LETTERS
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Permafrost thawing in organic Arctic soils accelerated by ground heat production

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Decomposition of organic carbon from thawing permafrost soils and the resulting release of carbon to the atmosphere are considered to represent a potentially critical global-scale feedback on climate change[1,2]. The accompanying heat production from microbial metabolism of organic material has been recognized as a potential positive-feedback mechanism that would enhance permafrost thawing and the release of carbon[3,4]. This internal heat production is poorly understood, however, and the strength of this effect remains unclear[3]. Here, we have quantified the variability of heat production in contrasting organic permafrost soils across Greenland and tested the hypothesis that these soils produce enough heat to reach a tipping point after which internal heat production can accelerate the decomposition processes. Results show that the impact of climate changes on natural organic soils can be accelerated by microbial heat production with crucial implications for the amounts of carbon being decomposed. The same is shown to be true for organic middens[5] with the risk of losing unique evidence of early human presence in the Arctic.

Approximately 50% of the global below-ground organic carbon pool is stored in the northern circumpolar permafrost region[6,7]. Permafrost thaw and subsequent microbial decomposition are expected to increase the amount of carbon being released to the atmosphere with a potential global impact[1,8]. The organic carbon in organic soils is more labile and thereby more prone to decomposition than in mineral soils because of a markedly higher content of O-alkyl carbon and less aromatic carbon[9]. Some of the most labile carbon pools described from the Arctic are found at sites where the organic carbon was deposited relatively quickly (months to years), buried and subsequently kept under near water saturation ever since[10]. These are mainly peatlands (with or without palsas) holding 15–20% of the total northern circumpolar permafrost organic carbon[1] but also sites such as archaeological middens made by humans and representing an archive of the earliest human presence in the Arctic[11]. We test the hypothesis that internal heat production can accelerate decomposition in high-latitude organic soils and amplify permafrost thawing.

We investigated the heat production in 21 contrasting organic permafrost soils from 6 sites in Greenland that were all within the continuous permafrost zone (Fig. 1 and Supplementary Table 1). The heat production was measured calorimetrically at 16 °C on triplicates of each sample as previously described[12]. The results show a heat production between 1.3 and 12.3 J g dry soil^{-1} d^{-1} with a mean of 2.97 ± 2.06 J g dry soil^{-1} d^{-1} (Fig. 2 and Supplementary Fig. 1). This is 10–130 times higher than what has previously been reported at a similar temperature from a mineral permafrost soil in northeast Greenland[13]. This highlights the importance of heat production from organic soils (peat) compared with non-organic sediments with an organic carbon content of typically less than 5%. Except for markedly more heat-producing samples from Disko Island, the observed heat production was similar across soil types and locations and could not be related to the total carbon content in the samples (15–45% carbon, Supplementary Table 1).

Direct measurements of heat production rates are difficult to perform at low temperatures owing to the risk of condensation within the equipment. Instead, we used the oxygen consumption method[14] to quantify the temperature sensitivity of decomposition at temperatures relevant for permafrost thaw by measuring the oxygen consumption at 0.5 and 16 °C on all samples (Supplementary Fig. 2a). Rates at 16 °C varied between 0.1 and 0.7 mg O_2 g dry soil^{-1} d^{-1} and variations between samples were significantly and positively correlated with observed heat production ($r^2 = 0.89, p < 0.01$). Furthermore, it was possible to obtain a good estimate of the absolute heat production when assuming that one mole of oxygen is used to oxidize one mole of carbon releasing 40 MJ kg C^{-1} as previously proposed[3] (Supplementary Fig. 1).

Oxygen consumption results showed consistent Q_{10} values between 1.5 and 3.6, with a mean of 2.5 ± 0.5 (±1 s.d.), which are in good agreement with other studies of organic permafrost soils[15,16]. This approach was successfully validated on the basis of additional measurements of heat production on three of the samples at 20, 25 and 30 °C. No significant difference was found in the Q_{10} values derived from the two methods (Supplementary Fig. 2b and Supplementary Table 2).

