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1 **Erosion of organic carbon in the Arctic as a geological carbon dioxide sink**

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16 **Soils of the northern high latitudes store carbon over millennial timescales (10^3 yrs) and**
17 **contain approximately double the carbon stock of the atmosphere¹⁻³. Warming and**
18 **associated permafrost thaw can expose soil organic carbon and result in mineralisation**
19 **and carbon dioxide (CO₂) release⁴⁻⁶. However, some of this soil organic carbon may be**
20 **eroded and transferred to rivers⁷⁻⁹. If it escapes degradation during river transport and**
21 **is buried in marine sediments, then it can contribute to a longer-term ($>10^4$ yrs),**
22 **geological CO₂ sink⁸⁻¹⁰. Despite this recognition, the erosional flux and fate of**
23 **particulate organic carbon (POC) in large rivers at high latitudes remains poorly**
24 **constrained. Here, we quantify POC source in the Mackenzie River, the main sediment**
25 **supplier to the Arctic Ocean^{11,12} and assess its flux and fate. We combine measurements**

26 **of radiocarbon, stable carbon isotopes and element ratios to correct for rock-derived**
27 **POC^{10,13,14}. Our samples reveal that the eroded biospheric POC has resided in the basin**
28 **for millennia, with a mean radiocarbon age of 5800±800 yr, much older than large**
29 **tropical rivers^{13,14}. Based on the measured biospheric POC content and variability in**
30 **annual sediment yield¹⁵, we calculate a biospheric POC flux of 2.2^{+1.3}_{-0.9} TgC yr⁻¹ from**
31 **the Mackenzie River, three times the CO₂ drawdown by silicate weathering¹⁶. Offshore**
32 **we find evidence for efficient terrestrial organic carbon burial over the Holocene,**
33 **suggesting that erosion of organic carbon-rich, high latitude soils may result in a**
34 **significant geological CO₂ sink.**

35 Photosynthesis and the production of organic carbon by the terrestrial biosphere
36 (OC_{biosphere}) is a major pathway of atmospheric carbon dioxide (CO₂) drawdown. Over
37 millennial timescales (10³ yrs), some OC_{biosphere} escapes oxidation and contributes to a
38 transient CO₂ sink in soil^{2,3,17}. Longer-term CO₂ drawdown (>10⁴ yrs) can be achieved if
39 OC_{biosphere} is eroded, transferred by rivers and buried in sedimentary basins^{9,10,18,19}. Burial of
40 OC_{biosphere} represents a major geological CO₂ sink (and O₂ source) alongside the chemical
41 weathering of silicate minerals by carbonic acid, coupled to carbonate precipitation^{16,19}.
42 These fluxes negate CO₂ emissions from the solid Earth²⁰ and from oxidation of rock-derived
43 OC²¹, contributing to the long-term regulation of global climate^{19,20}. Physical erosion is
44 thought to play a significant role in this OC_{biosphere} transfer because it controls the rate of
45 biospheric particulate organic carbon (POC_{biosphere}) export by rivers²² and influences sediment
46 accumulation and the efficiency of OC burial^{10,18,23}.

47 In the northern high latitudes, large amounts of OC_{biosphere} are stored in soil^{1,2}. The
48 upper three meters of soil in the region of northern circumpolar permafrost are estimated to
49 contain 1035±150 PgC, approximately double the carbon dioxide (CO₂) content of the pre-
50 industrial atmosphere¹⁷. Many of these soils accumulated during the retreat of large

51 continental ice sheets following the Last Glacial Maximum, with a peak expansion between
52 12,000 and 8,000 cal. yr BP²⁴ and the OC_{biosphere} can be thousands of years old⁸. This vast
53 carbon reservoir is located in a region sensitive to environmental change over glacial-
54 interglacial timescales²⁴ and to warming over the coming century³. Much focus has been
55 placed on its potential to become a CO₂ source^{3-6,8}. However, geological CO₂ drawdown by
56 POC_{biosphere} erosion at high latitudes has remained poorly constrained⁹.

57 Here we sample POC carried by the major rivers in the Mackenzie Basin and
58 investigate its fate using an offshore sediment core extending over the Holocene (Extended
59 Data Fig. 1). The Mackenzie River is the largest source of sediment to the Arctic Ocean^{11,12,15}
60 and erosion of mountainous topography in the basin results in a high sediment discharge,
61 similar to the combined total of 16 Eurasian rivers draining to the Arctic^{11,15}. We collected
62 river depth profiles to characterise POC across the range of grain sizes carried by large
63 rivers^{13,14,25} at the main conduit for sediment export to the Arctic Ocean in the Mackenzie
64 Delta, at key points on the Mackenzie River and from its major tributaries (Extended Data
65 Fig. 1). To investigate temporal variability of POC composition, river depth profiles were
66 collected shortly after ice-break up at high/rising stage (June 2011) and during falling stage
67 (September 2010), while river surface and bank samples were collected in June 2009. To
68 correct for rock-derived, 'petrogenic' POC (POC_{petro}), likely to be important in the
69 Mackenzie Basin^{7,25}, we combine measurements of radiocarbon (¹⁴C, reported as the 'fraction
70 modern' F_{mod}), total OC content ([OC_{total}], %), stable isotopes of OC ($\delta^{13}\text{C}_{\text{org}}$), nitrogen to OC
71 ratio (N/OC_{total}) and aluminium to OC ratio (Al/OC_{total}), which allow us to assess the age and
72 concentration of POC_{biosphere} (Methods)^{7,10,13,14,22}. Published surface samples from the
73 Mackenzie River^{4,7} (n=5) have ¹⁴C-ages between 6,010 yr and 10,000 yr but the ¹⁴C-depletion
74 caused by POC_{petro} versus aged POC_{biosphere} has not been assessed. We also examine the

75 hydrodynamic behaviour of POC, using the aluminium to silicon ratio (Al/Si) ratio as a proxy
76 of sediment grain size²⁵.

