

## Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins

Peter T. Fretwell<sup>1✉</sup>, Aude Boutet<sup>2</sup> & Norman Ratcliffe<sup>1</sup>

The spring season of 2022 saw record low sea ice extent in Antarctica that persisted throughout the year. At the beginning of December, the Antarctic sea ice extent was tracking with the all-time low set in 2021. The greatest regional negative anomaly of this low extent was in the central and eastern Bellingshausen Sea region, west of the Antarctic Peninsula where, during November, some regions experienced a 100% loss in sea ice concentration. We provide evidence of a regional breeding failure of emperor penguin colonies due to sea ice loss using Sentinel2 satellite imagery. Of the five breeding sites in the region all but one experienced total breeding failure after sea ice break-up before the start of the fledging period of the 2022 breeding season. This is the first recorded incident of a widespread breeding failure of emperor penguins that is clearly linked with large-scale contractions in sea ice extent.

<sup>1</sup>British Antarctic Survey, Madingley Road, Cambridge, UK. <sup>2</sup>Independent Researcher, Paris, France. ✉email: [ptf@bas.ac.uk](mailto:ptf@bas.ac.uk)

Abrupt reductions in sea ice extent can have profound effects on ecosystems and the species that depend on the sea ice for breeding, moulting or foraging<sup>1</sup>. One such species is the emperor penguin (*Aptenodytes forsteri*), which is reliant on sea ice for all parts of its life cycle<sup>2</sup>. Almost all emperor penguin colonies depend upon stable land-fast sea ice, which they use for breeding and moulting, while also using the marginal ice zone as a foraging habitat<sup>3</sup>. They arrive at their preferred breeding sites in late March to April, and lay eggs from May to June. Eggs hatch after 65 days and chicks fledge during December and January<sup>3</sup>. Thus, the land-fast ice on which they breed must remain stable between April to January to ensure successful breeding.

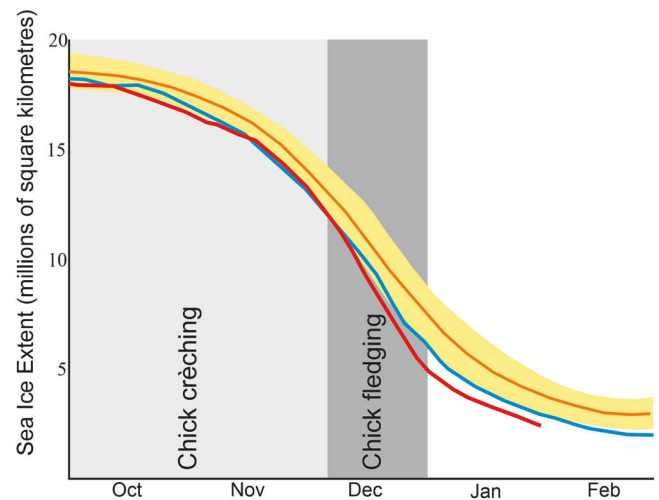
Emperor penguins are an iconic symbol of Antarctica threatened by climate change<sup>4–7</sup>. There have been a number of studies linking this species' demography with sea ice loss driven by climate change, from initial studies showing the effects on breeding success<sup>4</sup> to losses of colony sites driven by long-term sea ice decline<sup>8</sup> or sea ice regime shift<sup>9</sup>. Recent efforts to predict emperor penguin population trends from forecasts of sea ice loss have painted a bleak picture, showing that if present rates of warming persist over 90% of emperor colonies will be quasi-extinct by the end of this century<sup>7</sup>. Their populations have never been subject to large-scale hunting, or suffered from habitat loss, overfishing or other local anthropogenic interactions in the modern era<sup>5</sup> and therefore, unusually for a vertebrate species, climate change is considered the only major driver of their long-term population change. Recent effort to provide additional protection and conservation measures in response to predicted population declines associated with projected sea ice loss have been partially successful but have failed at the Antarctic Treaty Consultative Meeting<sup>10</sup>.