The importance of soil water drainage on heat production was investigated (at 16 °C) by measuring the heat production in 6 depth-specific samples from the organic-rich Qajaa kitchen midden (part of the Ilulissat Icefjord World Heritage Site) in the eastern part of the Disko Bay region in the central part of West Greenland (Supplementary Fig. 3). In this experiment, sterilized deionized water was first added to mimic the anoxic conditions expected during initial thawing, and after the first round of measurements, the samples were freely drained and exposed to air for 24 h to mimic oxic conditions before repeating the measurements. Results showed a heat production in the organic cultural layers of between 1.3 and 2.6 J g dry soil^{-1} d^{-1} (mean = 1.8 J g dry soil^{-1} d^{-1}), but on drainage, the average heat generation increased by more than 200% and in some layers by as much as 350% (Supplementary Fig. 4). This marked increase in heat production is consistent with the increasing oxygen availability following drainage, faster decomposition and higher heat production rates.

We used the well-established heat and water flow model The CoupModel[17] to perform a detailed investigation of the coupling between climate change, permafrost thaw, decomposition and

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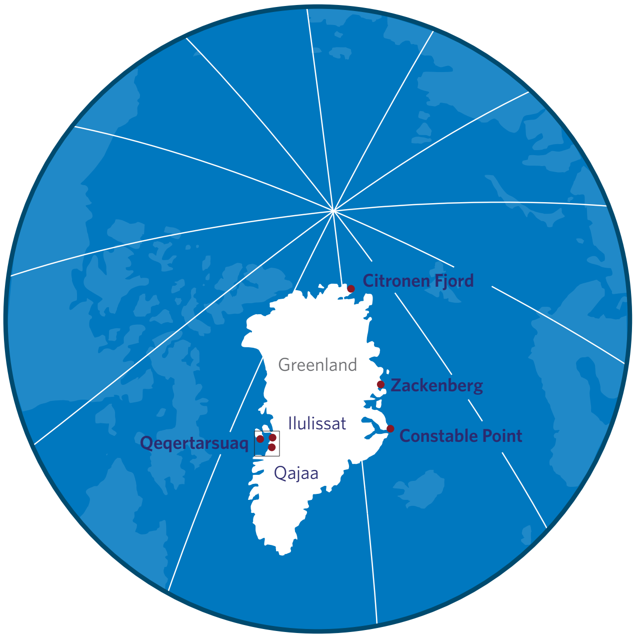

Figure 1 | Study site locations. Study sites spread across the continuous permafrost zone in Greenland. Red circles represent the 6 areas where 21 different samples of organic permafrost soils were collected for the analysis. The location of the Disko Bay region is shown as a black square. Figure courtesy of Kent Pørksen, Univ. Copenhagen.

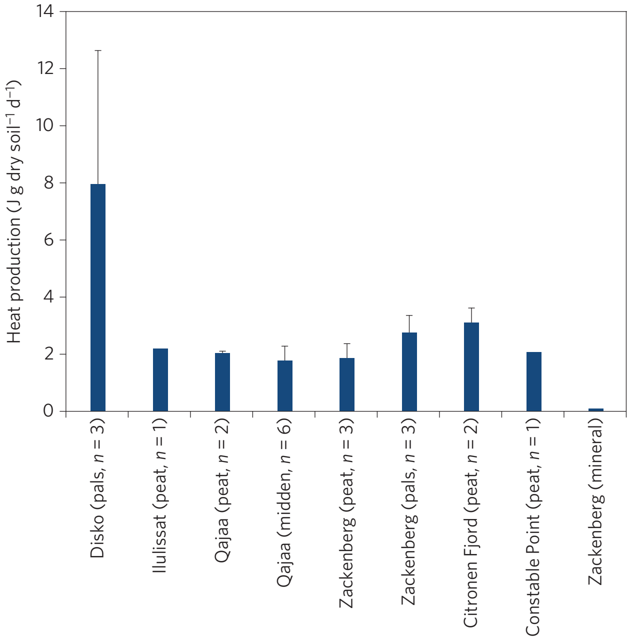

Figure 2 | Heat production during incubation at 16 °C. Observed heat production in 21 different organic-rich permafrost samples (*in situ* water content) grouped according to soil type and sample area. The *n*-values represent different locations within a specific area—except for the Qajaa midden where *n* represents the number of different archaeological layers investigated. Error bars show +1 s.d. For comparison heat production from a mineral soil at Zackenberg[13] is included.

