

Carbon loss from an unprecedented Arctic tundra wildfire

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Arctic tundra soils store large amounts of carbon (C) in organic soil layers hundreds to thousands of years old that insulate, and in some cases maintain, permafrost soils^{1,2}. Fire has been largely absent from most of this biome since the early Holocene epoch³, but its frequency and extent are increasing, probably in response to climate warming⁴. The effect of fires on the C balance of tundra landscapes, however, remains largely unknown. The Anaktuvuk River fire in 2007 burned 1,039 square kilometres of Alaska's Arctic slope, making it the largest fire on record for the tundra biome and doubling the cumulative area burned since 1950 (ref. 5). Here we report that tundra ecosystems lost $2,016 \pm 435 \text{ g C m}^{-2}$ in the fire, an amount two orders of magnitude larger than annual net C exchange in undisturbed tundra⁶. Sixty per cent of this C loss was from soil organic matter, and radiocarbon dating of residual soil layers revealed that the maximum age of soil C lost was 50 years. Scaled to the entire burned area, the fire released approximately 2.1 teragrams of C to the atmosphere, an amount similar in magnitude to the annual net C sink for the entire Arctic tundra biome averaged over the last quarter of the twentieth century⁷. The magnitude of ecosystem C lost by fire, relative to both ecosystem and biome-scale fluxes, demonstrates that a climate-driven increase in tundra fire disturbance may represent a positive feedback, potentially offsetting Arctic greening⁸ and influencing the net C balance of the tundra biome.

The Arctic terrestrial C cycle has the potential to influence global climate through feedbacks to recent warming, but the net sign, magnitude and pace of these feedbacks remains uncertain^{7,9,10}. Wildfire is a climate-sensitive process that can rapidly transfer large stocks of terrestrial C to the atmosphere, reduce landscape C storage and alter ecosystem C balance¹¹. In the boreal forest biome, where fire has been part of the historic disturbance regime, burned area has increased over the past several decades, concurrently with summer warming and drying^{12,13}. Arctic tundra has experienced similar climatic changes in the past two decades¹⁴ and although the tundra has little history of fire, models^{15,16} predict increasing fire here if the climate continues to warm. Recent observations already indicate increasing burned area in Alaskan Arctic and subarctic tundra regions over the past two decades, even though large fires have been infrequent since the early Holocene^{3,4}.

Little is known about the impacts of fire on the carbon stocks and cycling of tundra ecosystems that have no recent history of fire disturbance. Cool, wet soils underlain by permafrost (permanently frozen ground) may restrict burning to plant litter and aboveground biomass, causing relatively little change in ecosystem C pools. However, Arctic tundra landscapes store large pools of C in organic-rich surface soil horizons that have accumulated over millennia², and peatland organic soils, at least in boreal and temperate ecosystems, can be highly flammable when dry and may burn deeply^{17,18}. As much as 18% of

the one-metre-depth soil C pool in Arctic tundra may be vulnerable to direct loss through combustion because it is contained in surface organic horizons¹. This proportion has been intensively quantified for the 100 Pg C stored in North American Arctic soils¹, and is probably similar for the 496 Pg C stored across the circum-Arctic permafrost region¹⁹. Thus, if tundra soils burn, increasing fire in this biome could rapidly transfer a substantive amount of C to the atmosphere, reducing landscape C storage, increasing atmospheric CO₂ levels, and amplifying climate warming.

Beyond direct emissions of C, disturbance by fire has the potential to cause threshold changes in ecosystem structure and function by altering the surface reflectance (albedo) and energy balance of landscapes underlain by permafrost²⁰. Fire effects on albedo can be variable and, in some cases, are one of the few factors that have been shown to offset positive climate forcing from fire-driven C loss²¹. But fire also removes the soil organic layer that insulates permafrost from warm summer temperatures, leading to thaw and destabilization of the ground surface and presumably altered ecosystem C balance⁹. Processes that destabilize permafrost expose organic C deep in the soil profile to increased decomposition and future release to the atmosphere²², further amplifying the positive feedback to high-latitude warming.

In the late summer and autumn of 2007, the Anaktuvuk River fire burned 1,039 km² of Arctic tundra on the North Slope of the Brooks Range, Alaska, USA, doubling the cumulative area burned in this region over the past 50 years (Supplementary Fig. 1 and Supplementary Table 1). This fire was an order of magnitude larger than the average fire size in the historic record for the North Slope (Supplementary Table 1). Sediment cores from lakes within the burn perimeter showed no evidence of regional fires in the past 5,000 years (ref. 4). Here we report results from a 2008 field campaign to examine C loss from the vegetation and soils of moist acidic tundra ecosystems that covered 54% of the area burned in the fire. We examined concurrent nitrogen (N) loss because this is the element most likely to limit plant productivity in this system and thus its loss could constrain post-fire C uptake over longer timescales. We developed a biometric method for estimating pre-fire soil organic layer depth in burned tundra, based on the persistent crowns of the dominant, tussock-forming sedge species, *Eriophorum vaginatum* L., which survived to re-sprout after fire (Supplementary Methods). We measured post-fire residual soil organic matter and reconstructed fire-driven losses of C and N in 20 sites widely distributed across the burn (Supplementary Fig. 3). The radiocarbon age of the residual soil surface was measured to determine whether the fire burned into soil C pools that were hundreds or even thousands of years old (Supplementary Methods).