77 We find that river POC is ¹⁴C-depleted throughout the Mackenzie Basin (Extended
78 Data Table 1). F_{mod} values range between 0.28 (¹⁴C age = 10,106±42 yr) and 0.63 (¹⁴C age =
79 3675±36 yr) in the suspended load (n=27) and $F_{\text{mod}} = 0.12$ (¹⁴C age = 17,002±84 yr) to 0.16
80 (¹⁴C age = 14,601±64 yr) in the river bed materials (n=4). To investigate the cause of this
81 ¹⁴C-depletion, we examine the N/OC_{total} ratio. Degradation of organic matter in soils can
82 increase the relative N abundance^{6,26}, differentiating degraded POC_{biosphere} (high N/OC_{total})
83 from young, fresh POC_{biosphere} (low N/OC_{total}). Suspended load samples display a negative
84 relationship between N/OC_{total} and F_{mod} (Fig. 1), similar to measurements from a peat core in
85 the Mackenzie Basin²⁶ away from permafrost. There, N/OC_{total} ratios increased with ¹⁴C age
86 (1,250 yr to 10,200 yr) and soil depth (0m to 3m). In contrast, river bed materials have lower
87 F_{mod} values and a relatively restricted range of N/OC_{total} values and are distinct from
88 suspended load (Fig. 1). A dominance of POC_{petro} in bed materials^{10,14} with a N/OC_{total} ratio
89 of ~0.07 can explain their composition.

90 Together, the F_{mod} and N/OC_{total} values suggest that POC in the Mackenzie River is a
91 mixture of POC_{petro} and POC_{biosphere}, itself varying in ¹⁴C age from ‘modern’ to ~8000 yrs
92 (Fig. 1). The $\delta^{13}\text{C}_{\text{org}}$ values and Al/OC_{total} ratios support this inference (Extended Data Fig. 2).
93 Using an end member mixing analysis^{10,13} we quantify POC_{petro} content of sediments
94 (Methods) and find that suspended load at the Mackenzie River Delta is dominated by
95 POC_{biosphere} (~70-90% of the total POC). Having corrected for POC_{petro}, we investigate the
96 source of POC_{biosphere} by estimating its average ¹⁴C age. This varies from 3030±150 yr to
97 7900±400 yr (Extended Data Fig. 3) with an average ¹⁴C age of POC_{biosphere} = 5800±800 yr
98 (±2SE) in suspended sediments of the Mackenzie River Delta. These values are older than
99 estimates of POC_{biosphere} age from the Amazon River (1120-2750 yr)¹⁴ and Ganges River

100 (1600-2960 yr)¹³. The ages reflect mixing of young, fresh POC_{biosphere} present in each of these
101 large river basins, with an older POC_{biosphere} in the Mackenzie Basin (Fig. 1), likely to be
102 peats which expanded between 9,000 yr and 8,000 yr (¹⁴C-age)²⁴. POC_{biosphere} can be eroded
103 by slumping and landsliding on river banks, across deep soil profiles^{4,7}. Sections of the
104 landscape which have discontinuous permafrost and those undergoing permafrost
105 degradation²⁷ may be important sources of aged POC_{biosphere}, in addition to river banks which
106 are undercut during peak water discharge following ice-break up¹⁵. Our samples suggest that
107 erosion and fluvial transfer of millennial-aged POC_{biosphere} is extensive in the Mackenzie
108 Basin.

109 Once in the river, POC_{biosphere} is sorted with river depth, revealed by the Al/Si ratio
110 (Fig. 2b) a proxy for grain size²⁵. In bed materials with low Al/Si, POC_{petro} dominates (Fig. 1)
111 and leads to low F_{mod} values (Fig. 2c). Just above the river bed, during the two sampling
112 campaigns coarse suspended sediments (low Al/Si) hosted the youngest, least degraded
113 POC_{biosphere} (low N/C) leading to a significant contrast in ¹⁴C age from the bed materials.
114 Towards the river surface, older, more degraded POC_{biosphere} appears to dominate, and is
115 transported with fine sediment and clays (high Al/Si)²⁵. The significant contribution of
116 degraded, very old POC_{biosphere} (>5000 yrs) contrasts with large tropical rivers where organic
117 matter turnover in terrestrial ecosystems is more rapid (Fig. 2c)^{13,14}.

118 To assess how erosion in the Mackenzie River may lead to long-term CO₂ drawdown,
119 we estimate POC_{biosphere} discharge. River depth profiles collected at high and falling stage
120 suggest that the [OC_{total}] of the suspended sediment load did not vary systematically with
121 sediment grain size (Extended Data Fig. 4). Future work should seek to assess temporal
122 variability in POC content and composition. Our samples suggest that changes in grain size
123 with water discharge (Fig. 2b) could be important in setting the variability of POC_{biosphere} age
124 carried by the river (Fig. 2c). The [OC_{total}] values at the Delta were 1.6±0.5% (n=8, ±1σ),

