiocarbon Ages. Rannoch Moor (average elevation 300–350 m) occupies a broad topographic depression underlain primarily by Caledonian granite and granodiorite. The moor is ringed by high-relief mountains, many of which exceed 1,000 m in elevation, and is drained by a radial system of glacially carved valleys. The west-flowing valleys terminate in the sea as deep fjords. During the LLA (and earlier during the Devensian glaciation), Rannoch Moor was a major ice-distribution center (7): ice accumulating in the surrounding cirques coalesced in the basin before draining via numerous large outlet glaciers. At the height of the stadial, the moor was occupied by an ice dome with a maximum surface elevation exceeding 800 m (8, 9). A recent modeling study by Golledge et al. (8), in addition to earlier reconstructions (e.g., 10), indicates that Rannoch Moor was one of the last places in Scotland to become ice-free at the close of the LLA. For this reason, robust constraint of the deglaciation of Rannoch Moor represents the end of glaciation not just in this central highland location but throughout the whole of Scotland.

The objective of our investigation was to obtain samples of the earliest vegetation on Rannoch Moor following the LLA, thereby providing minimum-limiting ages for deglaciation. We chose the site because, as described above, Rannoch Moor lay at the former center of the LLA ice cap and, therefore, was one of the last places in Scotland to become ice-free. We stress that the radiocarbon ages do not date the deglaciation itself, rather the onset of plant colonization of the newly deglaciated landscape. Thus the LLA ice cap had to have been gone before this date in order for this pioneer vegetation to flourish.

Distributions of Radiocarbon Ages and Implications. We examined the basal ages from each core to constrain as closely as possible the onset of plant colonization of Rannoch Moor. In the case of core RM-10–3A, we ran four replicate samples (OS-89841, OS-99977, OS-89842, and OS-99978) from the lowermost 4 cm (Fig. S1). Because the ages are in close agreement (Dataset S1), overlapping within 1σ, we included the average of these replicate samples in our interpretations. Similarly, we ran replicate samples from cores RM-12–3B, RM-12–4A, and RM-13–3. The distribution of all 20 basal ages (in ^{14}C y) is given in Fig. 3 and Fig. S5 and ranges from 9,140 ± 180 to 10,550 ± 65 ^{14}C y. Calibrated to calendar years, this distribution has a possible range (within 2σ) of 9,701–12,648 calendar years (cal yr) (Dataset S1).

This broad distribution is characteristic of minimum-limiting (and maximum-limiting) datasets for several reasons. First, in contrast to the deposition of glacial landforms such as moraines, plant colonization of a landscape is not a distinct event but a protracted process, commonly occurring over considerable timescales. As in newly deglaciated terrain today, initial vegetation cover at Rannoch Moor after the LLA would have been thin and discontinuous, and therefore is relatively poorly represented in the sedimentologic record. Over time, both vegetation cover and the organic content of sediments would have increased. Second, the lag time between deglaciation and the onset of plant colonization cannot be assessed via this method. Pioneer species could have moved into the newly deglaciated landscape within years to centuries, or as long as millennia, while the presence of remnant buried ice in topographic depressions may have prevented plant colonization for some time after deglaciation. Third, to provide a minimum-limiting age for deglaciation it is necessary to obtain the oldest organic material from as close to the glacial contact as possible. Due to sediment focusing, the oldest organic materials are often found in the deepest part of a basin. However, even with careful depth surveying, locating and sampling the deepest sediments from the surface remains challenging. Moreover, the sparsely vegetated nature of recently deglaciated terrain further reduces the chances of pinpointing the oldest organics.

Together, these factors result in an age distribution reflecting the overall likelihood of obtaining basal ages that are significantly younger than the onset of plant colonization. Thus the majority of ages in a dataset constitute only broadly limiting ages for deglaciation, whereas more closely limiting (i.e., older) ages will be relatively few (Fig. S7). For this reason, the geologic convention is to take the single oldest date in a set as that most closely representing the onset of plant growth and, therefore, deglaciation (11, 12). Applied to our dataset, this approach yields a mean age of 10,550 ± 65 ^{14}C y (OS-99685), corresponding to a mean calibrated age of 12,481 ± 95 cal yr, and a 90% confidence interval of 12,385–12,580 y. Thus, assuming our oldest basal age is reliable, the earliest probable age (within the 90% confidence interval) for the onset of plant growth at Rannoch Moor, as represented by this radiocarbon date, is 12,580 cal yr (Fig. 4*A*, Fig. S5, and Table 1). Deglaciation of the site had to have been complete before this date.