Five known emperor penguin colonies occur in the central and eastern part of the Bellingshausen Sea. There are, from east to west, Rothschild Island, Verdi Inlet, Smyley Island, Bryan Peninsula and Pfrogner Point. All of these colonies were discovered using medium resolution satellite imagery in the last 14 years<sup>11</sup> and their populations counted using very high-resolution imagery<sup>12</sup>. So far, only Rothschild Island colony has been visited and, of the others, only Smyley Island has been seen from aerial survey (British Antarctic Survey, unpubl.). There are no records of large aggregations of non-breeding emperors between October and December, so we make the assumption that these sites, which are present in the same location every year in the breeding season, are breeding sites. None of the colonies are large, with Smyley Island, the largest of the six, averaging ~3500 pairs, and Rothschild, averaging ~630 pairs, one of the smallest.

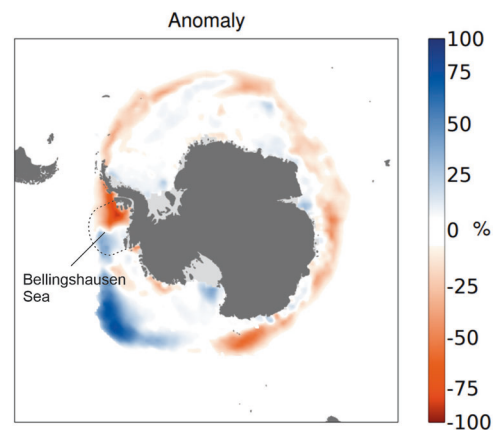
At the beginning of December 2022, at the start of the emperor chicks fledging period<sup>13</sup>, the sea ice extent across Antarctica was tracking the all-time low set in 2021 (Fig. 1)<sup>14</sup>. The greatest regional negative anomaly of this low extent was in the Bellingshausen Sea region, west of the Antarctic Peninsula where, during November, some regions saw a 100% loss in sea ice extent (Fig. 2)<sup>15</sup>. This paper describes the likely impact of this event upon emperor penguin breeding success across the region.

## Results

In late 2022, four of the five colonies in the central and eastern Bellingshausen Sea were affected by early sea ice loss (Fig. 3) and these were in the area where the November sea-ice anomaly was most intense (Fig. 4). Three of these colonies, which were easily visible in late October or early November, were abandoned due to lack of sea ice at the start of the fledging period in early December. Here abandonment is classified as an absence of visible sign of a colony (i.e. brown indicative pixels on sea ice)



**Fig. 1 Antarctic sea ice extent in 2022–2023.** The red line shows sea ice extent (more than 15% concentration) for 2022–2023, blue line shows 2021–2022 and the orange line is the 1981–2010 mean. The yellow ribbon is  $\pm 2$  SD of the satellite record (1979–2022). The grey shading refers to breeding stages of emperor penguin chicks. Critically sea ice must be stable for emperor penguins until the end of the fledging stage for all chicks to survive. Between October and January 2022–2023 sea ice around the continent has been at or below to the lowest ever recorded in the 45 year satellite record. Only briefly in mid-November did the concentration fleetingly rise to the second lowest extent. This low period intersected with the end of crèching and fledging period in the emperors breeding cycle. Data courtesy of National Snow and Ice Data Centre, Boulder, Colorado.



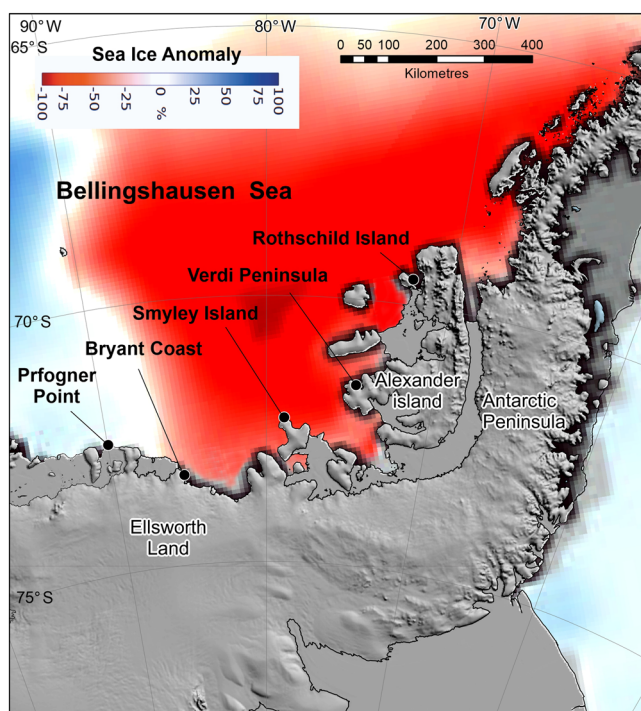
**Fig. 2 Antarctic sea ice anomaly for November 2022.** Blue areas in the map show positive sea ice anomaly, red shows negative. Although most of the continent has witnessed negative sea ice extent, the Bellingshausen Sea area has been particularly badly affected with up to 100% loss of ice in the region. (Data: ERA5. Reference period: 1991–2020. Credit: C3S/ECMWF).

