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Long-term CO₂ production following permafrost thawing

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Thawing permafrost represents a poorly understood feedback mechanism of climate change in the Arctic, but with a potential impact due to stored carbon being mobilised (1-5). We have quantified the long-term loss of C from thawing permafrost in NE Greenland from 1996 to 2008 by combining repeated sediment sampling to assess changes in C stock and >12 years of CO₂ production in incubated permafrost samples. Field observations show that the active layer thickness has increased by >1 cm per year but thawing has not resulted in a detectable decline in C-stocks. Laboratory mineralisation rates at 5° C resulted in a C loss between 9% and 75%, depending on drainage highlighting the potential of fast mobilisation of permafrost C under aerobic conditions, but also that C at near-saturated conditions may remain largely immobilised over decades. This is confirmed by a three-pool C dynamics model that projects a potential C loss between 13% and 77% for 50 years of incubation at 5° C.

40 The Northern Hemisphere permafrost region contains approximately 1,700 Pg of organic carbon
41 (C) of which about 90% occurs in permafrost deposits (1). This C pool represents about 50% of the
42 estimated global below-ground organic C pool (1). With the large amplitude of predicted arctic
43 climate change, this C pool has been used to imply a critical potential for global-scale feedbacks
44 from arctic climate change if these C reservoirs are destabilised (1, 3), but actual mobilisation rates
45 at decadal to century scales are unknown as well as the consistency on a circumpolar scale of the
46 few studies reporting multi-years incubation results (6). Long-term observations indicate that
47 permafrost thawing in NE Greenland, measured as increasing active layer depths, occurs at rates of
48 more than 1 cm/year (4, 7). In the present long-term incubation experiment we hypothesized that
49 natural drainage associated with permafrost thawing would considerably increase the potential
50 mineralisation and the associated release of CO₂.

51 Sites included two different landforms (see supporting Figures 1-3) with two different, but
52 dominating vegetation types (7); a sandy ground moraine with a *Cassiope tetragona* heath
53 vegetation covered in places by aeolian sediments, and the lower part of a nivation site containing a
54 large snowpatch with wet grassland vegetation (7-9). These two sites differ in geomorphological
55 activity, age, C-substrate quality and the environmental conditions controlling oxygen availability
56 and pH as described in Methods.

57 Depth and volume-specific samples from the active layer and top permafrost in Zackenberg
58 (NE Greenland) were collected down to about 1 m depth in three replicate profiles in 1996 and
59 repeated in 2008 and 2012. In 2008, two permafrost cores were obtained down to at least 2 m depth
60 at the same sites by drilling. Two CALM (Circumpolar Active Layer Monitoring Network) grids
61 were established in 1996 in the two landforms studied here (5, 7). Since then, thaw progression has
62 been recorded based on regular probing throughout the summers.

Top permafrost samples (n=3 per site) collected in 1996 at a depth of about 80-90 cm on the heath site and 60-70 cm on the wet grassland site were kept cold ($<7^{\circ}\text{C}$), and transported back to the laboratory for long-term incubation at $5 \pm 1.5^{\circ}\text{C}$. Each intact permafrost sample, consisting of 100-200 g soil, was incubated in glass jars with the top covered with Parafilm "M" with more than 10 (<1 mm) holes to allow atmospheric conditions during incubation, but to limit evaporation. Subsamples from the wet grassland site were drained prior to incubation using a sand bath and leaving the samples to drain freely at 5°C for 48 hours to mimic natural drainage following thawing.

Subsamples of 2-3 g from each of the replicate intact permafrost samples were taken 22 times (between October 1996 and April 2009) and used for soil respiration measurements (roughly every six months). After being transferred to 12.5 ml incubator vials, samples were left for pre-incubation overnight, and increasing CO_2 concentrations were measured three times the following day (over 8-10 hours) using a ML GC82 (Mikrolab Aarhus A/S, Denmark). Six times during the 12½ years incubation experiment, CO_2 production measurements were followed by measurements of total organic carbon and cold-water-extracted total dissolved C. Also, three times during the incubation experiment, the temperature-dependent CO_2 production was measured between 0 and 10°C to assess any long-term adaptation to the incubation temperature of 5°C .

In 2008 new top permafrost samples from the wet grassland vegetation site at Zackenberg as well as top permafrost samples (10-30 cm below permafrost table) from four other Arctic sites in Canada, West Greenland, North Greenland and Svalbard (Supplementary Table 1), were incubated under similar condition as described above, and used to assess CO_2 production over 3 years.