Because this widely used approach raises the possibility of basing paleoclimate interpretations on a potentially "old" outlier, a more cautious approach is to use the oldest replicable ages in our dataset as a more robust representation of the first vegetation on Rannoch Moor. We used χ^2 statistics to identify the oldest replicable basal ^{14}C ages in our dataset. Samples OS-99977 (10,400 ± 45 ^{14}C y), OS-99978 (10,350 ± 40 ^{14}C y), OS-89841 (10,300 ± 70 ^{14}C y), and OS-89842 (10,500 ± 50 ^{14}C y) from the basal 4 cm of core RM-10–3A together have a low χ^2 value [$\chi^2(3, n = 4) = 7.6$, $P = 7.8$] and thus can be taken as representing the same event. We take the mean calibrated age of this group (12,262 ± 85 cal yr) as a robust, conservative date for the onset of plant growth. However, because our objective ultimately is to provide the closest limiting age for deglaciation, rather than plant growth, we suggest that the oldest probable age for this group is a more appropriate value. Thus we used sum-probability statistics in conjunction with the IntCal 09 curve (13) to calibrate the grouping to calendar years and then measured the cumulative frequency of that calibration to determine the 90% confidence interval (Fig. S6). At 90% confidence, the oldest probable age in this interval (12,493 cal yr; Fig. 4*B*, Fig. S4, and Table 1) more closely reflects the earliest plant growth represented by this population.

It is noteworthy that the older basal ages in our dataset are highly consistent with previously published ^{14}C ages from Rannoch Moor (10, 14, 15) (Dataset S1), despite the latter being run more than 30 years ago as conventional (not AMS) measurements at laboratories different to those used in the present study. Moreover, we stress the close agreement between our data and those of Lowe and Walker (10, 14, 15) suggests that even those samples incorporating aquatic species [e.g., samples BIRM-723 (10, 15) and BIRM-858 (15)] are unlikely to reflect contamination by old carbon. The statistically close agreement among these different datasets reinforces our conclusion that plants were colonizing Rannoch Moor by the mid-Younger Dryas and thus that the LLA ice cap had gone from the Scottish landscape by that time.

