LETTER

https://doi.org/10.1038/s41586-019-1474-y

Increasing wildfires threaten historic carbon sink of boreal forest soils

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Boreal forest fires emit large amounts of carbon into the atmosphere primarily through the combustion of soil organic matter[1–3]. During each fire, a portion of this soil beneath the burned layer can escape combustion, leading to a net accumulation of carbon in forests over multiple fire events[4]. Climate warming and drying has led to more severe and frequent forest fires[5–7], which threaten to shift the carbon balance of the boreal ecosystem from net accumulation to net loss[1], resulting in a positive climate feedback[8]. This feedback will occur if organic-soil carbon that escaped burning in previous fires, termed 'legacy carbon', combusts. Here we use soil radiocarbon dating to quantitatively assess legacy carbon loss in the 2014 wildfires in the Northwest Territories of Canada[2]. We found no evidence for the combustion of legacy carbon in forests that were older than the historic fire-return interval of northwestern boreal forests[9]. In forests that were in dry landscapes and less than 60 years old at the time of the fire, legacy carbon that had escaped burning in the previous fire cycle was combusted. We estimate that 0.34 million hectares of young forests (<60 years) that burned in the 2014 fires could have experienced legacy carbon combustion. This implies a shift to a domain of carbon cycling in which these forests become a net source—instead of a sink—of carbon to the atmosphere over consecutive fires. As boreal wildfires continue to increase in size, frequency and intensity[7], the area of young forests that experience legacy carbon combustion will probably increase and have a key role in shifting the boreal carbon balance.

Natural wildfires have been the principal landscape disturbance in boreal forests for the last 6,000 years[10,11]. Such wildfires drive boreal net ecosystem carbon balance[4], emitting large amounts of carbon (C) to the atmosphere, primarily through combustion of organic soil[2,3]. Soil C pools have accumulated over millennia through a portion of soil escaping combustion beneath the burned layer[4], leading to a net accumulation of C from the atmosphere across multiple fire events. We term these soil C pools 'legacy C' because they are carryover pools sequestered over past disturbance cycles[12] and can be quantitatively defined as any organic-soil C that is older than the stand age at the time of fire.

Black spruce (*Picea mariana*) forests represent about 60% of the forested area in boreal North America and about 65% of the burned area[13]. Recent climate warming and drying in these forests has led to an increase in the frequency, extent, intensity and severity of wildfires[5,6]. Increasing fire severity, in combination with greater fire frequency and more burning of young stands, could drive deeper burning of organic soil[14] and greater proportional combustion[15] of organic-soil C. This could render legacy C vulnerable to combustion and shift boreal forests from a net carbon sink to a net carbon source over the fire cycle[1]. Boreal forests store 30% to 40% of terrestrial C, 70% to 80% of which is stored in organic soils[16], so this shift could impact the global C cycle and act as a positive feedback to climate warming.

The boreal forest of the Northwest Territories, Canada comprises nearly 20% of the Canadian boreal forest and 5% of the global boreal forest and has carbon-rich soils that can store up to 75 kilograms of carbon per square metre[2] (kg C m^{-2}). In the summer of 2014, wildfires burned the largest area annually on record for this region, presenting a unique opportunity to assess the combustion of legacy C across an extensive and diverse fire complex. Organic-soil accumulation and combustion are known to vary with moisture[2,17] and stand age[18], so we expected that these factors would also influence the presence and combustion of legacy C. We hypothesized that legacy C would (Fig. 1): (i) occur more in wet ecosystems owing to high rates of organic-soil accumulation and low-severity fires in the past, and would not occur in

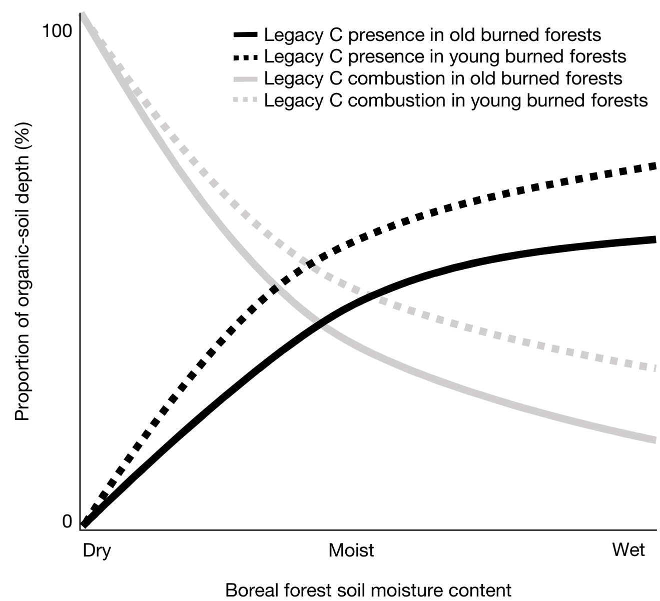

Fig. 1 | Hypothesized patterns of legacy C presence and combustion as a proportion of total organic-soil depth across the soil moisture gradient of a boreal forest. We hypothesized that: (i) legacy C occurs in wet ecosystems because of high rates of organic-soil accumulation (solid black line, 'wet') and low-severity fires in the past (solid grey line, 'wet'), and does not occur in dry ecosystems owing to low rates of organic-soil accumulation (solid black line, 'dry') and high-severity fires in the past (solid grey line, 'dry'); (ii) legacy C is most vulnerable to combustion in moist ecosystems ('moist') because these ecosystems harbour legacy C and are prone to moderate-to-severe burning; (iii) younger stands would be more vulnerable to legacy C loss compared with older stands because the overlying soil layers that were removed by the previous fire have not yet reaccumulated (dashed black line), resulting in greater proportional combustion of the organic soil (dashed grey line).