that can be identified in the satellite imagery. The most westerly of the colonies in the area, Pfrogner Point, was also abandoned in between the 29th of October and the 8th November, despite being located outside the November anomaly. Local fast ice conditions in mid-late October (1 month earlier than the anomaly shown in Fig. 3) provide evidence that this was also due to loss of sea ice.

There are no phenological data for emperor penguin chicks in the Bellingshausen Sea, so here we make the assumption that fledging times are similar to other colonies in east Antarctica (Cape Washington and Pointe Géologie) where fledging starts in early to mid-December and finishes in late December or early January. Accordingly, it is likely that the three colonies where

rapid loss of fast ice occurred prior to this date will have experienced total or near total breeding failure, as emperor penguin chicks do not develop waterproof feathers until fledging. Some chicks may have survived on grounded icebergs (as may have occurred on Smyley Island; see below), but the percentage of the chicks that may have survived on these refugia is impossible to say from satellite images, which are of insufficient resolution to discriminate chicks from adults. However, as staining from three of the colonies disappeared entirely before December it is likely adult emperors abandoned these sites shortly after unsuccessful breeding.

Between the initial collection of Sentinel2 data in Antarctica in 2018 until 2022 the archive of imagery shows only one of the five colonies had witnessed sea ice break up earlier than December (Bryant Peninsula; 2010). One instance of break up in the five colonies in the 4 years of imagery is a likely hood on 0.04. In 2022 the loss of four out of the five sites led to an early break-up a likelihood of 0.80.



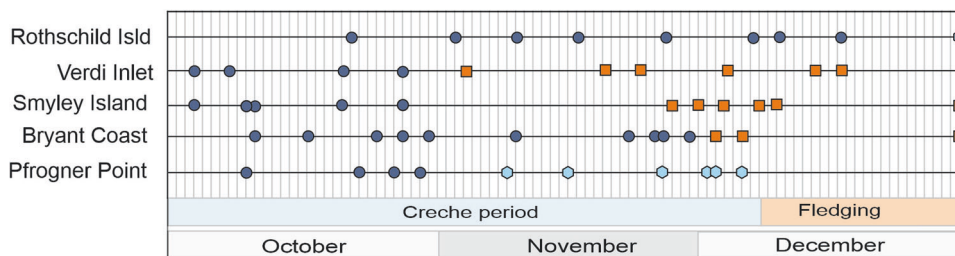
**Fig. 3 Emperor penguin colonies in the central and eastern Bellingshausen Sea.** The locations of the five emperor penguin colonies in this region superimposed over the regional sea ice concentration anomaly for November 2022 shown in red.

Below are reports for each of the five individual emperor penguin colonies in the central and eastern Bellingshausen Sea. Imagery of individual colonies from Sentinel2 is shown in Fig. 5 and these are available through Sentinel Copernicus Hub (see “Methods”).

**Verdi Inlet colony.** Verdi Inlet colony was discovered by satellite in 2018 and has been present each year in the Sentinel2 satellite record between 2018 and 2022. In 2018, 2019, 2020 and 2021, the sea ice in the bay did not break up until the New Year. A population estimate from WorldView3 imagery on 20th November 2021 (image ID 21NOV20142220) gave an estimate of ~3000 pairs. In September 2022 the colony was once again visible in Sentinel2 imagery, but very small—consisting of just 4 brown pixels. Between the 31st of October and the 4th of November the land-fast sea ice in the bay broke up. This ice had entirely dissipated by early December and no sign of any staining from guano could be found in the local area.