125 which were similar to the mean measured in the Mackenzie Delta in June-July 1987 of
126 1.4 ± 0.2 (n=10)¹². While our sample set is modest in size, it helps us to better constrain the
127 range of POC contents in suspended load of the Mackenzie River. In addition, our end
128 member mixing analysis allows us to provide the first estimates of [OC_{biosphere}], which varies
129 between $0.7 \pm 0.1\%$ and $2.4 \pm 0.2\%$. To estimate POC_{biosphere} discharge, we use the most
130 complete dataset of annual sediment discharge to the Mackenzie Delta (1974-1994)¹⁵, which
131 ranged from 81 Tg yr^{-1} to 224 Tg yr^{-1} . A Monte Carlo approach is used to account for the
132 modest sample size by using the full measured variability in both [OC_{biosphere}] and sediment
133 discharge (Methods). We estimate POC_{biosphere} discharge = $2.2^{+1.3}_{-0.9} \text{ TgC yr}^{-1}$ which is
134 sustainable over 10^3 - 10^4 years, depleting the soil carbon stock by $\sim 0.006\% \text{ yr}^{-1}$ (Methods).
135 We estimate the POC_{petro} discharge = $0.4^{+0.1}_{-0.1}$. These estimates do not account for ice covered
136 conditions when $<10\%$ of the annual sediment discharge is conveyed¹². Nevertheless, our
137 estimate of POC_{biosphere} discharge is greater than the combined POC discharge of $\sim 1.9 \text{ TgC yr}^{-1}$
138 ¹ by the major Eurasian Arctic Rivers (Ob, Yenisei, Lena, Indigirka and Koyma)^{11,27} which
139 cover $\sim 8.6 \times 10^6 \text{ km}^2$. Based on the available measurements, the Mackenzie River dominates
140 the input of POC_{biosphere} to the Arctic Ocean.

141 The mobilisation of millennial-aged POC_{biosphere} from soils at high latitudes has been
142 viewed as a short-term source to the atmosphere if decomposition releases greenhouse gases
143 (CH₄ and CO₂)^{2-6,8}. However, if POC_{biosphere} escapes oxidation during river transport and is
144 buried offshore, erosion acts as a long-term CO₂ sink^{10,18,20}. Offshore, aged POC_{biosphere} from
145 the Mackenzie River (Fig. 1) can explain the ¹⁴C depletion and $\delta^{13}\text{C}$ of bulk organic matter,
146 and old ¹⁴C ages of terrestrial plant wax compounds (up to 20,000 yr) in surface sediments of
147 the Beaufort Sea^{7,28,29}. We provide new evidence that terrestrial POC is buried efficiently
148 offshore and accumulates in sediments over 10^4 years. Benthic foraminifera ¹⁴C ages in a
149 borehole located at the head of the Mackenzie Trough (MTW01) indicates that 21m of

150 sediment have accumulated since 9183_{-156}^{+125} cal. yr BP, suggesting a high sedimentation rate
151 during the Holocene $2.7 \pm 0.1 \text{ m ka}^{-1}$ (Extended Data Table 2, Methods). These marine
152 sediments have $[\text{OC}_{\text{total}}]$ values similar to those measured in the Mackenzie River in both the
153 $<63\mu\text{m}$ (1.5% to 1.7%) and $>63\mu\text{m}$ (1.1% to 1.4%) size fractions (Fig. 3). Their $\text{N}/\text{OC}_{\text{total}}$ and
154 $\delta^{13}\text{C}_{\text{org}}$ values suggest that they are dominated by terrestrial POC with minor marine OC
155 addition (Extended Data Fig. 5). We use the change in $\text{OC}_{\text{total}}/\text{Al}$ ratios offshore to estimate
156 OC burial efficiencies have been $65 \pm 27\%$ or more over the Holocene at this site (Methods).
157 Rapid sediment accumulation and low temperature are likely to promote high POC burial
158 efficiency^{18,23,28}. Also, the fluvial transport dynamics of $\text{POC}_{\text{biosphere}}$ may promote burial (Fig.
159 2c). The oldest, most-degraded $\text{POC}_{\text{biosphere}}$ is transported with clays²⁵, whose association
160 with organic matter may enhance burial efficiency¹⁸, while the youngest, least-degraded
161 $\text{POC}_{\text{biosphere}}$ is carried near the river bed at the highest sediment concentrations. Our findings
162 suggest that erosion and riverine transfer at high latitudes can lead to the long-term
163 preservation of terrestrial POC in marine sediments (Fig. 3).

164 Erosion of high latitude soils and riverine export of $\text{POC}_{\text{biosphere}}$ may represent an
165 important geological CO_2 sink. Our estimate of the modern day $\text{POC}_{\text{biosphere}}$ discharge of
166 $2.2_{-0.9}^{+1.3} \text{ TgC yr}^{-1}$ in the Mackenzie River may be refined by additional temporal sampling.
167 However, it is three times the modern rates of CO_2 drawdown by weathering of silicate
168 minerals by carbonic acid in the Mackenzie River¹⁶, at $\sim 0.7 \text{ TgC yr}^{-1}$. Preservation of POC
169 offshore (Fig. 3) suggests that erosion of high latitude soils, riverine $\text{POC}_{\text{biosphere}}$ transport and
170 export to the ocean acts as the largest geological CO_2 sink operating in the Mackenzie Basin.
171 It is important to note that these longer-term fluxes are lower than estimates of greenhouse
172 gas emissions from high latitude soils in permafrost zones due to projected warming over the
173 coming century^{3,5,6,30}. While these fluxes remain uncertain, recent work³⁰ has proposed
174 emissions of $\sim 1\text{--}2 \text{ PgC yr}^{-1}$ which equate to a yield of $\sim 70 \text{ tC km}^{-2} \text{ yr}^{-1}$ over $17.8 \times 10^8 \text{ km}^2$ of

175 soils in permafrost zones. This estimate of accelerated release of CO₂ due to anthropogenic
176 warming³⁰ is more rapid than the natural geological drawdown fluxes, of which we estimate
177 POC_{biosphere} ~ 2–5 tC km⁻² yr⁻¹ for the Mackenzie Basin (Methods). Over longer-time periods,
178 we postulate that this geological CO₂ sink may be sensitive to climate conditions in the
179 Arctic. The carbon transfer can operate when high latitudes host significant POC_{biosphere}
180 stocks in soil, and while rivers can erode and transfer sediments to the Arctic Ocean. Over the
181 last 1Ma, the POC_{biosphere} transfer was likely to have been enhanced during interglacials²⁴
182 (Fig. 3), whereas during glacial conditions, lower soil POC_{biosphere} stocks and extensive ice-
183 sheet coverage suggest that POC_{biosphere} erosion may have been suppressed. We propose that
184 erosion of terrestrial POC_{biosphere} by large rivers draining the Arctic could play an important
185 role in long-term CO₂ drawdown^{19,20}, coupling the carbon cycle to climatic conditions at high
186 latitudes.