internal heat production. The model has previously been used successfully to predict permafrost thawing[13]. For this study, the model was first calibrated to fit measured soil temperatures and soil water contents (from 2011–2012) at the Qajaa kitchen midden (Supplementary Fig. 3). Site-specific measurements of meteorological conditions, snow depths, soil thermal and physical properties were used as input to the model (see Supplementary Methods and Supplementary Figs 5–7). A detailed description of the calibration process is found in the Supplementary Information. After the calibration process, the model set-up was successfully validated on the basis of measured soil temperatures and soil water contents from 2010–2011 (Supplementary Figs 8 and 9 and Supplementary Tables 3 and 4). Furthermore, to verify that the model was representative for other sites and types of organic soil, we also included environmental data from the study site near the Zackenberg Research Station in central northeast Greenland (74° 30′ N, 20° 30′ W). After changing only the meteorological input data and adjusting the snow density to measured values from Zackenberg (Supplementary Fig. 10 and Supplementary Table 5), the ground thermal regime was successfully validated against observed soil temperatures in Zackenberg. The fact that it was possible to use the model successfully on two contrasting sites confirmed the robustness of the model set-up.

The tested model set-up was used to investigate the effect of future climate warming on the active layer thickness by simulating two different climate change scenarios: a low and a high scenario based on the minimum and the maximum range of predictions from RCP4.5 (a moderate global warming projection used by the Intergovernmental Panel on Climate Change[18] (IPCC)) and amplified according to previous modelling for Greenland[19]. The scenarios were applied for two of the study areas (Fig. 1): the relatively warm Disko Bay area in West Greenland (mean annual air temperature −4 °C) and the relatively cold Zackenberg area in northeast Greenland (mean annual air temperature −9 °C).

To investigate the interactions between permafrost thaw, decomposition of organic carbon and heat production, a three-pool decomposition/heat production module was included in the CoupModel. On the basis of values used in other studies[8,16,20–23], the total pool of carbon was divided into a fast (5%), a slow (50%) and a passive pool (45%), and the total observed decomposition rate (heat production) was considered a sum of three pool-specific rates with turnover times (under drained conditions at 5 °C) of 2, 5 and >4,000 years respectively. The absolute loss of carbon was calculated for each soil layer at each time step (daily basis) and adjusted to the depth-specific temperatures and water contents according to the specific climate change scenarios. The response to temperature was described using a Q_{10} value of 2.5 (the average of measured values), and the response to soil moisture was described on the basis of a previously reported sensitivity function[24] that was set to fit the results from our drainage experiment with the decomposition being lower under wet and very dry conditions (Supplementary Fig. 11). The decomposition and corresponding heat production were applied in layers from the bottom of the current active layer and down to 3 m depth and only at soil temperatures above 0.5 °C.

The results (without considering heat production) show that a 2.2–5.2 °C warming from 2012–2100 is likely to increase the maximum active layer depth by 15–110 cm in the Disko Bay area and 5–20 cm in the Zackenberg area (Fig. 3a,b). Depending on the degree of warming given by the minimum/maximum range of predictions from RCP4.5, 1–4% of the total pool of organic carbon (depth integrated from 0.5–3.0 m depth) could be lost from the thawing permafrost layers in the Disko Bay area and 0.2–1.5% in the Zackenberg area (depth integrated from 0.3–3.0 m depth).

When including heat production in the simulations, results show that observed heat production is high enough to trigger a feedback loop between soil temperatures and decomposition—but only under sufficiently warm conditions. For the cold Zackenberg area, the effect of heat production is limited, even if temperatures increase by 5.2 °C, whereas for the warmer Disko Bay, heat production could