Results from Zackenberg (Fig. 1B; supporting Fig. 4S) indicate that the active layer thickness has increased significantly by 0.8 cm at the grassland site and 1.5 cm per year at the heath site (1996-2012). This represents only a fraction of the permafrost degradation taking the high ice

87 contents (40-80%) into account (see supporting Fig. 5S). Carbon stocks (to a depth of 1 m) were on
88 the heath site 11.1 ± 2.3 (mean $\pm$ SD) kg C m² in 1996, 10.8 ± 2.4 kg C m² in 2008, and 11.1 ± 2.4
89 kg C m² in 2012, and on the wet grassland site 29.3 ± 3.2 in 1996, 32.3 ± 4.1 in 2008 and 31.6 ± 4.0
90 in 2012 (based on solid bulk density and organic C content). The top 1 m C stocks reveal no
91 detectable changes in total C from 1996 to 2012, as was also the case if only the 0.5 – 1 m depth
92 interval was considered (supporting Fig. 6S). But caution should be taken before generalising this
93 conclusion to a larger area as data only represent two landforms with very limited sampling, and
94 because soil collapse and ground surface lowering following thawing may change soil porosity and
95 thus SOC stocks due to physical changes following thawing. The newly thawed upper permafrost in
96 the wet grassland indicates decreasing C concentrations, but not a significant loss in C stock.

97 Long-term incubations at 5° C (Fig. 2) over a period of >12 years reveal a loss of C as CO₂
98 equal to 55% of the initial C content (>20% within the first 21 months) of the top permafrost from
99 the well-drained heath site, 9% loss in the top permafrost sample from the ambient wet grassland
100 site, and up to 75% loss at the drained top permafrost sample from the wet grassland site. This
101 variation is considered representative of the variability of labile C linked to the original C source
102 and the important role of oxygen availability during incubation. A mass balance of the total C
103 during the experiment indicates that the actual loss was 50%, 17% and 78%, respectively. This
104 indicates a fair match between the C loss and the measured production of CO₂. The ambient wet
105 grassland samples were the exception; here anaerobic conditions probably resulted in CH₄
106 production as previously observed in Siberia (6) and elsewhere (12, 13). However, as CH₄ was not
107 measured as part of this study, the importance of CH₄ on the net C loss remains unclear.

108 The constant incubation temperature at 5° C is significantly higher than under natural
109 conditions. Ground temperature in a newly thawed permafrost layer will typically be peaking very
110 close to 0°C for less than two months a year (August/September). Assuming a temperature-

111 dependency of 2 ($Q_{10} = 2$; 70% respiration rate at 0°C as compared to 5°C, supporting Fig. 10S)
112 during two months a year; 144-months incubation represents *in-situ* conditions for roughly 100
113 calendar years. Similarly, *in-situ* changes (1996-2008) represent 24 months in the laboratory. Based
114 on a Q_{10} of 2, the expected amount of C being mineralized in the field during 12 years can be
115 calculated to be <0.002 gC per g soil (dw) under drained conditions and <0.0004 gC per g soil (dw)
116 under wet conditions. These latter changes are too small to be detectable taking natural field
117 variability into account, meaning that the incubation experiment confirms that it is unlikely to detect
118 any significant changes in C-stock over 12 years, if newly-thawed permafrost layers remain near-
119 saturated and close to 0°C.

120 A three-pool C model (14) was used to deconvolute the total measured CO₂ production from
121 the incubation study into pool-specific decay rates using inverse analysis (see C dynamics model
122 performance and validation in supporting methods). The total observed respiration rate is the sum
123 of the three pool-specific respiration rates deriving from a fast, a slow and a passive C pool with
124 turnover times <2, ~3-7 and >4000 years, respectively. The per cent initial C pool loss (Fig. 2) was
125 highest during the first four years, and then declined slowly over time. During the whole incubation
126 period most C being lost originated from the fast and slow C pool, as shown by the highest % initial
127 C pool losses for these two pools (Fig. 2). However, small C losses from the passive C pool
128 occurred during the whole incubation period (cumulative C loss of the passive C pool for the heath
129 site was 0.25% at the end of the incubation and 1% after 50 incubation years, values were similar
130 for the other sites). Based on estimated parameters from the three-pool model output
131 (Supplementary Table 2), the decay rate of each C pool was used to extrapolate potential C losses
132 for each soil type over perspective 50 incubation years at 5°C (Supporting Fig. 11S). The dry
133 ground moraine heath site has a potential for losing on average 58% (confidence interval: 47.6-
134 68.8%) of initial C when estimating 50 incubation years and the drained nivation grassland site has

135 a potential of 77% (confidence interval 62.6-92.0) if all incubation parameters remain constant.
136 However, the C pool on the wet grassland site will largely remain (87%, confidence interval of 75-
137 94.3) within 50-years of projected incubation. This marked difference in decomposition rates over a
138 long period underlines the importance of oxygen availability and high ice content in permafrost
139 soils.