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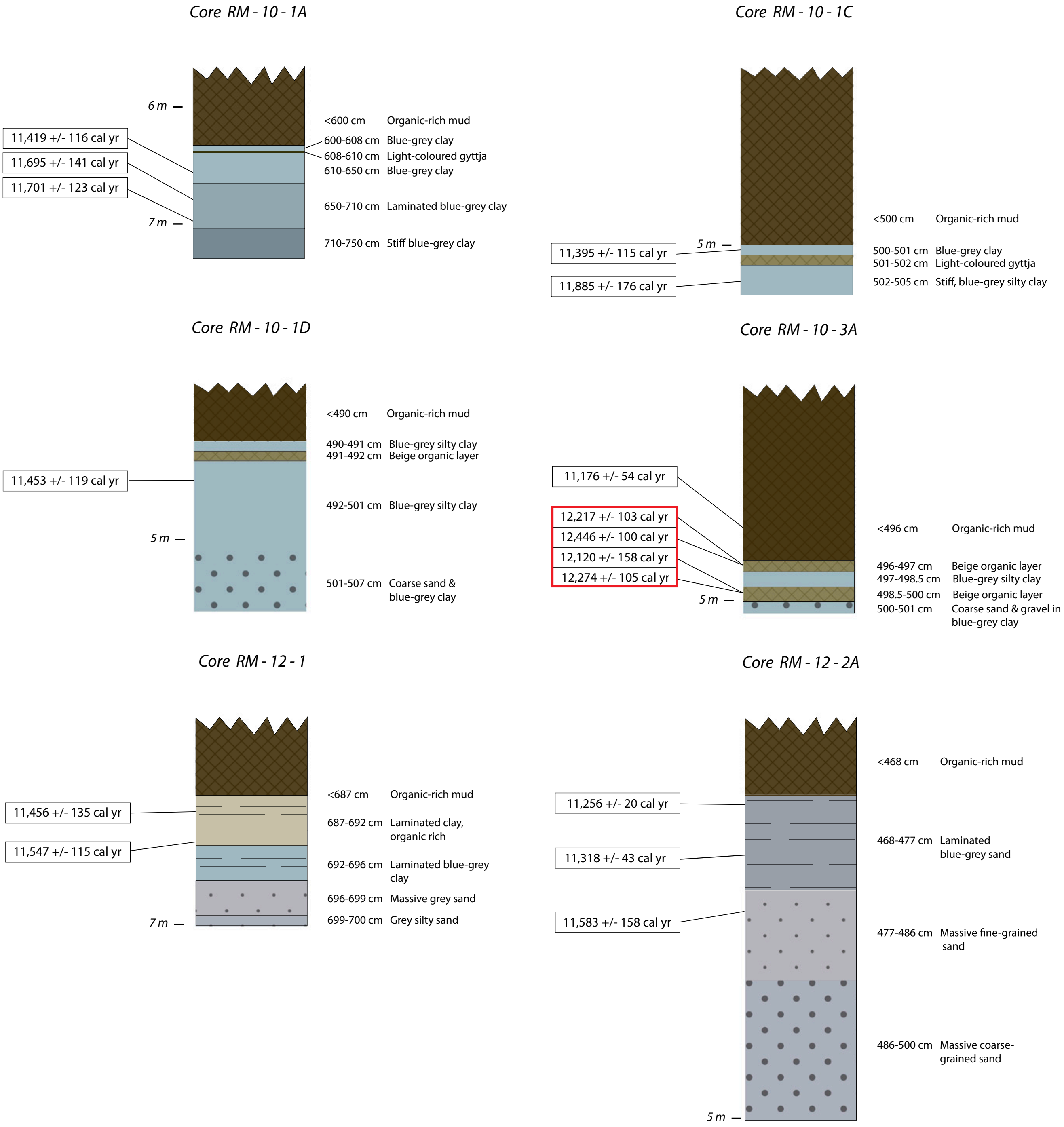

Fig. S1. Stratigraphy of six Rannoch Moor sediment cores (RM-10–1A, 1C, 1D, 3A, and RM-12–1, 2A), showing sample depths and corresponding radiocarbon (and calibrated) ages.