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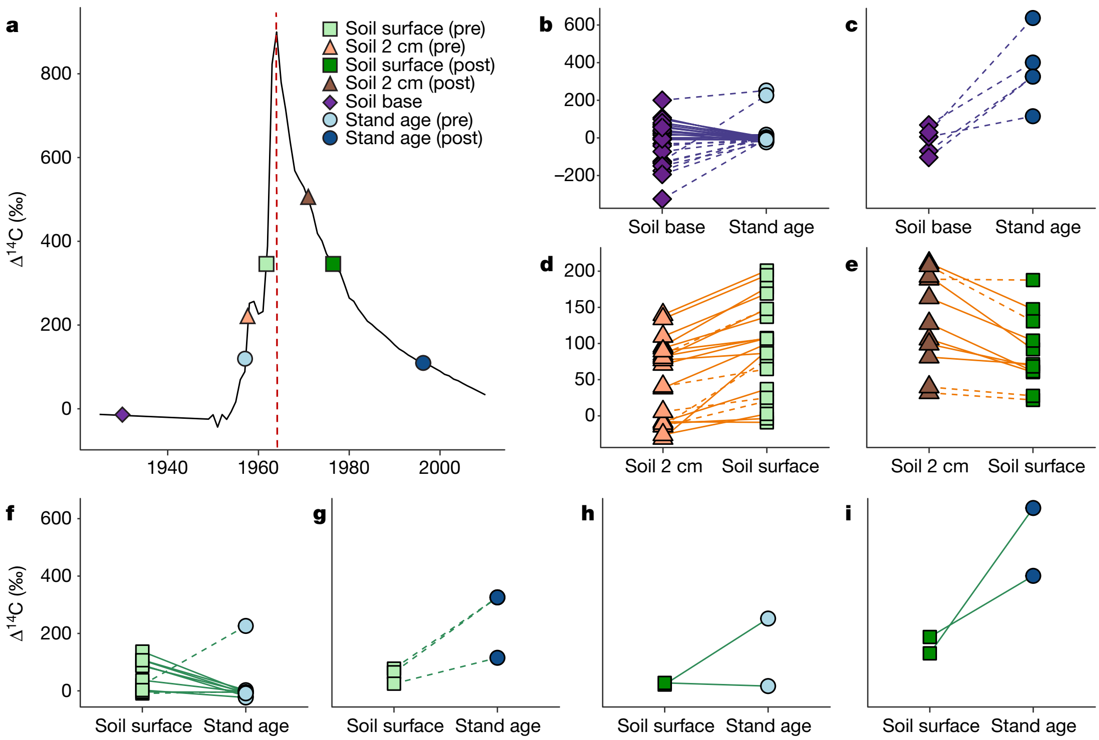

Fig. 2 | Radiocarbon concentration Δ^{14}C in the atmosphere over time, Δ^{14}C values of soil-depth increments and atmospheric concentration of ^{14}C during the year in which the stand established. a–i, In **a**, the radiocarbon concentration Δ^{14}C in the atmosphere over time (black line) shows the bomb peak in 1966 (vertical red dotted line) and examples of organic soil Δ^{14}C values at different depths (symbols) observed in real data (**b**–**i**; see Methods 'Assessing legacy C presence and combustion'). In **b** and **c**, the Δ^{14}C values of basal increments (diamonds) are compared to the atmospheric concentration of ^{14}C during the year in which the stand established (circles) to assess the presence of legacy C. In **b**, stands established pre-bomb-peak and in **c**, stands established post-bomb-peak. In **b** and **c**, legacy C is present (dashed lines) if the Δ^{14}C value of the basal increment is lower (soil less enriched in ^{14}C) than the Δ^{14}C values of the atmosphere at the time of stand establishment (solid lines indicate absence of legacy C). In **d** and **e**, surface increments are assigned to the correct side of the bomb peak by comparing the Δ^{14}C values of the residual surface increment (squares) to the soil-depth increment 2 cm below the surface (triangles). In **d**, the surface increment is pre-bomb-peak and in **e**, the surface increment is post-bomb-peak; dashed lines in **d** and **e** represent young burned plots (less than 60 years since the previous fire) and solid lines represent old burned plots (more than 70 years since the previous fire). In **f**–**i**, the Δ^{14}C values of the surface increments (squares) are compared to the atmospheric concentration of ^{14}C during the year in which the stand established (circles) to assess legacy C combustion. In **f**, the stand age is pre-bomb-peak and the surface increment is pre-bomb-peak; in **g**, the stand age is post-bomb-peak and the surface increment is pre-bomb-peak; in **h**, the stand age is pre-bomb-peak and the surface increment is post-bomb-peak; in **i**, the stand age is post-bomb-peak and the surface increment is post-bomb-peak. In **f**–**i**, legacy C is combusted (dashed lines) if the surface increment is older than the stand age (solid lines indicate that legacy C is not combusted).

dry ecosystems because of low rates of organic-soil accumulation and high-severity fires in the past; (ii) be more vulnerable to combustion in moist, compared to dry or wet, ecosystems because these ecosystems harbour legacy C and are prone to moderate-to-severe burning; and (iii) be more vulnerable to combustion in younger-aged stands compared to older-aged stands because overlying soil layers removed by the previous fire have not yet reaccumulated.

To test these hypotheses, in the summer of 2015 we established 211 field plots spanning seven spatially independent burn scars using a stratified random sampling design[2,19]. All plots experienced stand-replacing fires in 2014. In each plot, we measured the pre-fire tree density, basal area and stand age, and estimated the burn depth using adventitious roots[19]. We collected 1,205 soil profiles and analysed the carbon content of 1,786 soil samples to estimate carbon pools and emissions from the fires[2]. In 32 black-spruce-dominated plots, we measured Δ^{14}C (the parts-per-thousand difference between the ^{14}C/^{12}C ratio of the sample and an international standard) on 90 soil-depth increments as an index of soil age. In these plots, the depth of the residual organic soil ranged from 1.8 to 42.3 cm. The proportion of the pre-fire organic soil combusted (ratio of burn depth to pre-fire organic soil depth) ranged from 18% to 86%. The stand age at the time of fire ranged from 19 to 205 years. To each plot we assigned a moisture class (wet, moist, dry) on the basis of topography, drainage, soil texture and presence of permafrost[20]. We classified plots as young burned (stand age < 60 years at the time of fire; $n = 9$; mean, 45 years) or old burned (stand age > 70 years at the time of fire; $n = 23$; mean, 128 years) according to the historic fire-return interval of 70–130 years in northwestern boreal forests of North America[9].

Organic soil accumulates vertically through time and combustion propagates downwards during fire, so we used organic-soil Δ^{14}C values to examine the historic cycles of organic soil combustion and accumulation. We obtained Δ^{14}C values from multiple adjacent soil-depth increments and dated the samples using the atmospheric bomb peak[21,22] (Fig. 2). We then compared the Δ^{14}C values to the atmospheric value of $\Delta^{14}CO_2$ during the year in which the stand established in order to assess the presence and combustion of legacy C. We considered legacy C to be present if the organic soil at the base of the organic-soil profile was older than the stand age at the time of fire (Fig. 2b, c), and to be combusted if the organic soil at the top of the residual organic-soil profile was older than the stand age at the time of fire (Fig. 2f–i).