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273 V.G. and M.D. designed the fieldwork and collected the river samples. M.O. and H.C.

274 collected sediment and carbonate data from the offshore borehole. R.G.H., V.G., M.D., C.B.
275 and D.G. processed the samples and carried out the geochemical analyses. R.G.H. wrote the
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278 information is available at www.nature.com/reprints. The authors declare they have no
279 competing financial interests. Correspondence and requests for materials should be addressed
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281 **Figure Legends**

282 **Figure 1: Source of particulate organic carbon (POC) in the Mackenzie River Basin.**

283 Radiocarbon activity of POC (F_{mod}) versus the nitrogen to organic carbon ratio (N/OC_{total}) of
284 sediments from the Mackenzie River (circles) at the delta (black), Tsiigehtchic (grey) and
285 Norman Wells (white) and major tributaries the Liard (diamond), Peel (dark blue square) and
286 Arctic Red (light blue square). River depth profiles collected in 2010 and 2011 suspended
287 load (filled symbols), river bed materials (open symbols) and sieved bank samples (2009) are
288 shown with analytical errors (2 s.d.) as grey lines if larger than points. The dashed line shows
289 the compositions expected by mixing rock-derived, petrogenic POC (POC_{petro}) and biospheric
290 POC ($POC_{\text{biosphere}}$). Solid green line is the trend from a peat core in western Canada²⁶.

291 **Figure 2: Transport of particulate organic carbon (POC) in the Mackenzie River. a.**

292 River depth profile collection from the Mackenzie River Delta during falling stage, with
293 Acoustic Doppler Current Profiler data to determine channel geometry, water velocity and
294 water discharge ($\text{m}^3 \text{s}^{-1}$). **b.** Aluminium to Silicon ratio (Al/Si , molar), a proxy for sediment
295 grain size²⁵, with water depth normalised to maximum depth. Coarser materials are carried
296 throughout the profile during high stage. **c.** Radiocarbon activity of POC (F_{mod}) versus Al/Si
297 for the Mackenzie Basin (this study, symbols as Fig. 1), Amazon River¹⁴, and Ganges

298 River^{10,13}. River suspended load (filled) and river bed materials (open) are distinguished with
299 analytical errors (2 s.d.) shown as grey lines if larger than points.

300 **Figure 3: Fate of particulate organic carbon offshore. a.** Organic carbon concentration
301 ($[OC_{total}]$, %) of suspended sediments in the Mackenzie River Delta (n=8) where solid line
302 and grey box show the mean \pm standard error, whiskers show \pm standard deviation and the
303 circles indicate the minimum and maximum values. **b.** $[OC]_{total}$ in sediments $<63\mu m$ and
304 $>63\mu m$ from core MTW01 in the Mackenzie Trough (Extended Data Fig. 1) for depths dated
305 by the ^{14}C activity of mixed benthic foraminifera (Methods), where whiskers show analytical
306 error if large than the point size.

307 **Methods**

308 **River sample collection and preparation:** River depth-profiles from September 2010 and
309 June 2011 (Extended Data Table 1) were used to collect the full range of erosion products
310 and POC in large river systems, taking advantage of the hydrodynamic sorting of
311 particles^{10,13,14,25}. At each sampling site (Fig. 1) channel depth, water velocity and
312 instantaneous water discharge were measured by two or more transects with an Acoustic
313 Doppler Current Profiler (ADCP Rio Grande 600 kHz) before each depth profile was
314 collected at a single point ($\pm 10m$) in the middle of the channel. On the boat, each sample (~ 7 -
315 8L) was evacuated into a clean bucket and stored in sterilised plastic bags and the procedure
316 repeated depending upon the total water depth. Each bag was weighed to determine the
317 sampled volume, then the entire sample was filtered within 24 hrs through pre-cleaned Teflon
318 filter units through 90 mm diameter $0.2\mu m$ PES filters^{13,25}. Suspended sediment was
319 immediately rinsed from the filter using filtered river water into clean amber-glass vials and
320 kept cool. River bed materials were collected at the base of the depth transects from the boat,
321 using a metal bucket as a dredge, and decanted to a sterile bag. River bank deposits (June

322 2009) were collected from fresh deposits close to the channel (Extended Data Table 3) and
323 sieved at 250 μm and 63 μm to investigate the sorting of POC³¹. All sediments were freeze
324 dried upon return to laboratories within 2 weeks, weighed and homogenised in an agate
325 grinder.

326 **Offshore borehole sampling and benthic foraminifera sample preparation:** Benthic
327 foraminifera-containing marine sediment samples were obtained from the upper 22 m
328 Holocene sequence of an 85.1 m MTW01 borehole³² located at 69° 20' 53" N, 137° 59' 13"
329 in 45 m water depth in the Mackenzie Trough (Extended Data Fig. 1). Drilled by the
330 Geological Survey of Canada in 1984, the core is currently archived at the GSC-Atlantic core
331 repository. To isolate foraminifera, sediment samples were disaggregated over a <38 μm mesh
332 sieve using deionized water. Based on down-hole microfossils counts, 4 samples were
333 selected with sufficient specimens for radiocarbon dating.