140 The observations from the wet grassland site at Zackenberg are in line with four other arctic
141 locations with similar vegetation (Fig. 3, Suppl. Table 1). Although there is no direct link between
142 current vegetation and permafrost C pools or lability, there is a surprising consistency in C pool loss
143 rates. For aerobic conditions, Zackenberg (site 3B) is the site with the highest initial rate of C pool
144 loss, which suggests that the general conclusion from this site is not underestimating a more
145 regional tendency of permafrost C losses in the future. Only few other studies are available for
146 comparing results from our long-term incubations, however, the three years incubation experiment
147 using five Arctic sites reported here is comparable to a study based on Siberian permafrost (6).

148 We conclude that the top permafrost in NE Greenland is currently thawing, and the active
149 layer is deepening by more than 1 cm per year and long-term incubation reveals several C pools
150 with contrasting turnover times. The future release of CO₂ associated with permafrost thawing will
151 depend on both C substrate quality and long-term oxygen availability, ice contents and
152 temperatures. Incubations at 5° C reveal a loss of C in the form of CO₂ from 9% to 75% of the
153 initial C content over 12 years (Fig. 2D), which is a fair approximation of the loss of C under
154 natural condition during the next 100 years given the assumptions that this material will remain near
155 0° C for 2 months per year. Modelling results suggest that, during the next 50 incubation years at
156 5°C, the long-term decomposition of permafrost C pools may lose up to 92% of the initial C under
157 aerobic conditions and as little as 6% in the case of anaerobic conditions. Thus, we conclude that
158 the long-term prediction of permafrost thawing in terms of CO₂ emissions can only be made in a

159 meaningful way if the oxygen availability, controlled by water and ice contents and the long-term
160 water balance, is also included in the assessment.

161

162

163 **Methods**

164 **Study sites.** Zackenbergdalen (74°30'N, 20°30'W) is a wide lowland valley dominated by
165 Quaternary non-calcareous sediments with significant periglacial activity and continuous
166 permafrost (7-10), with a mean annual air temperature of -9.5°C (1996-2007). From the hilltops
167 towards the depressions, an increase in soil water content is seen from dry to wet conditions at the
168 foot of the slopes due to snow melt water being released during large parts of the summer. Roughly
169 1/3 of the lowland area in Zackenberg is poorly drained. Given the low summer precipitation, water
170 availability during the growing season is mainly controlled by the location of large snow patches
171 melting during the growing season, resulting in the distinct vegetation zonation around these. Sites
172 included two contrasting landforms (see supporting Figures 1-3) and dominating vegetation types
173 (7); *Cassiope tetragona* heath on sandy ground moraine covered by aeolian sediments (representing
174 5-10% of the vegetated area) and wet grassland below a snow patch (representing 10-20% of the
175 vegetated area). These two sites differ in geomorphological activity, age, C-substrate quality and the
176 environmental conditions controlling oxygen availability and pH. The ground moraine heath site
177 represents a stable landform with older organic layers at a depth of 40 cm associated with soil
178 formation older than 3,000 years based on indirect dating of the podzolation period 7,400-3,000
179 years BP (8). In contrast, a mean sedimentation rate of 0.25 cm per year for the upper 47 cm on the
180 wet grassland site, suggests a much younger carbon deposition here. On the wet grassland site, the
181 soil carbon pool in the top permafrost is mainly derived from graminoids providing potentially
182 easily degradable C-substrates compared to the recalcitrant litter of evergreen heath shrubs as
183 *Cassiope* (10). Finally, the heath site represents a landscape type with a potential of drainage
184 following permafrost thawing, whereas the wet grassland site already represents a landscape
185 depression which may receive additional melt water from the surroundings. Additional samples

186 were collected from four other Arctic grassland vegetation sites in Canada, West Greenland, North
187 Greenland and Svalbard (Supplementary Table 1).

188

189 **Field measurements**

190 Active layer observations in Zackenberg (1997-2008) are based on two CALM grids in the two
191 studied landforms. Here, thaw depths are determined by mechanical probing (7). The flat ground
192 moraine heath site consists of 121 points (entire ZEROCALM1 grid), while for the wet grassland
193 site only the wettest part of the ZEROCALM2 grid is included consisting of 24 points. Observed
194 changes in active layer thickness from 1996 to 2008 represent minimum permafrost thawing rates
195 because of the general lowering of the landscape (including the surface) following thawing of ice-
196 rich permafrost.