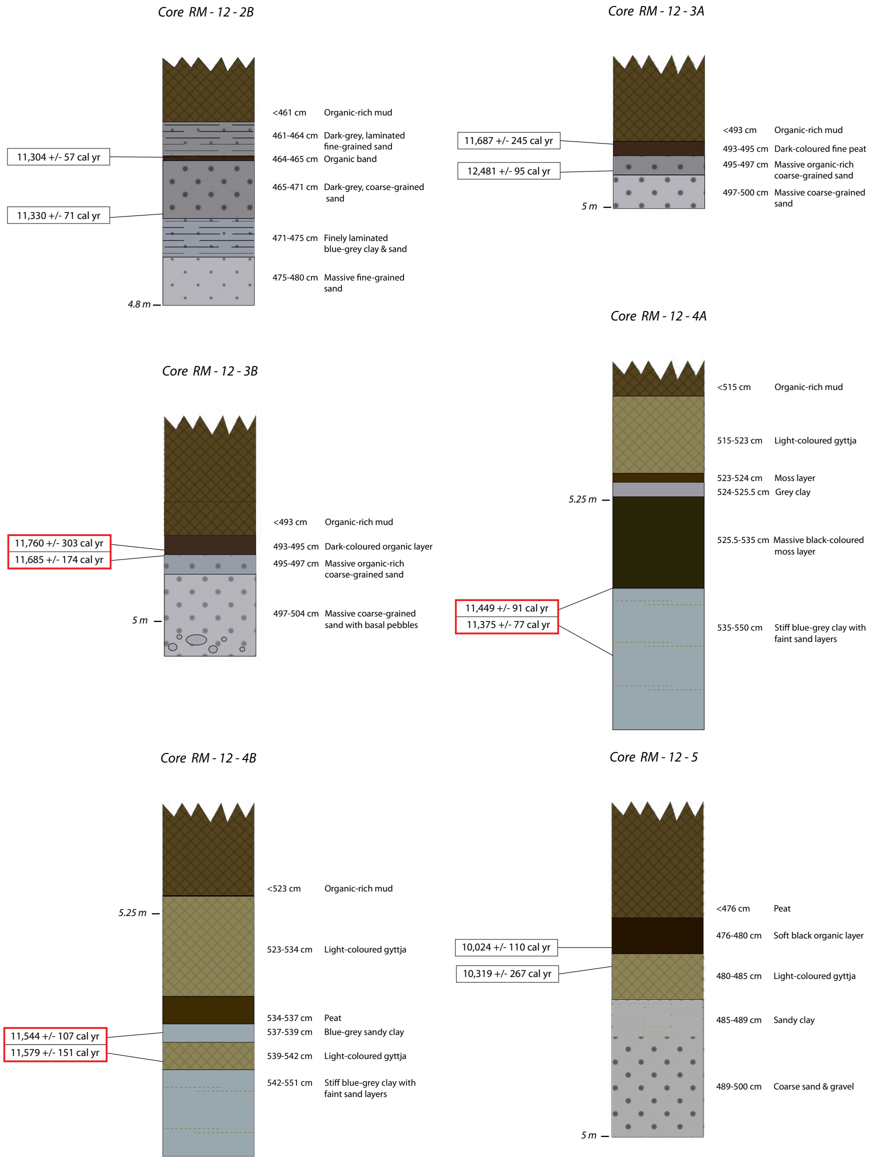

Fig. S2. Stratigraphy of six additional sediment cores (RM-12–2B, 3A, 3B, 4A, 4B, and 5), showing sample depths and corresponding radiocarbon (and calibrated) ages.

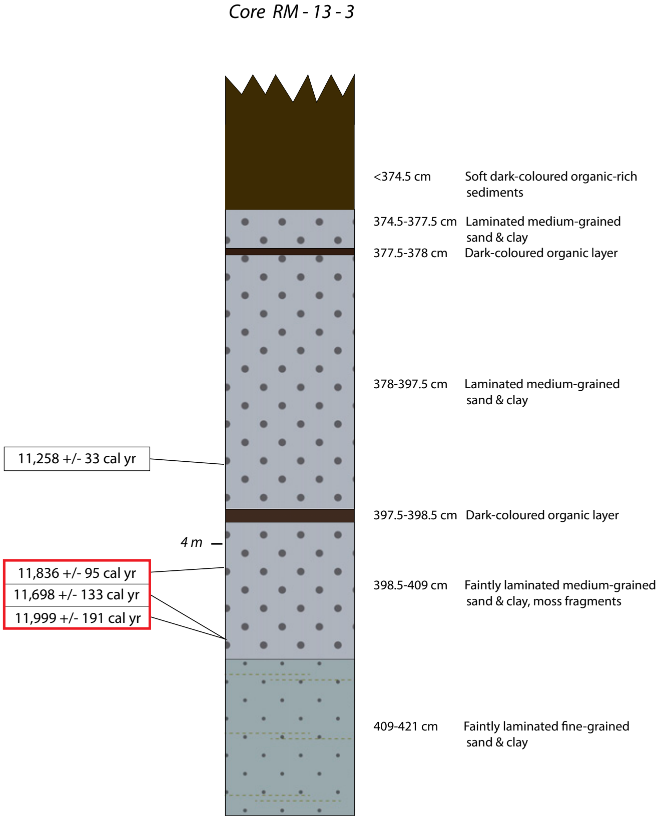

Fig. S3. Stratigraphy of sediment core RM-13–3, showing sample depths and corresponding radiocarbon (and calibrated) ages.