334 **Geochemical analyses:** For the river suspended sediments and core samples for organic
335 carbon analyses, inorganic carbon was removed using a HCl fumigation technique to avoid
336 loss of a component of POC which is known to occur during a HCl leach³³. An adapted
337 method to ensure full removal of detrital dolomite was used³⁴. In summary, samples were
338 placed in an evacuated desiccator containing ~50 ml 12N HCl in an oven at between 60 and
339 65 °C for 60 to 72 hours. Sample were then transferred to another vacuum desiccator charged
340 with indicating silica gel, pumped down again and dried to remove HCl fumes. River
341 sediment samples were analysed for organic carbon concentration [OC_{total}] on acidified
342 aliquots and nitrogen concentration ([N], %) on non-acidified aliquots by combustion at
343 1020°C in O₂ using a Costech elemental analyser (EA) in Durham. For river depth profile
344 samples, acidified aliquots were prepared to graphite at the NERC Radiocarbon Facility of
345 between 1-2 mg C for each sample and standard and ¹⁴C was measured by Accelerator Mass
346 Spectrometry at the Scottish Universities Environmental Research Centre and reported as

347 fraction modern (F_{mod}) by standard protocol³⁵. Process standards (96H humin) and
348 background materials (bituminous coal) were taken through all stages of sample preparation
349 and ^{14}C analysis and were within 2σ uncertainty of expected values. Stable isotopes of POC
350 ($\delta^{13}\text{C}_{\text{org}}$) were measured by dual-inlet isotope ratio mass spectrometer (IRMS) on an aliquot
351 of the same CO_2 . These measurements were consistent with $\delta^{13}\text{C}_{\text{org}}$ measurements made by
352 EA-IRMS normalised based on measured values standards ($n=7$) spanning $>30\text{‰}$ and long-
353 term analytical precision of 0.2‰ . River bank samples from 2009 were analysed by similar
354 procedures at the National Ocean Sciences Accelerator Mass Spectrometry Facility
355 (NOSAMS) at Woods Hole Oceanographic Institution.

356 Mixed benthic foraminifera samples picked from the MTW01 core were analysed at
357 NOSAMS for ^{14}C analyses. Samples were rinsed and no pre-treatments were used. The
358 samples were directly hydrolyzed with strong acid, H_3PO_4 , to convert the carbon in the
359 sample to CO_2 . Calibration of the ^{14}C dates was performed using CALIB (version 7.1)³⁶. All
360 ^{14}C dates were normalized to a $\delta^{13}\text{C}$ of -25‰ versus VPDB (<http://intcal.qub.ac.uk/calib/>).
361 Foraminifera dates were calibrated using the MARINE13 dataset³⁷, with a reservoir age
362 correction (ΔR) of 335 ± 85 yrs (Extended Data Table 2). The ΔR value is based on a recent
363 re-analysis of ages from 24 living molluscs collected before 1956 from the northwestern
364 Canadian Arctic Archipelago³⁸. This calibration set does not include specimens from the
365 Beaufort Sea and as such provides only a best available estimate for ΔR in the Mackenzie
366 Trough.

367 **End member mixing model:** The F_{mod} , $\text{N}/\text{OC}_{\text{total}}$ (Fig. 1), $\delta^{13}\text{C}_{\text{org}}$ values and $\text{Al}/\text{OC}_{\text{total}}$
368 values (Extended Data Fig. 2) are consistent with a mixing of $\text{POC}_{\text{petro}}$ and $\text{POC}_{\text{biosphere}}$
369 dominating the bulk geochemical composition of river POC. Autochthonous sources are not
370 significant based on those measured values, which is consistent with the turbid nature of the
371 Mackenzie River (mean suspended sediment concentration of $\sim 300\text{-}400$ mg/L) meaning that

372 like other turbid river systems (e.g. the Ganges-Brahmaputra) light penetration is minimal. A
 373 mixture of POC_{petro} and POC_{biosphere} can be described by governing equations^{10,13,31}:

$$374 \quad f_{biosphere} + f_{petro} = 1 \quad (\text{Equation 1})$$

$$375 \quad f_{biosphere} \times \theta_{biosphere} + f_{petro} \times \theta_{petro} = \theta_{sample} \quad (\text{Equation 2})$$

376 where $f_{biosphere}$ and f_{petro} are the fractions of POC derived from biospheric and petrogenic
 377 sources, respectively. θ_{sample} is the measured composition (e.g. F_{mod}) of a river POC sample,
 378 and $\theta_{biosphere}$ and θ_{petro} are the compositions of biospheric and petrogenic sources. To quantify
 379 the f_{petro} in each sample we use the aluminium (Al) to OC_{total} concentration ratio in river
 380 sediments. At each locality, a linear trend between F_{mod} and Al/OC_{total} (Extended Data Fig.
 381 2b) can be explained by a mixture of an Al-rich, OC-poor material (rock fragments
 382 containing POC_{petro}) with Al-poor, OC-rich material (soils and vegetation debris as
 383 POC_{biosphere}). Taking advantage of the fact that the POC_{petro} has $F_{mod} \sim 0$, the intercept at $F_{mod} =$
 384 0 gives an estimate of the Al/OC_{total} values and associated uncertainty of the sedimentary
 385 rock end member. To estimate the average concentration of OC_{petro} of bedrocks in each basin
 386 ([OC_{petro}], %), we use the Al concentration of river bed materials as a proxy of for the Al
 387 concentration in the bedrocks²⁵ and the Al/OC_{total} value at $F_{mod} \sim 0$. Following previous work
 388 in large rivers, we then assume that the OC_{petro} is well mixed in the water column and has a
 389 relatively constant [OC_{petro}] (refs 10,13,14). This method may overestimate f_{petro} if OC_{petro} has
 390 been more extensively oxidised in fine grained weathering products carried in the suspended
 391 load²¹. f_{petro} is quantified using [OC_{petro}] and measured [OC_{total}].