197 Sampling was based on excavation of pits down to the frost table followed by drilling to
198 obtain intact permafrost cores. Top permafrost cores were collected to a depth of 1 m in 1996 (n=3
199 per site) using a metal core hammer, and adjacent similar cores to a depth of 1 m plus deeper cores
200 (n=1 per site) in 2008 by motorised hand-drilling equipment consisting of a Stihl drilling engine, an
201 expandable drill string and a 40-cm long core barrel with drill head. Sample lengths from 3-30 cm
202 were packed in plastic bags in the field and immediately stored in a freezer box. Samples were kept
203 below -5°C at the Zackenberg Research Station and during transportation. Samples taken in 1996
204 for long-term incubation were kept cold (roughly 5°C) until prepared for incubation. Volume-
205 specific sampling allows element concentrations and ice content to be calculated as stocks.

206

207 **Chemical analyses**

208 As part of the long-term incubation, subsamples used for analysis of CO₂ production were
209 subsequently analysed for total and dissolved C. Three replicates were pooled and hand-shaken for

three minutes with distilled water (1:1 by mass) at 5°C, centrifuged and the extracted soil water samples were filtered through Whatman GF-C glass-fibre filters, and the DOC was determined using a total organic C analyzer (Dohrmann DC-80). Subsequently, samples were dried and crushed and the mean content of total organic soil C content was determined using an ELTRA SC-800 Carbon Determinator.

215

216 **Three-pool carbon modelling**

Total modelled soil respiration R is the sum of three pool-specific respiration rates, which were each simulated (equation 1) as the pool-specific decay rate (k_i) times the total initial C pool (C_{tot}) times a fractionation coefficient (f_i) that describes the ratio of C pool i to the total C pool (equation 2). The fraction of the passive C pool was calculated as the total C pool minus the sum of the fast and slow C pool fractions.

$$222 \quad R = \sum_{i=1}^3 r_i = \sum_{i=1}^3 k_i C_{tot} f_i \quad (1)$$

$$223 \quad f_i = \frac{C_i}{C_{tot}}, \sum_{i=1}^3 f_i = 1 \quad (2)$$

To better model pool specific decomposition rates, we used data assimilation, which combines observed data and prior parameter knowledge with model structure to optimise parameter estimation (see Supplementary Table 2).

227

228 **Statistics**

Linear and non-linear regression analyses have been used to test trends and variations reported to be significant only when $p < 0.05$. The temperature sensitivity (Q_{10}) was calculated using a first-order exponential fit (15).

232

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249 **Author contribution**

250 B.E initiated the experimental work in 1996 and compiled data and wrote most of the paper; A.M
251 performed most of the chemistry analyses, C.S and E.A.G.S made the C dynamics model; B.E and
252 H.H.C performed the 2008 permafrost coring, L.B was involved in the 2008 sampling and data
253 analyses, H.H.C initiated the 1996 ZERO CALM monitoring as part of the GeoBasis programme,
254 and M.P.T and C.S. were responsible for CALM measurements as part of the GeoBasis programme.
255 All co-authors contributed to the writing.

256

257 **Competing financial interests**

258 The authors declare no competing financial interests.

259

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298 **Figure legends**

299

300 Figure 1: a: Soil organic carbon profiles (shown as solid squares) sampled in 1996 and again in
301 2008 (% by weight; one standard deviation shown as horizontal bars). The permafrost table
302 shown as horizontal lines (solid for the wet grassland site and dashed for the heath site); b:
303 Maximum measured active layer thickness (shown as circles) from 1996 to 2008 (one
304 standard deviation shown for wet grassland $n = 24$ and for heath $n = 121$). Temporal trends in
305 maximum thickness of the active layer from 1996 to 2008 are shown as linear regression lines
306 (solid for the wet grassland site and dashed for the heath site, $p < 0.05$).

307

308 Figure 2: Observed and modeled C loss in % of initial C per year calculated from respiration rates
309 of long-term incubated permafrost samples at 5°C for a) heath site; b) wet grassland site; and
310 d) drained grassland site. Observed values are represented with symbols (squares for heath
311 site, circles for wet grassland site and triangles for drained grassland site) and modeled pool
312 specific C losses are shown with lines (red for sum of modeled C loss, orange for fast, grey
313 for slow and brown for passive C pool loss per day). Observed values represent the mean of
314 three replicates and standard deviation. Plot d shows cumulative C release in % initial C for
315 the three different sites, symbols are the same as in plots a-c.

316

317 Figure 3: Observed C loss in % of initial C per year based on CO₂ production rates during 3 years at
318 5°C at (a): anaerobic and (b): aerobic incubation based on top permafrost samples collected at
319 five Arctic grassland sites (c). The main study site Zackenberg (site 3) has been emphasized.