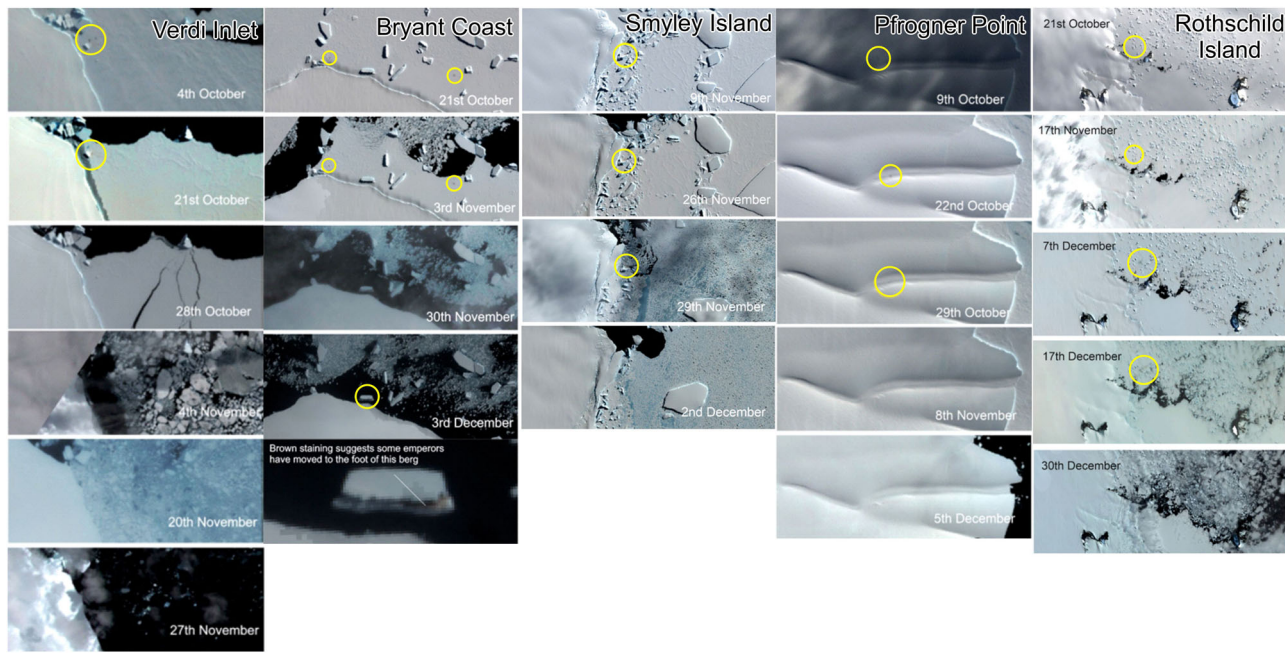
**Smyley Island colony.** Smyley Island colony was discovered in 2009 by Landsat satellite imagery. Very High-Resolution satellite imagery has been taken of it during most years since then to reveal that numbers vary between 1000 and 6500 breeding pairs with a 10 years average of 3500 pairs (British Antarctic Survey data unpublished, in prep). These satellite records shows that the land-fast sea ice at the colony location remained intact until at least early December except in 2022, when the fast ice broke up some time in mid-November. In this year, the colony had split into two groups approximately four kilometres apart. In Sentinel2 imagery from early December, the sea ice had clearly broken up leaving only loose pack ice and a few large bergs. It appears that at least some of the penguins had moved onto the foot of a large berg which was grounded near the coast. Whether any of the chicks survived on the berg is unknown.

**Bryant Coast colony.** The Bryant Coast colony was discovered in Landsat imagery in 2014. It has had a number of population estimates by VHR satellite imagery with numbers ranging from ~2000 in 2014 to 0 in 2010, which was the only year that birds were absent from the site. From 2010 to 2021, inclusive, multi-year fast ice persisted at the site, providing a stable platform for emperor penguins throughout the year. In 2022 the colony was visible in mid-November in Sentinel2 imagery but appeared smaller than normal. By the 25th of November, the sea-ice edge was approaching the colony location and by the 29th the fast ice had broken into pack. There was still evidence of brown staining on some of the broken pack ice. However, a few days later on the 2nd of December this brown staining had disappeared from the pack ice, suggesting the abandonment of the colony. No other evidence of the colony could be found in the local area.



**Fig. 4 The timing of satellite imagery showing sea ice break up and colony disappearance at the five colonies, in comparison with the timing of the breeding stage of the species.** The dark blue circles denote Sentinel2 images where the colony can be seen. Light blue hexagons denote where ice was still present but there was no sign of the colony (no brown pixels) and orange squares denote images where sea ice had broken up or dispersed. Note that four of the five colonies were abandoned by the start of the fledging season.