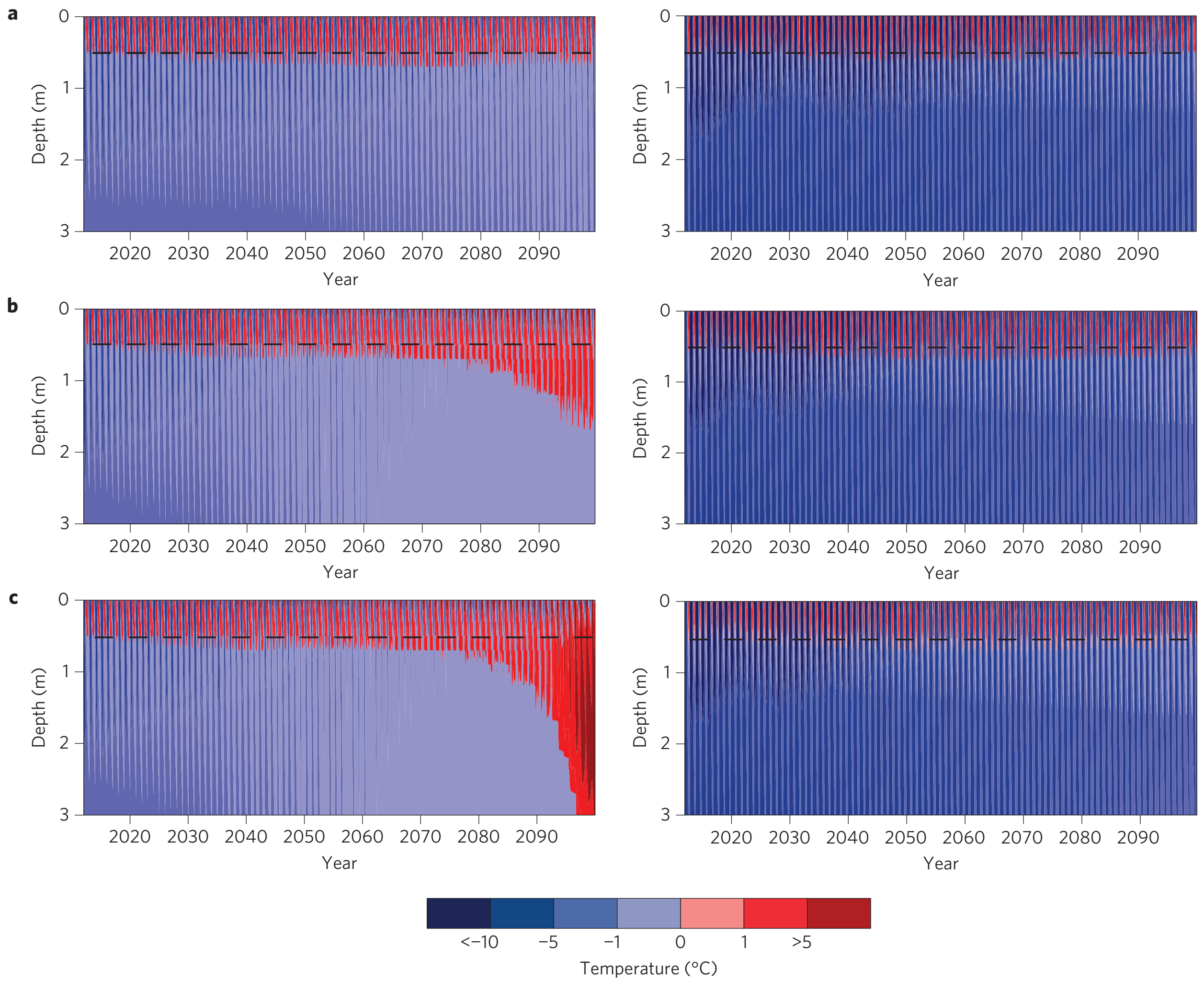

Figure 3 | Simulated soil temperatures. The Disko Bay area is shown on the left, and the Zackenberg area on the right. **a**, Climate change scenario 1 (low). **b**, Climate change scenario 2 (high). **c**, Climate change scenario 2 (high) with mean measured heat production. Model simulations based on the mean measured heat production ±1 s.d. are shown in Supplementary Figs 12 and 13.

have a major effect (Fig. 3c and Supplementary Figs 12 and 13). Simulations show that a 5.2 °C warming with internal heat production included (mean ± 1 s.d.) could increase the mean annual ground temperatures (from 2090 to 2099) with an additional 1.8–6.7 °C (mean = 3 °C). This warming leads to thawing of the entire organic permafrost layer from 0.5–3.0 m depth (Fig. 3c) and a carbon loss of 15–40% (mean = 24%) by 2100 (Fig. 4 and Supplementary Fig. 14). This equals a carbon loss of 20–52 kg C m^{-2} (mean 32 kg C m^{-2}) over the next 90 years that is markedly higher than the 1–5 kg C m^{-2} loss (1–4%) without considering heat production.