Reconstructed pre-fire soil organic layer C pools averaged 7,682 g C m⁻² (Table 1) across moist acidic tundra in the Anaktuvuk River fire scar, a value similar to the average (7,500 g C m⁻²) reported for upland tundra sites throughout the North American Arctic¹. Fire

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Table 1 | Ecosystem effects of the 2007 Anaktuvuk River fire

	Statistics	Soil depth (cm)	C pool (g C m ⁻²)			N pool (g N m ⁻²)		
			Soil	Plant	Total	Soil	Plant	Total
Pre-fire (measured)	Mean (s.e.m.)	21.5 (1.5)	7,682 (766)	559 (33)	8,241 (764)	287 (36)	17 (1)	303 (35)
	Min	12.3	2,842	355	3,197	84	9	93
	Max	43.3	19,470	840	19,833	847	28	856
Post-fire (reconstructed)	Mean (s.e.m.)	15.4 (1.1)	6,354 (613)	0	6,354 (613)	245 (34)	0	245 (34)
	Min	8.5	2,718	0	2,718	67	0	67
	Max	28.0	12,007	0	12,007	624	0	624
Loss (reconstructed)	Mean (s.e.m.)	6.1 (1.0)	1,456 (445)	559 (33)	2,016 (435)	47 (18)	17 (1)	64 (17)
	Min	3.4	379	355	753	9	9	19
	Max	22.8	9,460	840	9,823	370	28	379

Measured or reconstructed soil organic layer depth, and soil and combustible aboveground plant C and N pools in 20 upland moist acidic tundra sites that burned in the 2007 Anaktuvuk River fire, North Slope of the Brooks Range, Alaska, USA.

reduced combustible ecosystem C pools by $31 \pm 3\%$ (mean ± 1 standard error) resulting in a net loss of about $2,016 \text{ g C m}^{-2}$ and 64 g N m^{-2} (Table 1). This is in the mid-range of emissions reported for North American boreal forest fires^{15,17,18}. On average, $62 \pm 4\%$ of ecosystem C and a similar percentage of N loss came from soil, with the remainder from plant biomass. The depth of the soil organic layer was reduced by $30 \pm 3\%$ and residual organic layer depth, a factor likely to influence insulation of permafrost, averaged 15 cm (Table 1). Survivorship of *E. vaginatum* tussocks averaged $87 \pm 11\%$, while the mosses, lichens and dwarf shrubs that inhabited spaces among tussocks before the fire were almost completely combusted.

Despite wide variation in pre-fire soil organic layer depth (12.3–43.3 cm) and organic layer carbon pools ($2,842\text{--}19,470 \text{ g C m}^{-2}$), the depth burned and C and N lost were relatively constant across sites. Pre-fire soil organic layer depth was not related to depth lost but was highly predictive of post-fire residual depth ($R^2 = 0.82$, $P < 0.001$, $n = 20$ sites). This is consistent with observations of organic soil burning in Alaskan boreal forest¹⁷ and suggests that in these structured organic soils, burning is restricted to surface soil by a mechanism independent of potential fuel, such as variation with depth of bulk density, particle size and hydraulic connectivity with the water table. Our results indicate that residual soil organic layer depth is not an adequate proxy for fire severity, depth of burning, or C emissions from tundra soils because of the large variation in pre-fire depth. As a result, estimates of emissions that index consumption as a fraction of pre-fire C pool size will overestimate consumption in deep organic soils.

Age and density of soil C typically increase with depth in peat soils²³. Plant production continuously adds new material at the surface of the soil while decomposition and leaching remove organic matter throughout the soil profile, resulting in older, deeper strata that are thinner and higher in density than younger strata near the surface. Radiocarbon dating of residual soil surfaces showed that burning in the Anaktuvuk River fire was limited to younger, upper soil layers. All samples of moss macrofossils removed from the surface soils of the burned sites contained bomb-enriched radiocarbon, setting the maximum age of lost soil C at 50 years (Fig. 1). Across the 20 soil profiles sampled for radiocarbon, the fire burned down to strata with an average year of formation of 1970 (95% confidence intervals: 1959–1981). The relationship between age and depth—6.1 cm and 37 years—observed here is similar to the accumulation rates of surface organic soils elsewhere on the North Slope²⁴ and Canada²³. The profile that had the deepest burning (15 cm lost) also had the oldest burned surface date (1954), but there was no evidence that the fire burned into old, pre-bomb layers in any of the profiles despite the existence of organic soil layers >30 cm deep.