We found evidence of legacy C in 17 out of the 32 plots that we sampled (Fig. 2b, c). Legacy C ranged in age from about 118 to 1,670 years and was older than 380 years in 10 plots, suggesting that it had escaped combustion in two or three previous fires. In support of our hypotheses, the probability of a plot harbouring legacy C increased with depth of the pre-fire organic soil ($P < 0.05$) and decreased with stand age ($P < 0.05$) (Fig. 3a, b, Extended Data Table 1). Specifically, legacy C was present in all plots with pre-fire organic soil depth greater than 30 cm (Fig. 3a),

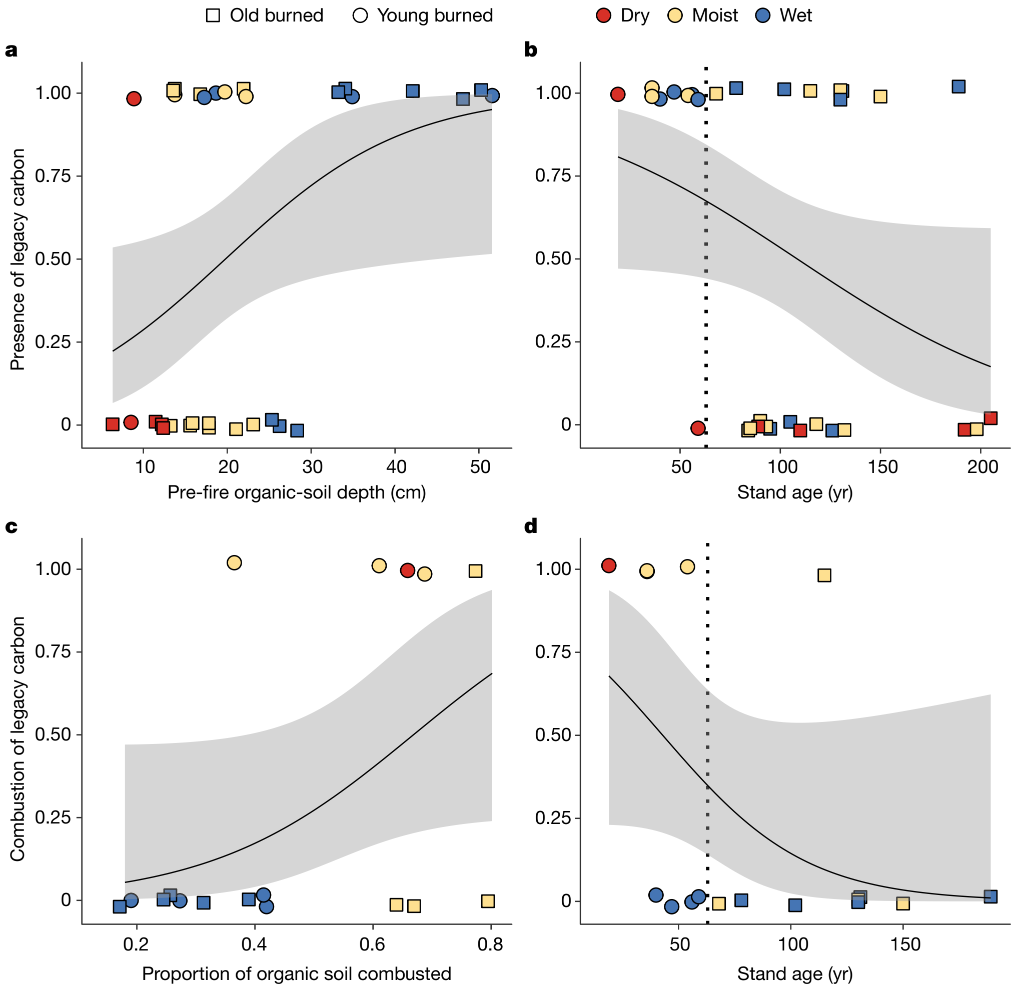

Fig. 3 | Predicted presence and combustion of legacy carbon. **a**–**d**, Data are grouped according to stand age at the time of fire (old or young burned) and moisture (dry, moist or wet). Shading represents the 95% prediction intervals and symbols are staggered for visual differentiation. The vertical dotted line represents the age threshold used to differentiate between young burned and old burned plots. The presence of legacy carbon was modelled as a function of pre-fire organic-soil depth (**a**) and stand age at the time of burning (**b**; pseudo-R^2 of 0.26, $n = 32$ plots). The combustion of legacy carbon was modelled as a function of the proportion of organic soil combusted (**c**) and stand age at the time of burning (**d**; pseudo-R^2 of 0.43, $n = 17$ plots). See Extended Data Table 1 for model results.

which is characteristic of wetter ecosystems[19], in 8 of the 9 young burned plots and in 9 of the 23 old burned plots (Fig. 3b). When the pre-fire organic-soil depth was less than 30 cm (7 young burned and 18 old burned plots), proportionally more young burned plots (86%) harboured legacy C than old burned plots (22%). We attribute the high proportion of young burned plots harbouring legacy C to the younger ages of the plots at the time of burning, and not to the presence of older organic-soil C, because the $\Delta^{14}C$ values of the basal increments (see Methods) did not differ between young and old burned plots (Extended Data Table 2). This signifies that younger and older stands experienced similar cycles of organic soil combustion and accumulation before the most recent disturbance event.

In the majority of the sampled plots (21 out of 32), all of the organic soil that had accumulated since 1966 combusted (Fig. 2d, e). Of the 17 plots that harboured legacy C, we found evidence of its combustion in 5 plots, all of which had residual soil surfaces that pre-dated 1966 (Fig. 2f–i). In support of our hypotheses, the probability of legacy C loss increased with an increase in the proportion of pre-fire organic soil combusted ($P < 0.05$) and decreased with stand age ($P < 0.05$) (Fig. 3c, d, Extended Data Table 1). Across all plots, an average of 48% of pre-fire organic soil was combusted. Among the 7 plots with more than 48% combustion, legacy C loss occurred in 4 plots (57%), all of which were classed as dry or moist. Among the remaining 10 plots with less than 48% combustion, only 1 plot (10%) exhibited legacy C loss. This plot was classified as moist, whereas the 9 plots with no legacy C loss were classed as wet (Fig. 3c).

Legacy C was most likely to be lost from stands that were young at the time of fire (Fig. 3d); it was lost from half of the young burned plots, but from only 1 of the 11 old burned plots, that had it (Fig. 3d). However, young burned plots classed as wet were still resistant to legacy C combustion and thus accumulated C over the fire-succession cycle, even in this record-setting fire year.

Burn depth and C emissions were similar, regardless of legacy C combustion (Extended Data Table 3). These results suggest that legacy C combustion in young burned plots is due to its more shallow position in the organic soil, because the shorter time between consecutive fires limited organic-soil accumulation. Furthermore, the $\Delta^{14}C$ values of residual soil surface increments in young burned plots were similar to those of the old burned plots, and these soil surface increments had $\Delta^{14}C$ values greater than zero (Extended Data Table 2). This demonstrates that relatively young legacy C combusted and that the amount of organic-soil C lost during the latest fire was higher than that accumulated since the previous fire but lower than the amount accumulated over preceding fire intervals. Taken together, our results suggest that an increase in fire frequency (that is, shortened interval between fires, resulting in more young burned forests) will be an important determinant of future legacy C loss. It follows that measuring the magnitude of C emissions alone is insufficient for assessing the long-term impacts of wildfire on the net carbon balance of boreal ecosystems.