Our results suggest a critical shift from a first phase of relatively slow permafrost thaw driven by climate changes and low heat production to a second phase of accelerated permafrost thaw when water is drained and increasing oxygen availability markedly triggers a higher heat production. The most critical model parameters for determining the tipping point of the accelerated permafrost thawing include initial ice/water content, soil hydraulic conditions, and the reactivity of the soil. As shown (Supplementary Fig. 15), accelerated subsurface heat production is closely related to the time when all ground ice has melted and the total water content subsequently starts to decrease.

In the simulations, we have provided a conservative estimate of the importance of heat production using moderate climate scenarios, assuming that decomposition takes place only in non-saturated thawing layers (Supplementary Fig. 11) excluding anoxic decay processes that may produce additional heat in water-saturated layers[3]. We assumed that the present-day water balance and vegetation cover are representative for the future, which may not be the case. More precipitation may keep the soil water saturated and reduce the effect of heat production reported here. On the other hand, drier conditions may increase the heat production and further accelerate thawing. Oxygen depletion caused by the decomposition itself was not included in our model. This could be an important limiting factor, especially in soils where temperatures increase rapidly owing to heat production. However, in some types of organic soil (palsas, pingos and kitchen middens), this may be counteracted by soil settling and erosion exposing deeper layers to atmospheric conditions.

We have shown that different types of organic soil from different parts of Greenland all have great heat production potential. We have estimated the impact of the internal heat production in thawing permafrost and conclude that climate-change-induced permafrost decomposition can be markedly enhanced in organic soils compared with other soil types owing to internal heat production. The heat production is not only expected to accelerate the organic carbon decomposition and potentially the amounts of carbon emitted to the atmosphere but could be the tipping point that will lead to the loss of evidence of early human history in the Arctic, which so far has been extremely well preserved in the top permafrost.

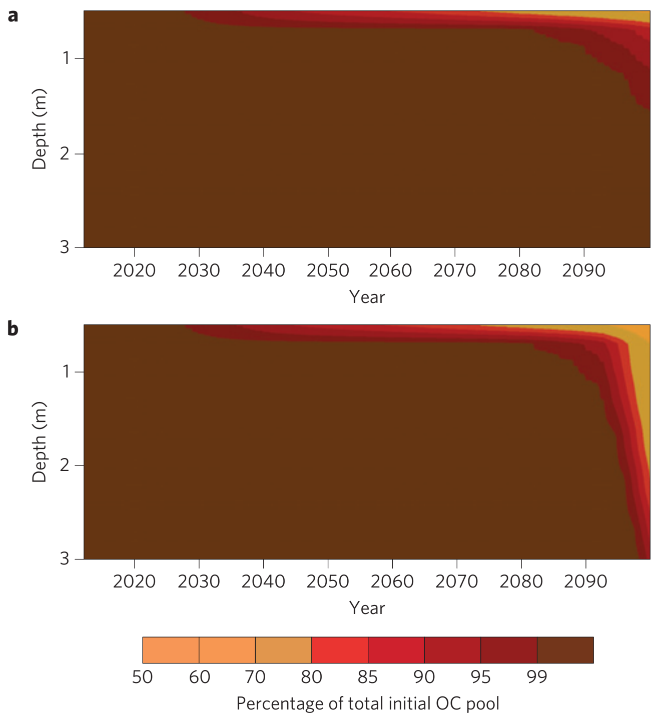

Figure 4 | Simulated organic carbon loss in the Disko Bay area. a, Climate change scenario 2 (high). **b**, Climate change scenario 2 (high) with mean measured heat production. The results for the mean measured heat production ±1 s.d. are shown in Supplementary Fig. 14. OC: organic carbon.

Methods

Study and sampling sites. We used 21 samples that were collected from 16 contrasting organic permafrost soils located in 6 different areas in Greenland that were all within the continuous permafrost zone (Fig. 1). In the model, we focused on two contrasting sites: a kitchen midden at Qajaa in West Greenland and a peatland at Zackenberg in northeast Greenland.