On a per unit area burned basis, C and N losses from the Anaktuvuk River fire were substantially larger than annual input or output fluxes of undisturbed tundra. Carbon loss was approximately five times

greater than annual net primary productivity of moist acidic tundra (450 g C m^{-2} ; ref. 25) and two orders of magnitude larger than the annual balance between production and decomposition (net ecosystem carbon exchange, $29.5 \text{ g C m}^{-2} \text{ yr}^{-1}$; ref. 6). Nitrogen deposition rates in Arctic Alaska are low ($0.008\text{--}0.06 \text{ g N m}^{-2} \text{ yr}^{-1}$; ref. 26) and inputs from biological N fixation are estimated to be slightly higher: at most, $0.1 \text{ g N m}^{-2} \text{ yr}^{-1}$ in unburned tundra²⁶. Assuming steady-state dynamics, the fire emitted about 400 years of N accumulation.

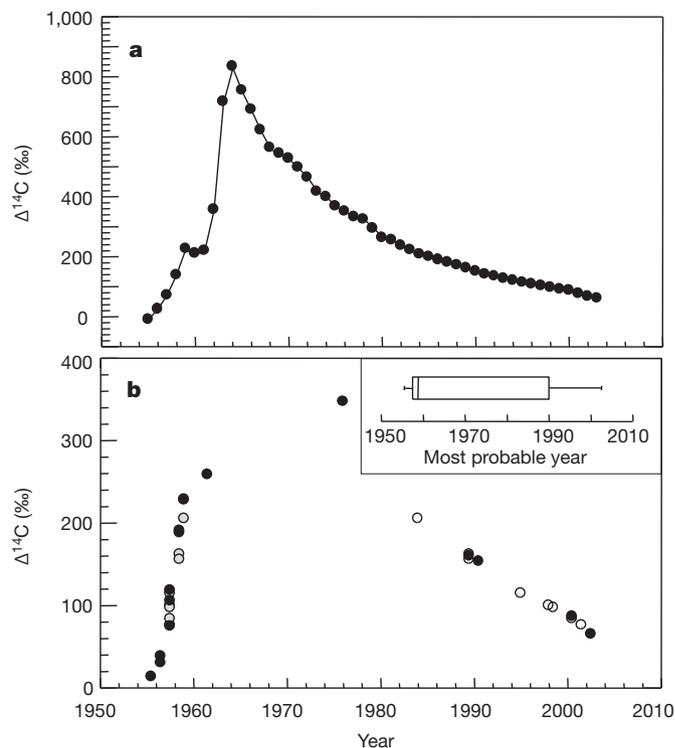


Figure 1 | Atmospheric radiocarbon values over the past 57 years and radiocarbon values of the burned soil surface in the Anaktuvuk River fire scar, Alaska, USA. **a**, Atmospheric radiocarbon content versus time (adapted from ref. 47 in the Supplementary Methods). **b**, Radiocarbon content of moss macrofossils removed from the burned surface versus estimated age of $n = 20$ profiles sampled in the Anaktuvuk River fire scar. Black circles indicate samples where location on the bomb curve (ascending or descending) was confirmed by measuring two depths (0–1 cm and 1–2 cm), while grey or white circle pairs indicate the two possible ages of samples where one depth (0–1 cm) was measured (Supplementary Methods). The inset shows a box plot of median most probable age (vertical line in rectangle), the range within which the central 50% of the values fall (length of rectangle), hinges (first and third quartiles) and whiskers (range of values within 1.5 Hspreads of the hinges).

Scaled to the 1,039 km² burned area, the fire released approximately 2.1 Tg C to the atmosphere. Extrapolating from moist acidic tundra alone excludes the potential for different emissions from shrub tundra, which occupied 30% of the vegetated burn area. Higher aboveground biomass in shrubs, however, may have been offset by the presence of fire-resistant woody stems and lower density and shallower depth of organic soil²⁷, such that emissions per unit area may not be widely different. Carbon emissions from the entire burn were then similar in magnitude to the annual net C sink simulated by process models for the entire Arctic tundra biome (3–4 Tg C yr⁻¹) over the last quarter of the twentieth century⁷.

Our results show how rapidly a single tundra fire—even one that burned relatively superficially—can offset local and biome-scale C uptake. The rate of soil C loss per unit burned area was more rapid than other climate-driven pathways of loss that may affect tundra ecosystem C balance in the future. Combustion losses were 30–50 times more rapid than decomposition-related mechanisms such as the stimulation of soil organic matter decomposition from a 5 °C increase in mean annual temperature²⁸, temperature-driven increases in N availability that can directly stimulate microbial activity²⁹, or ground subsidence as a consequence of permafrost thaw and melting ground ice²². At both local and regional scales, fire emissions of this magnitude can instantaneously offset or reverse C cycling processes hypothesized to feedback negatively to warming such as greening of the Arctic^{8,30}.