**Fig. 5 Sentinel2 imagery from the five colonies in 2022 showing the progressive sea ice extent through the créching and fledging season.** Each of the five columns shows multiple images from a single colony, with the earlier images at the top and the later images below. Images where the brown pixels of guano staining, indicative of emperor penguin colonies can be seen are highlighted with yellow circles.

**Pfrogner Point colony.** Pfrogner Point colony was discovered in 2019 and only one VHR satellite population estimate has been conducted, estimating the population at 1200 pairs. It is one of the few emperor colonies that is situated on an ice shelf<sup>16</sup>, as in all years of the Sentinel2 record (2018–2022), the colony has been located for at least some of the year in a creek on the ice tongue or on the shelf itself. In 2022, the brown stain of the colony was visible by Sentinel2 in the ice creek on at least three dates in October (9th, 22nd, 29th), although in all instances the staining was small and only encompassed between 7–10 pixels.

However, by 8th November the stain had disappeared and did not return in Sentinel2 later images. The abandonment of the colony was confirmed by VHR imagery captured later in the month (26th November). By the 12th December 2022, all the sea ice had dissipated. This confirmed that no penguins were visible, either on the shelf or the surrounding sea ice by this time. The reason for abandonment of the colony site is difficult to say with certainty.

The VHR imagery also revealed that the ice cliff leading onto the shelf was ~4.5 metres high (estimated from sun angle and shadow length) and that a snow ramp between the sea ice and the ice shelf existed at the foot of the ice creek. Earlier Sentinel2 images, in early October, show that the sea ice beneath the ramp appeared to have broken up to the ice cliff or just short of it. This would have removed the snow ramp and with it access colony. After this, the emperors would have to abandon the colony as they would not have been able to get back to their chicks. This did not happen in previous years as, due to the geometry of the ice shelf, the edge of the ice cliff was further back inside the creek which protected it from sea ice loss.

**Rothschild Island colony.** Rothschild Island colony is the furthest north of the five sites, located in a bay between Alexander Island and Rothschild Island. It is a small colony, averaging ~700 breeding pairs. As of 5th of December fast ice beneath the colony remained intact, although several open water patches opened up close to the colony. Counts from aerial imagery taken from

helicopters from the cruise ship *Commandant Charcot* on 20th November, showed that there were 820 chicks and 228 adults at the site. Subsequent Sentinel2 imagery confirmed that fast ice persisted at the site until 17th December and only began to break up on the 30th December. This confirms that some fledging was successful at this location in 2022 despite being in the centre of the negative sea ice anomaly. The location of the colony is in an embayment between Rothschild and Alexander islands and the presence of many icebergs suggest shallow water. The geometry of the bay and the presence of icebergs may have helped to stabilise the sea ice at this location and afforded protection from breakout until after the chicks had fledged.

## Discussion

Since the use of satellite imagery to monitor emperor penguins first started in 2009, there have been isolated cases of catastrophic breeding failure due to fast ice loss across Antarctica. For a few marginal colonies, such as the colony at Leda Bay in Marie Byrd Land, this happens regularly<sup>17</sup> and is termed as “blinking”. However, as yet, there has been no record of a widespread failure of breeding emperor penguins due to a regional sea ice loss affecting multiple sites before fledging in early December. Moreover, only one of the sites in our study region had experienced catastrophic breeding failure prior to 2022 (Bryant in 2010). Our finding of probable breeding failure across multiple, non-blinking, sites in a single season is without precedent.

Emperor penguins are known to adapt to breeding failures caused by localised sea ice loss by moving to alternative, more stable, sites in the following year. For example, at Halley Bay in Weddell Sea, the loss of local sea ice from 2016 onward resulted in the emperor penguins relocating their colony to Dawson Lambton Glacier, 85 km to the south, where the sea ice had remained stable<sup>9</sup>. However, such a strategy will not be possible if breeding habitat becomes unsuitable at a regional scale, unless local refugia such as the one identified at Rothschild Island persist.