392 The mixing analysis returns a [OC_{petro}] = 0.12±0.03% (±2σ) in the Liard River and
 393 Mackenzie River at Tsiigehtchic, higher values in the Peel River [OC_{petro}] = 0.63±0.30%,
 394 with the Mackenzie River at the delta with an intermediate value [OC_{petro}] = 0.29±0.05%.
 395 This is consistent with the known presence of POC_{petro}-bearing sedimentary rocks in the

396 Mackenzie River Basin and high OC_{total} contents of bedrocks in the upper Peel River Basin
397 and Mackenzie mountains³⁹. To quantify the average ^{14}C age of $\text{POC}_{\text{biosphere}}$ in each sample,
398 Equations 1 and 2 can be solved for $\theta_{\text{biosphere}}$, using the f_{petro} and assumed unmeasurable above
399 background ^{14}C content of $\text{POC}_{\text{petro}}$ ($F_{\text{mod}} = 0$). The uncertainty mainly derives from that on
400 f_{petro} and $[\text{OC}_{\text{total}}]$ and has been propagated through the calculations.

401 To test if the mixing of $\text{POC}_{\text{biosphere}}$ and $\text{POC}_{\text{petro}}$ can describe the composition of the
402 suspended load samples, we predict the $\delta^{13}\text{C}_{\text{org}}$ measurements which were not used in the
403 mixing analysis. The calculated f_{petro} values and end member values of $-26.2 \pm 0.5\text{‰}$ for
404 $\text{POC}_{\text{biosphere}}$ and $-28.6 \pm 0.5\text{‰}$ for $\text{POC}_{\text{petro}}$ were used, informed by measurements of
405 bedrocks³⁹ and vegetation and soil in the basin⁴⁰. The mixing model (equation 2) can robustly
406 predict the $\delta^{13}\text{C}_{\text{org}}$ differences between the Peel and Liard rivers, and between suspended load
407 and bed material $\delta^{13}\text{C}_{\text{org}}$ values (Extended Data Fig. 2c), supporting a mixing control on the
408 variables.

409 **Mackenzie River POC discharge:** To quantify the discharge of POC we need to account for
410 the variability in suspended sediment discharge and the variability in the $\text{POC}_{\text{biosphere}}$ and
411 $\text{POC}_{\text{petro}}$ content of sediments in the basin. We use the longest, most complete quantification
412 of sediment flux by the Mackenzie River from 1974-1994¹⁵, which has an average $127 \pm 40 \text{ Tg}$
413 yr^{-1} ($\pm 1\sigma$). Annual sediment yield varied from 81 Tg yr^{-1} to 224 Tg yr^{-1} . While the POC
414 samples were not collected at the same time period, our measurements of $[\text{OC}_{\text{total}}]$ at the
415 Delta, mean = $1.6 \pm 0.5\%$ ($n=8$, $\pm 1\sigma$) and do not vary systematically between falling and high
416 stage (Extended Data Fig. 4) and are consistent with available data from samples¹² collected
417 in 1987 (1.4 ± 0.2 , $n=10$). While future work should aim to constrain the variability in POC
418 composition further, these observations suggest that temporal variability may be less
419 important than the potential variability in $[\text{OC}_{\text{total}}]$ with depth at a given time, where we find
420 $[\text{OC}_{\text{total}}]$ values can range from 1.0% to 2.7%. We use our measured range of $[\text{OC}_{\text{biosphere}}]$ and

421 [OC_{petro}] values and the full range of annual sediment yields¹⁵ to quantify POC_{biosphere} and
 422 POC_{petro} discharge and associated uncertainty using a Monte Carlo approach. Over 100,000
 423 simulations, we use a ‘flat’ probability for the range of values for both variables (i.e. equal
 424 probability of all measured values). This allows us to fully explore the range of estimates
 425 given the available measurements. Future work seeking to expand the number of [OC_{biosphere}]
 426 measurements to assess its flux-weighted mean and variability, while assessing temporal
 427 variability in more detail, will allow POC discharge estimates and their uncertainty to be
 428 refined. POC_{biosphere} ($2.2^{+1.3}_{-0.9}$ TgC yr⁻¹) and POC_{petro} ($0.4^{+0.1}_{-0.1}$) discharges are reported as the
 429 median (50%) ± 1 s.d. Over the sediment source areas of the Mackenzie (Downstream of the
 430 Great Slave Lake¹⁵) of 774,200 km², these equate to yields of POC_{biosphere} = $2.9^{+1.7}_{-1.1}$ tC km⁻²
 431 yr⁻¹ and POC_{petro} = $0.6^{+0.2}_{-0.2}$ tC km⁻² yr⁻¹. The total POC discharge is slightly higher than a
 432 previous estimate (2.1 TgC yr⁻¹)¹² based on measurements of POC content made in 1987
 433 because we: i) account for higher POC_{biosphere} concentrations which may occur in water-
 434 logged POC_{biosphere} near the river bed (Figs. 2c, Extended Data Fig. 4); and ii) account for the
 435 potential for very high annual sediment discharge¹⁵. Based on estimates of soil carbon stock
 436 in the Mackenzie Basin² of $\sim 50 \times 10^3$ tC km⁻² and the upstream sediment source area
 437 (downstream of the Great Slave Lake, 774,200 km²), the present rate of POC_{biosphere} export
 438 represents a depletion of the soil carbon stock by $\sim 0.006\%$ yr⁻¹, which is sustainable over 10³-
 439 10⁴ years.