The limited evidence that we found of legacy C combustion in old burned plots suggests that these plots were either neutral or a net carbon sink relative to the atmosphere since the previous fire event. Young burned plots were much more likely to experience legacy C combustion and act as a net source. In the 2014 wildfires in the Northwest Territories, Canada, approximately 0.77 ± 0.07 Mha (27%) of the burned forest area were <60 years old at the time of fire (ha, hectare; 1 ha $= 10^4$ m^2; all uncertainties are mean $\pm$ s.e.m.). As legacy C combusted in roughly 45% of the young burned plots, we estimate that 0.34 ± 0.03 Mha (12%) of forests were vulnerable to legacy C combustion and emitted approximately 8.62 ± 1.05 Tg C during the 2014 fire season. These emissions amount to more than 20% of the mean annual net ecosystem production in boreal forests across the globe over the period 1997–2006 (41 Tg C yr^{-1})[23]. Although the amount of legacy C combusted from the 2014 fires in the Northwest Territories is small relative to mean annual global C emissions from fires (about 2.2 Pg C yr^{-1} during 1997–2016)[24], our results highlight the importance of considering the type of C that is emitted when evaluating the impacts of fire on the global C cycle. The majority of global fire emissions come from tropical savannahs that re-sequester their C within months or years. Recent results suggest that even these ecosystems may experience multi-decadal decreases in soil C with increased fire frequency[25]. Similarly, legacy C emissions from increasing fire frequency in boreal forests, which take a century to re-sequester, represent a fundamental switch from a long-term carbon sink to a source.

Our application of soil radiocarbon dating enabled us to assess both the presence and combustion of legacy C in boreal forest ecosystems at a landscape scale. We found that legacy C never accumulates in dry stands because of complete combustion, whereas in wet stands it readily accumulates in deep organic soils that burn at low severity. Despite these moisture-driven variations, it is the burning of young aged stands that renders legacy C vulnerable to combustion and shifts forests into a new domain of C cycling. This new domain is a product not only of legacy C loss in the disturbance event but also of the residual legacy C being exposed to decomposition[26] between fire events, which acts to further accelerate C loss to the atmosphere. Although our inference is limited to North American boreal black spruce forests, Eurasian boreal forests that experience stand-replacing fire regimes[27] and even infrequently burned tundra ecosystems[21] have similarly stratified organic soils, where age increases with depth, and may also be vulnerable to legacy C loss as fire regimes shift. The frequency of boreal forest fires is projected to increase even more with expected climate warming and drying[28] and, as a result, the total burned area is expected to increase to 130%–350% by mid-century[29]. These changes will increase the proportion of young forests vulnerable to burning and increase both the loss of legacy C per unit area burned and the expanse of forests transitioning from net C uptake over consecutive fire intervals to net C loss. Accounting for fire frequency and associated legacy C loss is therefore important for assessing the effects of wildfire on the future boreal net ecosystem carbon balance and its impacts on the global C cycle and the climate.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-019-1474-y.

Received: 16 October 2018; Accepted: 3 July 2019;
Published online 21 August 2019.

1. Bond-Lamberty, B., Peckham, S. D., Ahl, D. E. & Gower, S. T. Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature* **450**, 89–92 (2007).
2. Walker, X. J. et al. Cross-scale controls on carbon emissions from boreal forest megafires. *Glob. Change Biol*. **24**, 4251–4265 (2018).
3. Amiro, B. D. et al. Direct carbon emissions from Canadian forest fires, 1959–1999. *Can. J. For. Res*. **31**, 512–525 (2001).
4. Chapin, F. S. et al. Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems* **9**, 1041–1050 (2006).
5. Kasischke, E. S. & Turetsky, M. R. Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. *Geophys. Res. Lett*. **33**, 09703 (2006).
6. Balshi, M. S. et al. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Glob. Change Biol*. **15**, 578–600 (2009).
7. de Groot, W. J., Flannigan, M. D. & Cantin, A. S. Climate change impacts on future boreal fire regimes. *For. Ecol. Manage*. **294**, 35–44 (2013).
8. Li, F., Lawrence, D. M. & Bond-Lamberty, B. Impact of fire on global land surface air temperature and energy budget for the 20th century due to changes within ecosystems. *Environ. Res. Lett*. **12**, 044014 (2017); corrigendum **12**, 069501 (2017).
9. Johnstone, J. F. et al. Fire, climate change, and forest resilience in interior Alaska. *Can. J. For. Res*. **40**, 1302–1312 (2010).
10. Kelly, R. et al. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proc. Natl Acad. Sci. USA* **110**, 13055–13060 (2013).
11. Johnson, E. A. *Fire and Vegetation Dynamics* (Cambridge Univ. Press, 1992).
12. Little, D., Farrell, E. & Collins, J. Land-use legacies and soil development in semi-natural ecosystems in the marginal uplands of Ireland. *Catena* **30**, 83–98 (1997).
13. Rogers, B. M., Soja, A. J., Goulden, M. L. & Randerson, J. T. Influence of tree species on continental differences in boreal fires and climate feedbacks. *Nat. Geosci*. **8**, 228–234 (2015).
14. Turetsky, M. R. et al. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nat. Geosci*. **4**, 27–31 (2011).
15. Boby, L. A., Schuur, E. A., Mack, M. C., Verbyla, D. & Johnstone, J. F. Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest. *Ecol. Appl*. **20**, 1633–1647 (2010).
16. Lorenz, K. & Lal, R. in *Carbon Sequestration in Forest Ecosystems* (eds Lorenz, K. & Lal, R.) 159–205 (Springer, 2010).
17. Harden, J. W. et al. The role of fire in the boreal carbon budget. *Glob. Change Biol*. **6**, 174–184 (2000).
18. Hoy, E. E., Turetsky, M. R. & Kasischke, E. S. More frequent burning increases vulnerability of Alaskan boreal black spruce forests. *Environ. Res. Lett*. **11**, 095001 (2016).
19. Walker, X. J. et al. Soil organic layer combustion in boreal black spruce and jack pine stands of the Northwest Territories, Canada. *Int. J. Wildland Fire* **27**, 125–134 (2018).
20. Johnstone, J. F., Hollingsworth, T. N. & Chapin, F. S. *A Key for Predicting Postfire Successional Trajectories in Black Spruce Stands of Interior Alaska*. General Technical Report PNW-GTR-767 (US Department of Agriculture, 2008).
21. Mack, M. C. et al. Carbon loss from an unprecedented Arctic tundra wildfire. *Nature* **475**, 489–492 (2011).
22. Levin, I. & Hesshaimer, V. Radiocarbon – a unique tracer of global carbon cycle dynamics. *Radiocarbon* **42**, 69–80 (2000).
23. Hayes, D. J. et al. Is the northern high-latitude land-based CO_2 sink weakening? *Glob. Biogeochem. Cycles* **25**, GB3018 (2011).
24. van der Werf, G. R. et al. Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data* **9**, 697–720 (2017).
25. Pellegrini, A. F. A. et al. Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. *Nature* **553**, 194–198 (2018).
26. Schuur, E. A. G. et al. Climate change and the permafrost carbon feedback. *Nature* **520**, 171–179 (2015).
27. Minayeva, T. Yu. et al. Carbon accumulation in soils of forest and bog ecosystems of southern Valdai in the Holocene. *Biol. Bull*. **35**, 524–532 (2008).
28. Young, A. M., Higuera, P. E., Duffy, P. A. & Hu, F. S. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography* **40**, 606–617 (2017).
29. Yue, X. et al. Impact of 2050 climate change on North American wildfire: consequences for ozone air quality. *Atmos. Chem. Phys*. **15**, 10033–10055 (2015).