How sea ice, and in particular land-fast sea ice, will react to future anthropogenic induced climate warming is unclear and

difficult to predict. Although it is difficult to link specific extreme seasons to climate change, a longer-term decline in sea ice extent is expected from the current generation of climate models<sup>18</sup>. Since 2016, Antarctica has experienced the four lowest sea ice extents observed in the 45 year satellite record, with the two lowest years in 2021/22 and 2022/23. Whether these continent-wide conditions are symptomatic of an ongoing trend or a more episodic phenomenon is as yet unknown, and this question is currently a priority for climate and sea ice scientists. The regional anomaly in the Amundsen and Bellingshausen Seas is likely to have been influenced by the Triple-Dip La Niña that is affecting many areas of the southern Pacific<sup>19</sup>, leading to a strongly negative Southern Annular Mode (SAM) which is typically characterised by a deep low pressure in the Amundsen Sea sector<sup>20</sup>. It is expected that as the La Niña weakens and SAM turns positive, sea ice extent in the region may grow. Nonetheless, our findings show a clear link between negative sea ice anomalies and emperor penguin breeding failures that may represent a snapshot of a future, warming Antarctica where such events become more frequent and widespread, with grave consequences for emperor penguin population viability.

## Methods

The locations and presence of emperor penguins was assessed using two satellite imagery platforms. The primary source was ESAs Sentinel2 platform, part of the Copernicus programme. These data were accessed through the Copernicus Sentinel Hub, viewed in Sentinel Playground [[apps.sentinel-hub.com/sentinel-playground/](https://apps.sentinel-hub.com/sentinel-playground/)] and downloaded using the Sentinel Hub EO browser [<https://apps.sentinel-hub.com/eo-browser/>]. Sentinel2 imagery has been taken continuously in Antarctica since 2018 and collection can vary between several times per week to several times per month. All imagery taken between August and the end of December 2022 was assessed manually for the presence of emperor penguins at each of their five colony locations in the Bellingshausen Sea. Sentinel2 imagery has a spatial resolution of 10 m in the visible bands and groups of emperor penguins can easily be distinguished on the sea ice as they leave distinctive brown guano stains on the ice<sup>11,21</sup>, which can be viewed manually on a pixel-by-pixel basis. Here we assume that the presence of brown pixels is indicative of penguin guano staining and hence the location of their colony. This staining may exist for several days after abandonment until the next snowfall, so it possible that there is some lag in the dates reported here. To ensure the best contrast when using the Sentinel Playground browser, the custom parameters [B08\*0.8,B04\*0.8,B03\*0.8] were used. These data were supplemented using Very High-Resolution WorldView3 data from MAXAR, with a spatial resolution of 0.31 m at two sites; Pfrogner Point and Rothschild Island. At Pfrogner Point (image ID 10300100DE30A800 26th November 2022) this image was used to confirm that no penguins were present. At Rothschild Island, the WorldView3 image could confirm the presence of emperors and enable a rough count of individuals. This count was later confirmed and re-counted by oblique hand-held aerial survey from the helicopters of the ship Commandant Charcot. Previous population estimates have been calculated from supervised classification of MAXAR very high-resolution imagery using machine-learning supervised classification using a similar method to Fretwell et al.<sup>12,22</sup>. These count data are part of a large international ongoing project to assess annual emperor penguin populations and will be published in subsequent work.

## Data availability

ESA Copernicus Sentinel2 satellite images used in this study are available through <https://scihub.copernicus.eu/> or <https://apps.sentinel-hub.com/eo-browser>. Location data for the five emperor penguin colonies mentioned in the text is available as a shapefile from: NERC EDK US Polar Data Centre, <https://doi.org/10.5285/a777e89c-ffcc-4ff4-981c-8f37e5ca84c2>.

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## Author contributions

P.T.F.: project design, collection of data, analysis of data, writing of paper. N.R.: project design, analysis of data writing of paper. A.B.: collection and analysis of data.

## Competing interests

The authors declare no competing interests.

## Ethical approval

At the British Antarctic Survey (BAS), we are committed to ensuring that everything we do is ethical and rigorous. This commitment reaches from our impact on the environment in the remote and pristine areas in which we work, to the methods we use in our research. For more on our inclusion and ethics policy see: <https://www.bas.ac.uk/about/about-bas/our-organisation/our-policies/>.

**Additional information**

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s43247-023-00927-x>.

**Correspondence** and requests for materials should be addressed to Peter T. Fretwell.

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