440 **OC burial efficiency in MTW01:** To estimate the burial efficiency of terrestrial POC at the
 441 MTW01 site, we normalise the measured [OC_{total}] concentrations (Fig. 3) by Al
 442 concentration, an immobile inorganic element hosted by major mineral phases. The OC_{total}/Al
 443 normalization allows the effects of dilution to be distinguished from net OC gain (increased
 444 ratio) or OC loss (decreased ratio). The mean OC_{total}/Al of the MTW01 samples was
 445 0.17 ± 0.02 (g g⁻¹, n=4, ±2SE). This is lower than the mean OC_{total}/Al of the suspended load

446 samples from the Mackenzie River delta of 0.26 ± 0.10 (g g^{-1} , $n=8$, $\pm 2\text{SE}$). The decrease in the
447 ratio offshore may suggest a higher relative proportion of $\text{POC}_{\text{petro}}$ (Extended Data Fig. 2b),
448 however this is not consistent with the less negative $\delta^{13}\text{C}_{\text{org}}$ values (Extended Data Fig. 5).
449 The decrease can therefore be interpreted in terms of OC loss, with the ratio of core to river
450 samples ($0.17 \pm 0.02 / 0.26 \pm 0.10$). Assuming that all the change in $\text{OC}_{\text{total}}/\text{Al}$ is driven by OC
451 loss, and taking into account the measurement variability in these values, we estimate that
452 $65 \pm 27\%$ of the OC has been preserved. However, we note that the $\text{OC}_{\text{total}}/\text{Al}$ ratios in the core
453 are not statistically different from the river suspended load samples (one-way ANOVA,
454 $P > 0.1$) which suggest the OC burial efficiency could be higher (i.e. 100%). In addition, if we
455 use the $\text{OC}_{\text{total}}/\text{Al}$ of finer river sediments carried near the channel surface which may be
456 more easily conveyed offshore of 0.20 ± 0.04 (g g^{-1} , $n=4$, $\pm 2\text{SE}$), we calculate burial efficiency
457 $= 85 \pm 20\%$. Future work should seek to better constrain these burial efficiencies with
458 additional terrestrial and marine samples. Nevertheless, despite the remaining uncertainty,
459 these high burial efficiencies¹⁸ are consistent with the high sedimentation rate and low
460 temperature setting. The long-term burial of POC delivered to sites deeper in the Beaufort
461 Sea²⁸ still remains to be assessed, in order to provide a complete picture of source to sink
462 carbon transfers.

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491 **Extended Data**

492 Available by contacting the lead author (r.g.hilton@durham.ac.uk) or on the online version of
493 the paper: doi:10.1038/nature14653.