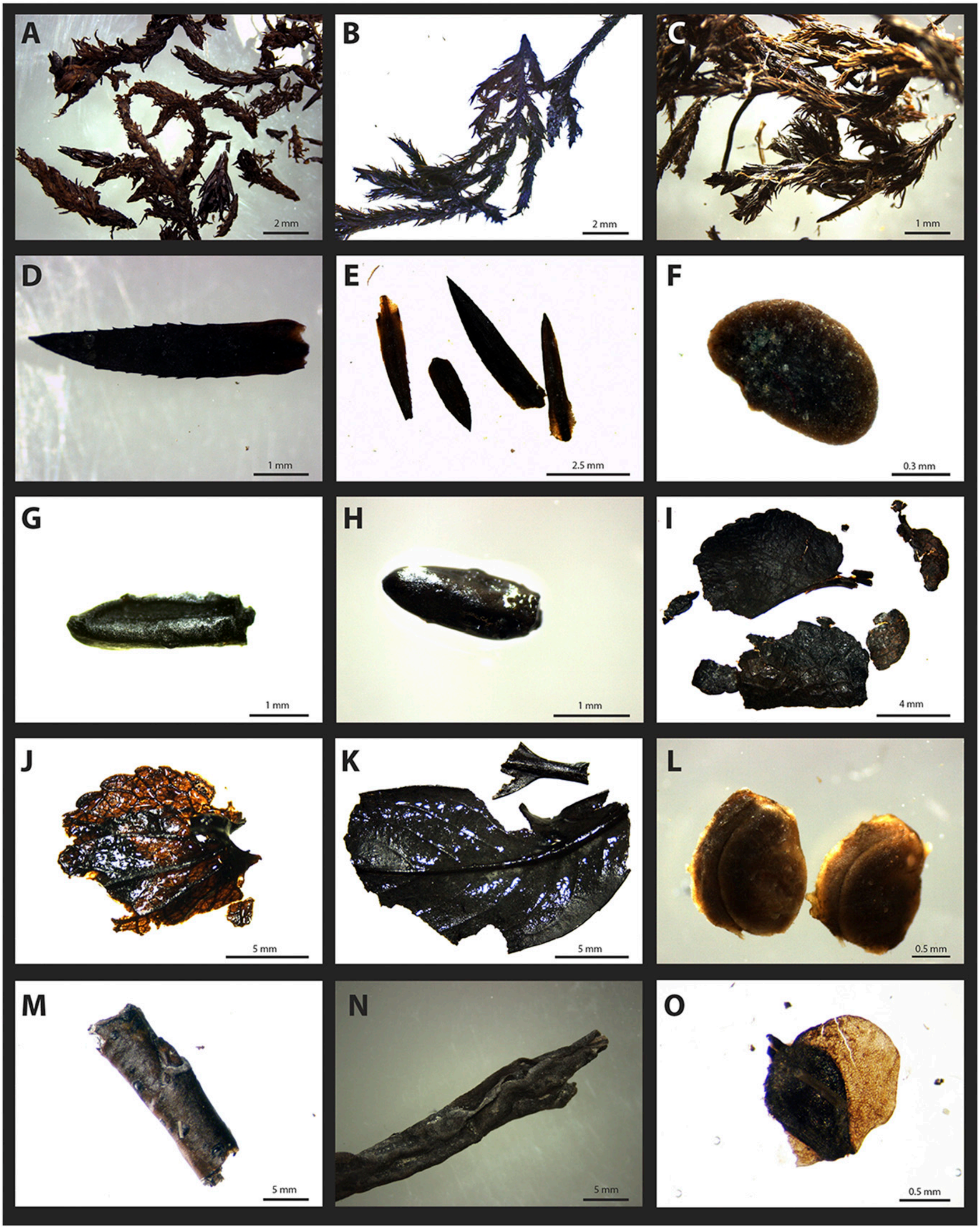

Fig. S4. Examples of plant macrofossils on which radiocarbon measurements were performed. (*A*–*C*) *Rhacomitrium* moss. (*D* and *E*) *Pogonatum* moss. (*F*) *Empetrum* (crowberry) seed. (*G* and *H*) *Empetrum* leaves. (*I* and *J*) *Betula nana* (dwarf birch) leaves. (*K*) *Vaccinium* leaf. (*L*) *Potamogeton* seeds. *Betula* (*M* and *N*) twigs and (*O*) seed.