A novel disturbance of this magnitude also has implications for future interactions between ecosystems and climate change. The relatively young age of soil C lost and the high survivorship of graminoids (sedges) in the Anaktuvuk River fire create the potential for plant and soil C losses to be replaced by new plant production before the next fire, assuming a fire return interval of 80–150 years, similar to that of boreal forest south of the Brooks Range^{12,15}. This replacement time implies, however, that transition to a new fire regime would catalyse a net transfer of C from ecosystems to the atmosphere as subsequent fires shift never-burned tundra to early-successional ecosystems with lower C storage.

Another future scenario is that fire will act as a mechanism for threshold change such that graminoid tundra is replaced by shrub tundra after fire. A shift to shrub tundra has been independently occurring across Arctic Alaska³⁰, and vegetation transition from graminoid to shrub domination has been linked to fire in some palaeoecological studies³. This vegetation change could trigger additional positive feedbacks to climate warming because shrub-dominated ecosystems have higher productivity and plant biomass²⁵ offset by lower soil C stocks²⁷, in addition to direct regional warming induced by the lower albedo of shrubs than of graminoid tundra¹⁴.

Ecosystems also interact directly with climate through surface reflectance and energy partitioning. Alteration of the tundra surface by the Anaktuvuk River fire decreased albedo by 50–71% and increased partitioning of net radiation into ground heat flux³¹. Fire-induced changes in ecosystem albedo were, in the case of a boreal forest, found to offset other positive climate forcing factors over 80 years of succession, including changes in ecosystem C storage and initial post-fire decreases in albedo²¹. This negative feedback from albedo forcing, however, was largely driven by changes in tree canopy shading of spring snow, a factor unlikely to be important in moist acidic tundra ecosystems where few plant species extend above the snow pack. A more likely possibility for tundra is that the increased ground heat flux initiated by decreased albedo and reduced organic soil insulation will destabilize permafrost, leading to internal feedbacks that cause ground ice to melt and surfaces to subside⁹. Over centennial timescales, deep permafrost C pools have the potential for C loss an order of magnitude larger than the C gained in plant biomass by the transition to shrub tundra or even boreal forest^{19,22}.

The half-century record of Arctic and subarctic tundra area burned in Alaska points to increasing fire in tundra regions over the past two

decades, concurrent with increasing mean annual temperature and sea ice retreat⁴, trends that seem likely to continue¹⁰. Our observations of C loss from the Anaktuvuk River fire support the idea that tundra fires have the potential to release large amounts of C and decrease landscape C stocks, having an immediate impact on atmospheric C and climate that is rapid in comparison to other potential climate change feedbacks from tundra ecosystems. Although the future trajectory of ecosystem recovery in the Anaktuvuk River fire scar is yet unknown, most of the plausible short- and long-term scenarios lead to amplification of climate warming.

METHODS SUMMARY

The Anaktuvuk River fire scar is located on the North Slope of the Brooks Range, Alaska, approximately 23 km northwest of Toolik Field Station (68.5833 °N, 149.7167 °W). This region is underlain by permafrost. The mean annual temperature is approximately –10 °C and mean annual precipitation is 30 cm. Before the fire, 54% of the vegetated area within the burn perimeter was classified as upland moist acidic tundra (MAT; soil pH < 5.5), 15% as moist non-acidic tundra (soil pH > 5.5), and 30% as shrubland. MAT is pan-Arctic in distribution and covers as much as 336 × 10⁶ km² of the tundra biome³². We focused our study on MAT because of its widespread distribution and because crowns of the dominant plant species, *Eriophorum vaginatum*, persisted through fire and provided a benchmark of pre-fire soil organic matter depth and plant biomass. We sampled twenty MAT sites within the burn in July and August of 2008. Eleven widely distributed unburned sites were sampled to develop and test regional biometric relationships between *E. vaginatum* meristem height above the mineral soil versus pre-fire soil organic layer depth, and depth versus bulk density, [C] or [N]. We modified a boreal forest method¹⁷ for use in MAT and used it to calculate site-specific estimates of pre- and post-fire soil organic matter pools and estimate losses. We used the bomb peak method to radiocarbon date the post-fire soil surface and examine whether the fire burned into old and probably irreplaceable soil C pools. Further description of the region, sites and methods used are included in the Supplementary Information.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Information The data described in this study is publicly available in the Arctic Long Term Ecological Research data archive (<http://ecosystems.mbl.edu/arc/burn/data.html>). Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to M.C.M. (mcmack@ufl.edu).