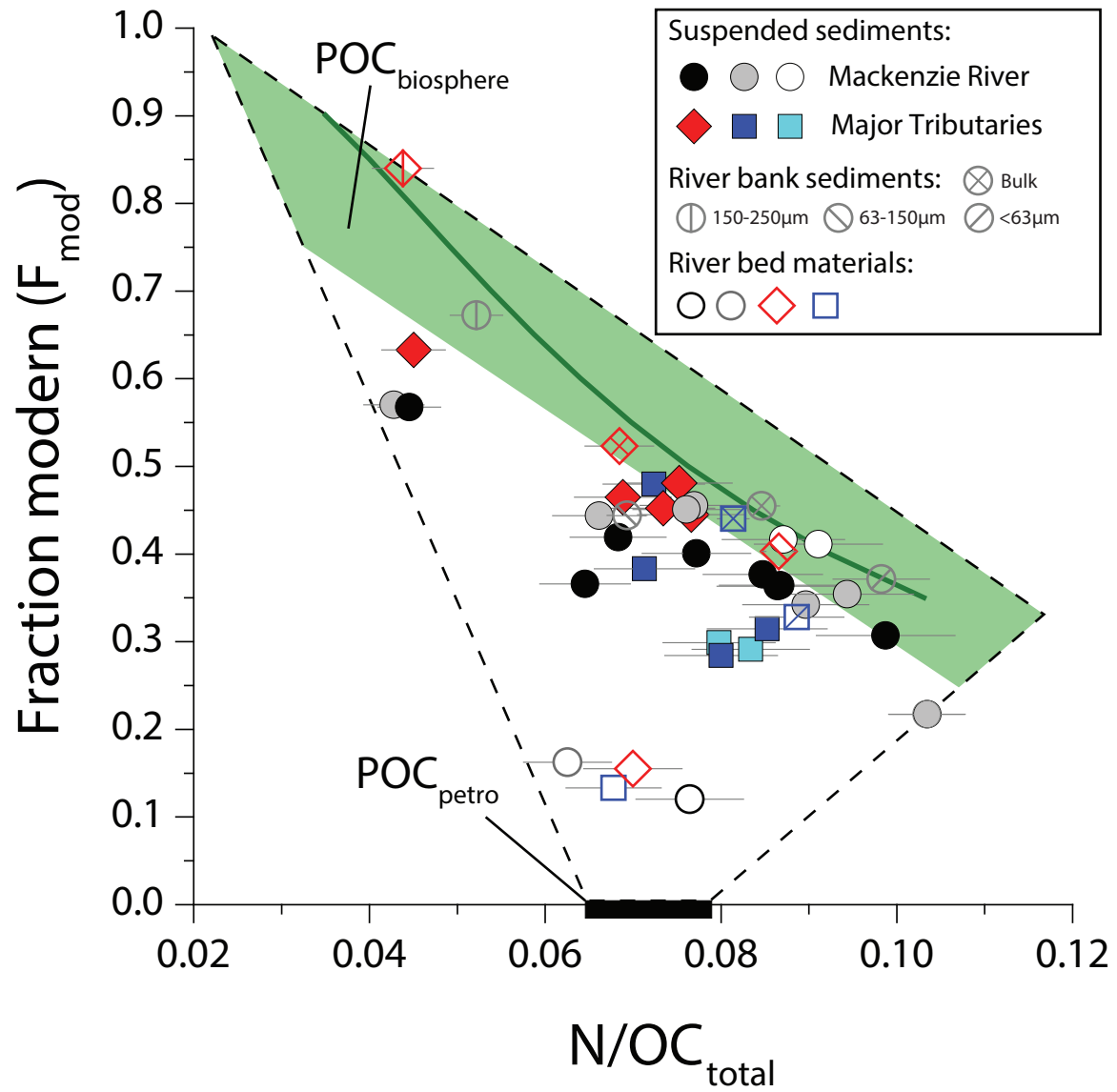


Figure 1

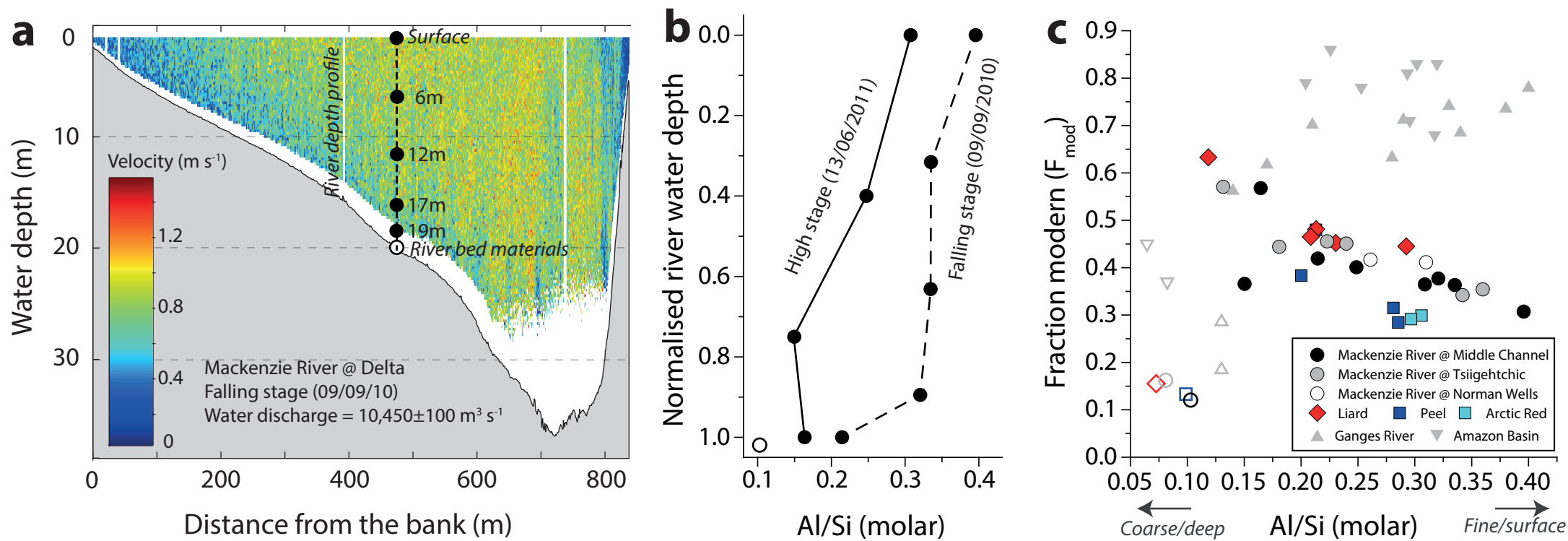


Figure 2

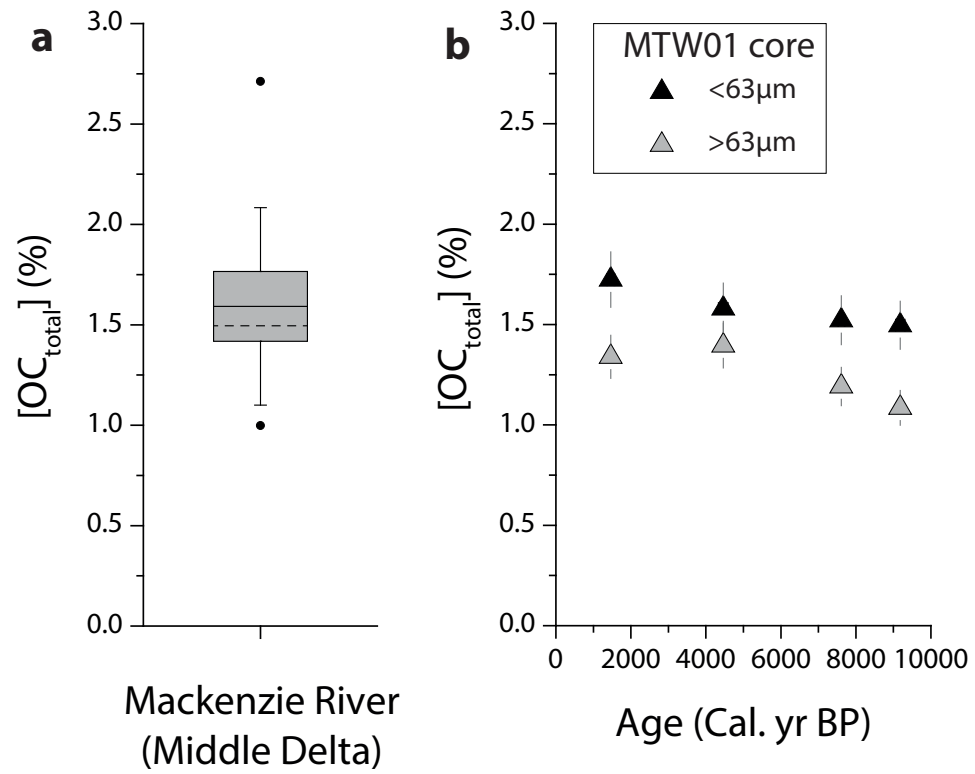


Figure 3