METHODS

Field methods. In the summer of 2015, we established 211 burned plots in 7 spatially independent burn scars: 4 in the Taiga Plains ecozone and 3 in the Taiga Shield ecozone of Northwest Territories, Canada[6]. Each plot consisted of two 30-m parallel transects at 2 m apart, running due north. At each plot, we recorded the latitude, longitude and elevation with a GPS receiver, and the slope and aspect with a clinometer and compass. In the field, each plot was assigned a moisture class on a six-point scale (ranging from xeric to subhygric) on the basis of topography-controlled drainage and adjusted for soil texture and presence of permafrost[2,20]. We also measured the densities and basal areas of tree species, and estimated aboveground C combustion[2]. We collected five basal tree disks in each plot. Tree disks were processed using standard dendrochronology techniques[30] and tree rings were counted as an estimate of time after the last fire[19]. We measured the depth of the residual soil organic layer (SOL) directly beside black spruce trees at ten points per plot. In association with these points, we measured the distance from the highest adventitious root height to the top of the residual SOL on 1–3 adventitious roots per tree, in order to estimate SOL burn depth[19]. At an additional ten points per plot, we measured the residual SOL. We then calculated pre-fire SOL depth (residual SOL depth plus burn depth) and the proportion of SOL combusted (burn depth divided by pre-fire SOL depth). Additionally, at five of the residual SOL measurement points we collected an intact soil monolith (5 cm $\times$ 10 cm with variable depth) of the entire depth of the residual SOL. In total, we obtained 1,025 soil monoliths, which were frozen until they could be processed at Northern Arizona University.

Laboratory methods. For radiocarbon analysis we selected 32 plots from the full dataset that were: (1) dominated by black spruce, the most abundant forest type pre-fire (171 out of 211 plots); (2) randomly distributed across the landscape (78 out of 211 plots; 'A' plots in supplementary methods of a previously published study[2]); and (3) representative of the full moisture gradient on this landscape, from xeric to subhygric. This selection of plots was designed to maximize our domain of inference and test our hypotheses. We then grouped plots into three moisture categories on the basis of the original six-point scale (dry: xeric or subxeric; moist: subxeric–mesic or mesic; wet: mesic–subhygric or subhygric). One soil monolith was randomly selected from each of these plots. The average total depth of the selected soil monoliths (mean, 10.9; s.e.m., 1.9) was not significantly different ($t = -0.53$, $P = 0.60$) from the average residual SOL (mean, 12.3; s.e.m., 1.8) in these plots. In five plots we randomly selected a second soil profile to validate the accuracy of our radiocarbon values and account for potential spatial heterogeneity within plots; in all cases the second soil profile corroborated the results of the first (Extended Data Table 4). We bisected all monoliths depth-wise using an electric carving knife and one-half of the monolith was processed to assess the residual SOL C and model the SOL C combustion[2]. From the remaining half, all of the live moss and vascular plants were sliced off and discarded. We then cut a 1-cm-deep increment from the surface of the soil monolith (surface increment) and a 1-cm-deep soil increment directly below it (2-cm increment). In addition, we cut a 1-cm-deep increment directly above the mineral soil (basal increment). There were three monoliths in which the basal increment was located above frozen organic soil instead of mineral soil. These monoliths were from wet plots in which the SOL depth was greater than 30 cm and legacy C was present (see Fig. 3a). There were six soil monoliths from which only two depth increments remained (that is, residual SOL less than 3 cm deep). For these monoliths, we classified the 2-cm increment as the basal increment. We froze one-half of each depth increment for archival purposes.

Given that soil age increases with depth[17,31] and considering the expense of radiocarbon dating, we chose to sample three depth increments per soil profile instead of dating the entire profile. This allowed us to maximize the number of profiles that we could analyse in order to test our hypotheses about landscape patterns of legacy C presence and combustion. Previous radiocarbon dating of boreal and tundra soils have used either moss macrofossils[21] or a combination of moss macrofossils and bulk soil[31,32], and similar dates were found for soil and macrofossil samples[32]. We chose to isolate all particulate organic matter with diameter up to 250 μm from the bulk soil for our radiocarbon dating. In isolating this fraction from bulk soil, all of the root material was removed under a microscope to mitigate a bias from roots towards younger ages, and all of the heavier mineral soils were removed to prevent an older-age bias[33]. We believe that this isolated fraction represents material that accrued at that increment depth and at that point in time. Given that all of the increments were taken from organic soil (carbon content greater than 20%)[2], where the mineral soil content was very low, age estimates from this fraction are probably biased towards young ages because of newer plant material inputs that cannot be removed through visual inspection. This would make our estimates of legacy C presence and combustion conservative.

We isolated all of the particulate organic matter <250 μm from the bulk soil by removing the roots, shaking the soil increment in a Nanopure water system for 2 h and passing the soil–water solution through a 250-μm sieve onto a glass microfibre filter. We vacuum-filtered and oven-dried the filter at 60 °C for 24 h. We then weighed 3–12 mg of the isolated fraction into a quartz tube, topped it with ~0.1 g of cupric oxide and vacuum-sealed the tube. These tubes were then heated in a muffle furnace at 900 °C for 2 h. The carbon dioxide produced was then cryogenically purified under vacuum, and ~0.7–1.0 mg C was subsampled for graphitization. The samples were converted to graphite at 550 °C with an iron catalyst in a hydrogen atmosphere[34] at Northern Arizona University. Our primary standard for ^{14}C analysis is NIST oxalic acid II (SRM 4990C, National Institute of Standards and Technology). For a secondary standard, we used FIRI-D and FIRI-G (Fourth International Radiocarbon Inter-comparison). Our blank was anthracite coal cleaned with a standard acid–base–acid treatment. All of the standards and radiocarbon blanks used for the ^{14}C measurements were combusted and purified similarly to the samples. The ^{14}C content of the graphite was measured at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine. In total, we analysed 105 soil-depth increment samples from 32 plots.