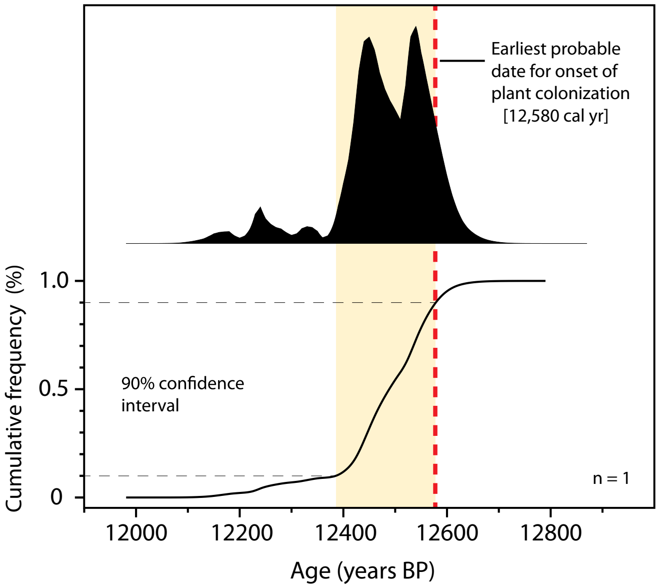

Fig. S5. Sum-probability (*Top*) and cumulative-frequency (*Bottom*) distributions for the single oldest basal age (OS-99685), showing the 90% confidence interval (shaded). The maximum probable age for the onset of plant colonization at Rannoch Moor (12,580 cal yr), at 90% confidence, is marked by the red dashed line.

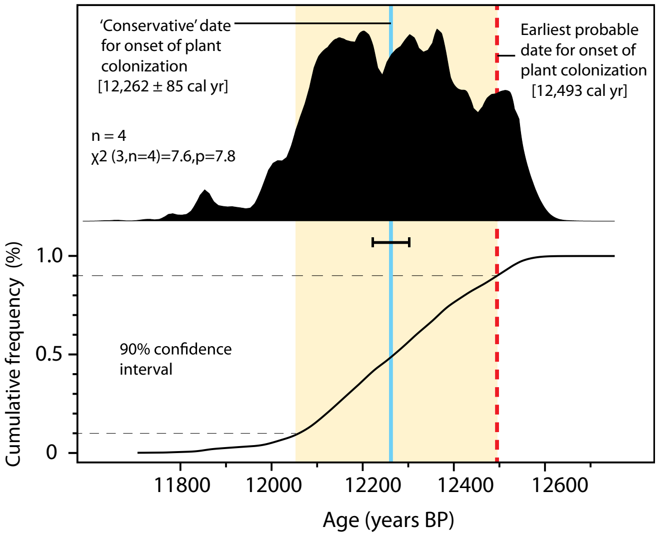

Fig. S6. Sum-probability (*Top*) and cumulative-frequency (*Bottom*) distributions for the oldest replicable basal ages (*n* = 4), showing the statistical significance of the grouping and 90% confidence interval (shaded). The error-weighted mean calibrated age (12,262 ± 85 cal yr), represented by the vertical blue line (horizontal black bar depicts 1σ uncertainty), provides a conservative date for the onset of plant colonization at Rannoch Moor. The maximum probable age for this grouping (12,493 cal yr), at 90% confidence, is marked by the red dashed line.

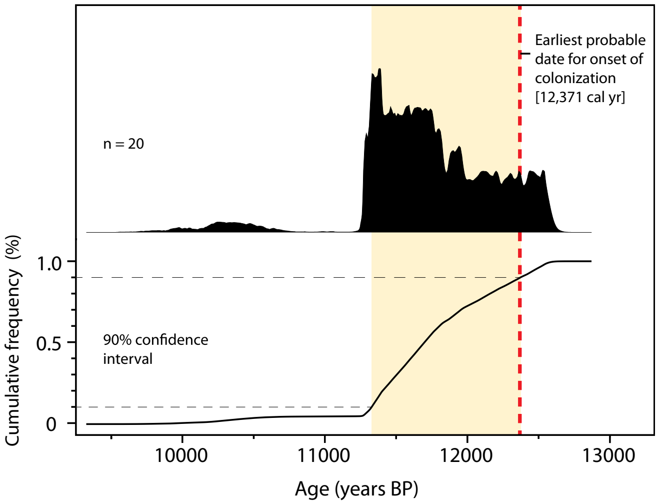

Fig. S7. Sum-probability (*Top*) and cumulative-frequency (*Bottom*) distributions for all 20 basal ^{14}C ages. The nonnormal distribution reflects the fact that minimum-limiting ages do not represent a single event but the gradual colonization by plant of Rannoch Moor following deglaciation of the LLA ice cap.

Dataset S1. Rannoch Moor sample details, radiocarbon data, and calibrated ages

Dataset S1