The Qajaa midden, situated 18 km southeast of Ilulissat in the western central part of Greenland, was selected as the main study site for investigating the coupling between climate, soil temperatures, decomposition and heat production. The midden has been known at least since 1871 and is considered the site with the best preserved organic remains from the Palaeo-Eskimo Saqqaq and Dorset cultures in all of Greenland[11,25]. It covers an area of approximately 2,900 m^2, has a maximum thickness of 3 m and consists of peat as well as rocks from fireplaces, animal bones and wood[11]. Owing to its great historical value, the midden has been monitored since 2009 to evaluate current and future preservation conditions[11,25,26]. The climate in the area is arctic with a mean annual temperature of −4.5 ± 1.7 °C (1974 to 2004) and a mean annual amount of precipitation of 266 mm (1961 to 1984; ref. 27).

The peatland is situated in the Zackenberg Valley near the Zackenberg Research Station in central northeast Greenland (74° 30′ N; 20° 30′ W). The climate is high arctic, with a mean annual air temperature of −9.1 °C and a mean annual amount of precipitation of 220 mm, with 90% falling as snow and sleet. Zackenberg is located in the continuous permafrost zone, and the permafrost thickness has been estimated to be around 400 m (ref. 28).

Sampling and analyses. Sampling was based on excavation of pits down to the frost table followed by drilling to obtain intact permafrost cores. Top permafrost cores were collected by motorized hand-drilling equipment consisting of a Stihl drilling engine, an expandable drill string and a 40-cm-long core barrel with a drill head. Sample lengths from 3 to 30 cm were packed in plastic bags and kept frozen. The heat production was measured at 16 °C using a thermal activity monitor (type 2277, Thermometric, Sweden, or C3-analysentechnik, Germany) equipped with ampoule cylinders (4 ml twin, type 2277-201, and 20 ml twin, type 2230). Oxygen consumption rates were measured by monitoring the decrease of headspace O_2 concentrations over time using oxygen optodes (PreSens) in three replicates[14]. Three replicate sub-samples (1–2 g) of humid soil were transferred to 12.1 ml glass vials flushed with atmospheric air and the vials were sealed carefully using a disc of transparent commercial oxygen barrier film (Escal), a silicone gasket and a screw cap with aperture.

Modelling. Atmospheric conditions were governed by time-variant meteorological inputs, and the model incorporated interface processes from snow and vegetation cover at the boundary between atmosphere and soil. The model regime consisted of a 20-m-deep profile divided into 82 layers. The upper 55 layers (3 m) were considered to be completely organic except for the upper 20 cm organic-rich top soil layer. The soil below 3 m was considered similar to the entisol/cryosols normally found in these parts of Greenland[29]. The temperature was kept constant at the lower boundary of the model regime. The thermal conductivity (k_h) was calculated as a function of soil solids and soil moisture on the basis of empirical equations adjusted to accommodate observations on the volumetric water content from previous investigations[30]. The unfrozen and frozen values of k_h were adjusted to match measured values (Supplementary Fig. 5). For the layers below 3 m, values of k_h were based on default values for mineral soils. To adjust the thermal conductivity individually for each soil layer, a scaling coefficient was applied[17].

Total modelled soil respiration R was the sum of three pool-specific respiration rates, each of which was simulated (see Supplementary Methods Equation (1)) as the pool-specific decay rate multiplied by the total initial carbon pool multiplied by a fractionation coefficient that describes the ratio of the carbon pool to the total carbon pool (see Supplementary Methods Equation (2)). The heat production used in the model was the mean value of all measurements (excluding the high values from Disko that were considered as outliers).

Climate change scenarios used in the CoupModel to predict future ground temperatures were based on IPCC RCP4.5 (ref. 18) with the increase in air temperature by 2100 relative to the 1986–2005 mean and an Arctic amplification by a factor of two[19]. The two scenarios are: a low range with a summer warming of 1.1 °C and winter warming of 3.3 °C; and a high range with a summer warming of 4.2 °C and winter warming of 6.2 °C.

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Author contributions

B.E. and H.M. initiated the collaboration project; B.E., J.H. and H.M. collected samples and performed fieldwork. J.H. and A.B.M. performed laboratory investigations, and J.H. compiled and analysed the data and performed the modelling. J.H. and B.E. wrote the paper with input from all co-authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.E.

Competing financial interests

The authors declare no competing financial interests.