Assessing legacy C presence and combustion. The vertical accumulation of boreal-forest organic soils and the downward propagation of fire combustion allow us to infer whether any legacy C was burned in a fire from the radiocarbon content of the post-fire surface SOL. Because we dated a bulk sample that represents an open system, ages assigned are not expressed in true calendar years but in a relative age metric[33]. The sharp increase in radiocarbon values that begins in 1955 and peaks in 1966 (Fig. 2a) is due to ^{14}C production by atmospheric testing of nuclear weapons and can be used for accurate dating of organic C within soil profiles[22,35]. Owing to the shape of this atmospheric bomb curve[22], the appropriate location of the radiocarbon value for the residual surface increment ('soil surface' in Fig. 2a, d, e) cannot be determined during the bomb period (1950 to present) without reference to the radiocarbon value of the 2-cm increment[21] ('soil 2 cm' in Fig. 2a, d, e). The soil surface increment was classified as 'pre-bomb-peak' if the 2-cm increment was less enriched in ^{14}C and as 'post-bomb-peak' if the 2-cm increment was more enriched in ^{14}C (Fig. 2d, e). All basal increments were pre-bomb-peak (before 1966) because they were less enriched in ^{14}C than the surface and 2-cm increments. We compared Δ^{14}C values of the basal increments to the atmospheric concentration of ^{14}C during the year in which the stand established based on tree-ring counts to assess the presence of legacy C (Fig. 2a–c). When the stand established before 1966 (Fig. 2b), legacy C was present if the Δ^{14}C value of the basal increment was lower than the Δ^{14}C value of the atmosphere during the year that the stand established. When stands established after 1966 (Fig. 2c), legacy C was present because all basal increments were pre-bomb-peak. To determine whether legacy C combusted, we compared the Δ^{14}C value of the soil surface increment to the atmospheric concentration of ^{14}C during the year in which the stand established (Fig. 2a, f–i). If a stand established before the 1966 bomb peak and the soil surface was pre-bomb-peak, then legacy C was combusted if the Δ^{14}C of the soil surface was lower than the atmospheric concentration of ^{14}C during the year in which the stand established (Fig. 2f). If a stand established after the bomb peak and the soil surface was pre-bomb-peak, then legacy C was combusted (Fig. 2g). If a stand established before the bomb peak and the soil surface was post-bomb-peak, then no legacy C combusted (Fig. 2h). If a stand established after the bomb peak and the soil surface was post-bomb-peak, then legacy C was combusted if the Δ^{14}C value of the soil surface was higher than that during the year in which the stand established (Fig. 2i). In cases in which the radiocarbon age indicated legacy C combustion, the actual amount of pre-stand-age C that was lost could not be estimated, because the location of the boundary between recent and legacy C in the pre-fire SOL is unknown and probably exhibits unconformities (that is, missing strata from past fires).

Estimation of young burned area. To determine the total area of young burned forests, polygon records from the Canadian National Burned Area Composite (NBAC)[36,37] and National Fire Database (NFD)[3,38–40] were used. Although NBAC is available only since 2004, it is more accurate than NFD. For the Northwest Territories of Canada, NFD goes back to 1965, but—according to our definition—fires that burned as far back as 1954 had the potential of exposing legacy carbon. Because of this, two approaches were taken: (1) fire records dating back to 1965 were intersected with those of the 2014 fires to determine the area of young burned forests per year, and (2) the linear relationship between the year since the fire and the area of young burned forests was calculated and used to fill in missing data (Extended Data Fig. 1). Without extrapolation to 1954, the total area of young burned forests is 0.51 Mha. With extrapolation, the total area of young burned forests is 0.76 Mha, which represents 26.83% $\pm$ 2.38% of the total area burned (Extended Data Fig. 1).

To estimate the carbon emissions associated with these young burned areas, we used the 30-m combustion product from previous studies[2,41]. Combustion was extracted from young burned polygons since 1965, and the sum was increased by 4% to account for missing imagery[41], resulting in 14.41 $\pm$ 1.21 Tg C (uncertainty derived from the combustion layers). We extrapolated this estimate from forests 49 years and younger to 50–60-year-old forests assuming the mean combustion and increase in burned area described above, resulting in an additional 4.75 ± 0.58 Tg C (uncertainty derived from combustion and extrapolated burned area). Finally, we assumed that 45% of these areas experienced legacy carbon combustion, resulting in 8.62 ± 1.05 Tg C.

Statistical analysis. All of the statistical analyses were performed using R statistical software (version 3.5.2)[42]. We used Firth's bias-reduced logistic regression in the R package logistf[43] to determine whether the stand age and the pre-fire SOL depth could predict the presence of legacy C ($n = 32$ plots). We used the pre-fire SOL depth because it strongly covaries with landscape moisture gradients, with wetter plots corresponding to deeper organic soil[19]. We also used Firth's bias-reduced logistic regression to assess whether the combustion of legacy C could be predicted from the stand age and the proportion of SOL that combusted, which is a measure of fire severity. This was completed on the subset of plots in which we detected legacy C ($n = 17$ plots). We scaled and centred all covariates and used Firth's logistic regression because it circumvents the problem of highly predictive covariates, which are common in logistic regression of small or sparse samples[44]. We also explored the use of mixed models, using individual fires as a random effect to account for spatial non-independence, but these analyses involved neither quantitative nor qualitative changes in our results (Extended Data Table 5). For both models, we first tested for an interaction among covariates using the Akaike Information Criterion for the selection[45] of the full model (with interaction) against the reduced model (no interaction). In both cases we were able to drop the interaction and only model marginal effects (Akaike weight of the reduced model greater than 0.9)[45,46]. For each model, we obtained the logarithmic likelihoods (loglik) for the intercept-only model (null) and the model of interest (model) in the package logistf. We then calculated McFadden's pseudo-R^2 as [1−loglik(model)]/loglik(null) (ref. [47]). To assess whether the Δ^{14}C values of the basal soil depth increments ($n = 32$), which are representative of the age of legacy C, were different for young burned plots ($n = 9$) and old burned plots ($n = 23$), we completed an independent t-test in the R base package. We also used independent t-tests to assess the difference in residual-soil-surface Δ^{14}C values between young and old burned plots classified as pre-bomb-peak ($n = 21$ plots; 16 old and 5 young) and post-bomb-peak ($n = 11$ plots; 7 old and 5 young).

Data availability

The raw data are included in Fig. 2 and are available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)[48]. Data for emissions are archived at ORNL DAAC[41,48].

Code availability

The R code for emissions is archived with the original publication[2]. The R code used for all analyses in this study is available from the corresponding author upon request.

30. Cook, E. R. & Kairiukstis, L. *Methods of Dendrochronology: Applications in the Environmental Sciences* (Springer Science and Business Media, 1990).
31. Trumbore, S. E. & Harden, J. W. Accumulation and turnover of carbon in organic and mineral soils of the BOREAS northern study area. *J. Geophys. Res. Atmos.* **102**, 28817–28830 (1997).
32. Melvin, A. M. et al. Differences in ecosystem carbon distribution and nutrient cycling linked to forest tree species composition in a mid-successional boreal forest. *Ecosystems* **18**, 1472–1488 (2015).
33. Trumbore, S. E. et al. in *Radiocarbon and Climate Change: Mechanisms, Applications and Laboratory Techniques* (eds Schuur, E. A. G. et al.) 279–315 (Springer, 2016).
34. Vogel, J. S., Southon, J. R. & Nelson, D. E. Catalyst and binder effects in the use of filamentous graphite for AMS. *Nucl. Instrum. Methods Phys. Res. B* **29**, 50–56 (1987).
35. Schuur, E. A. G., Druffel, E. R. & Trumbore, S. E. *Radiocarbon and Climate Change: Mechanisms, Applications and Laboratory Techniques* (Springer, 2016).
36. de Groot, W. J. et al. Estimating direct carbon emissions from Canadian wildland fires. *Int. J. Wildland Fire* **16**, 593–606 (2007).
37. Fraser, R. H., Li, Z. & Cihlar, J. Hotspot and NDVI differencing synergy (HANDS): a new technique for burned area mapping over boreal forest. *Remote Sens. Environ.* **74**, 362–376 (2000).
38. Burton, P. J., Parisien, M.-A., Hicke, J. A., Hall, R. J. & Freeburn, J. T. Large fires as agents of ecological diversity in the North American boreal forest. *Int. J. Wildland Fire* **17**, 754–767 (2008).
39. Parisien, M.-A. et al. Spatial patterns of forest fires in Canada, 1980–1999. *Int. J. Wildland Fire* **15**, 361–374 (2006).
40. Stocks, B. J. et al. Large forest fires in Canada, 1959–1997. *J. Geophys. Res.* **107**, 8149 (2002).
41. Walker, X. J. et al. ABoVE: wildfire carbon emissions and burned plot characteristics, NWT, CA, 2014–2016. *ORNL DAAC* https://doi.org/10.3334/ORNLDAAC/1561 (2018).
42. R Development Core Team. R: a language and environment for statistical computing (2018).
43. Heinze, G., Ploner, M., Dunkler, D. & Southworth, H. logistf: Firth's bias-reduced logistic regression (2016).
44. Heinze, G. & Schemper, M. A solution to the problem of separation in logistic regression. *Stat. Med.* **21**, 2409–2419 (2002).
45. Burnham, K. P. & Anderson, D. R. *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach* (Springer Science and Business Media, 2003).
46. Burnham, K. P., Anderson, D. R. & Huyvaert, K. P. AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. *Behav. Ecol. Sociobiol.* **65**, 23–35 (2011).
47. Hosmer, D. W., Lemeshow, S. & Sturdivant, R. X. *Applied Logistic Regression* (John Wiley & Sons, 2013).
48. Walker, X. J. et al. ABoVE: characterization of carbon dynamics in burned forest plots, NWT, Canada, 2014. *ORNL DAAC* https://doi.org/10.3334/ORNLDAAC/1664 (2019).

Acknowledgements This project was supported by funding awarded to M.C.M. from NSF DEB RAPID grant number 1542150, and from the NASA Arctic Boreal and Vulnerability Experiment (ABoVE) Legacy Carbon grant NNX15AT71A; by NSERC Discovery Grants to J.F.J. and M.R.T.; by Government of the Northwest Territories Cumulative Impacts Monitoring Program Funding project number 170 to J.L.B.; by an NSERC-PDF to N.J.D.; and by Polar Knowledge Canada's Northern Science Training Program funding awarded to Canadian field assistants. Logistical and financial support was provided through the Government of the Northwest Territories–Wilfrid Laurier University Partnership Agreement.

Author contributions M.C.M. conceived the study with help from S.G., J.F.J., E.A.G.S. and X.J.W. M.C.M., X.J.W., J.F.J., M.R.T., J.L.B., S.G.C. and N.J.D. designed the field sampling. X.J.W. and N.J.D. collected the field data. X.J.W. and C.E. completed the laboratory work with technical support from M.C.M. and E.A.G.S. X.J.W. analysed the data with help from M.C.M. and E.A.G.S. B.M.R. and S.P. provided the data and wrote the Methods section 'Estimation of young burned area'. X.J.W. wrote the manuscript and all co-authors edited the manuscript.

Competing interests The authors declare no competing interests.

Additional information

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Peer review information *Nature* thanks Mary Edwards and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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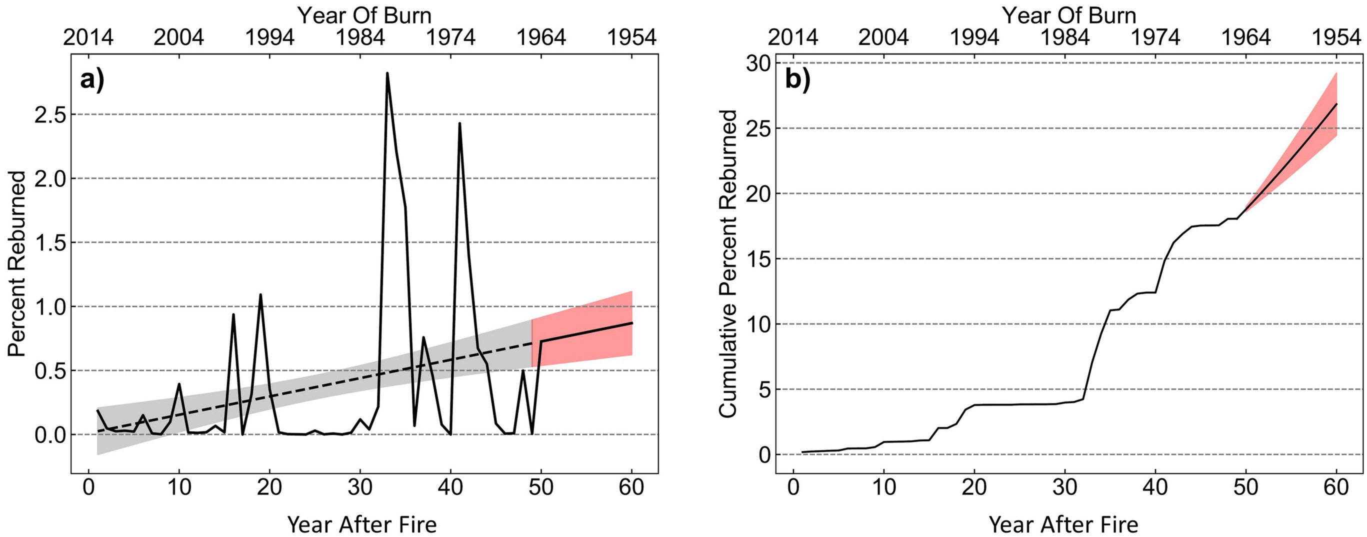

Extended Data Fig. 1 | Area burned in the 2014 wildfires in the Northwest Territories of Canada that was considered as young burned (younger than 60 years at the time of fire). **a**, **b**, Percentage (**a**) and cumulative percentage (**b**) of area burned in the 2014 wildfires, expressed in years since the fire and year of burn. In **a**, the dashed line represents the best fit between the observed values in the fire databases and the solid line represents the linear extrapolation to 1954. Grey shading indicates the standard error of the observed values and red shading indicates the predicted standard error ($y = 0.01430x + 0.01097$; $R^2 = 0.09$; $P < 0.05$).

Extended Data Table 1 | Firth's bias-reduced logistic regression results

Model	Variables	Coeff ± st.error	X^2	p-value	95% CI
Legacy C presence	Intercept	0.194 ± 0.425	0.219	0.637	-0.62, 1.07
	Pre-fire SOL Depth	1.168 ± 0.579	6.392	0.011**	0.22, 2.63
	Stand Age	-0.890 ± 0.479	4.577	0.032**	-1.97, -0.07
Legacy C combustion	Intercept	-1.439 ± 0.875	4.240	0.039	-4.18, -0.06
	Proportion SOL Combusted	1.43916 ± 0.886	4.498	0.033**	0.1, 4.42
	Stand Age	-1.550 ± 0.978	4.012	0.045**	-4.68, -0.03

Results shown for modelling: (1) the presence of legacy C as a function of pre-fire SOL depth (in centimetres) and stand age at the time of fire (years) and (2) legacy C combustion as a function of the proportion of SOL combusted (0–1) and stand age at the time of fire (years). Coeff, coefficient; st. error, standard error; CI, confidence interval.
**$P < 0.05$.

Extended Data Table 2 | *t*-test results

Model		Young (<60 years)	Old (>60 years)	*t-stat*	df	p-value	95% CI
$\Delta^{14}C$ of basal soil increment		-17.7	-18.7	-0.04	13.71	0.97	-96.41, 93.26
$\Delta^{14}C$ of soil surface increment	Pre-bomb	103.21	67.08	1.26	8.89	0.24	-28.77, 101.02
	Post-bomb	92.03	86.47	-0.13	3.52	0.90	-129.27, 118.16

Comparison of mean $\Delta^{14}C$ values of soil basal increments between old burned and young burned plots and of the residual soil surface increments between old burned and young burned plots for both pre-bomb-peak and post-bomb-peak increments. t-stat, *t*-statistic; df, degrees of freedom.

Extended Data Table 3 | SOL depth and carbon in pre-fire and burned pools

		Stand age category	# of plots	Burn depth (cm)	Pre-fire SOL depth (cm)	SOL C combusted (g C m^{-2})	Prefire SOL C (g C m^{-2})	Stand age (years)
Legacy C Presence	No	Old (>70 years)	14	8.2 ± 0.77	17.6 ± 1.7	3,054 ± 327	6,836 ± 826	123 ± 11
	Yes		9	11.6 ± 0.9	30.4 ± 4.8	5,174 ± 695	14,915 ± 3,187	122 ± 12
	No	Young (<60 years)	1	4.3	8.5	1,873	3,198	59
	Yes		8	8.8 ± 0.8	23.4 ± 4.8	2,891 ± 203	8,361 ± 1,379	43 ± 5
Legacy C Combustion	No	Old (>70 years)	8	11.7 ± 1.0	32.5 ± 5.0	5,384 ± 752	16,216 ± 3,299	122 ± 14
	Yes		1	10.6	13.8	3,485	4,505	115
	No	Young (<60 years)	4	8.7 ± 0.6	30.6 ± 8.1	2,816 ± 162	9,968 ± 2,210	50 ± 4
	Yes		4	9.0 ± 1.7	16.1 ± 3.0	2,966 ± 403	6,753 ± 1,505	36 ± 7
All black spruce dominated sites			171	9.39 ± 0.21	24.76 ± 1.11	3,508 ± 129	11,850 ± 774.7	109 ± 3

Data grouped according to stand age at the time of fire and the presence or combustion of legacy carbon. Values for all black-spruce-dominated plots originally sampled are also presented. Values are shown as mean ± s.e.m.

Extended Data Table 4 | Comparison between $\Delta^{14}C$ values of two soil profiles in five sites

Plot	Young/Old	Δ14C stand age	soil profile #	surface increment	2cm increment	basal increment	Legacy C present	Legacy C combusted
SS33-3A	Old	-12.88	0	71.4	81.2	40.9	0	na
			12	37.9	111.2	46.3	0	na
ZF20-10A	Old	-15.7	12	99.7	38.4	61.7	0	na
			18	182.6	113.7	21.9	0	na
ZF20-9A	Old	-15.23	0	177.2	96.2	23.4	0	na
			12	187.1	87.3	65.4	0	na
ZF35-11A	Young	2.3	0	107.6	82.4	-134.8	1	0
			12	27.6	20.7	-310.2	1	0
ZF46-5A	Old	-3.1	12	194.5	134.1	55.8	0	na
			24	124.9	94.9	11.3	0	na

$\Delta^{14}C$ values for the surface increment, the 2-cm increment directly below the surface and the basal increment directly above the mineral soil for five plots (one young and four old) where we obtained two soil profiles ('soil profile #' refers to the meter location on the sampling transect). The $\Delta^{14}C$ values of the atmosphere at the time of stand establishment ($\Delta^{14}C$ stand age) are provided for comparison with the basal increment, in order to determine the presence of legacy C (0, absent; 1, present), and with the 1-cm increment, in order to determine whether legacy C was combusted (0, absent; na, not applicable), which was completed only when legacy C was detected.

Extended Data Table 5 | Results of Firth's bias-reduced, mixed-effect model and simple logistic regression

Model	Legacy C presence			
	Variables	Coeff + st.error	X^2 or Z-value	p-value
Firth's bias reduced	Intercept	0.19 ± 0.43	0.23	0.63
	Pre-fire SOL Depth	1.17 ± 0.58	6.39	0.01**
	Stand Age	-0.89 ± 0.48	4.47	0.03**
Mixed Model (fire scar-random)	Intercept	0.17 ± 0.73	0.23	0.81
	Pre-fire SOL Depth	1.48 ± 0.78	1.90	0.05*
	Stand Age	-1.37 ± 0.67	-2.05	0.04**
Simple logistic regression	Intercept	0.25 ± 0.45	0.56	0.57
	Pre-fire SOL Depth	1.46 ± 0.68	2.16	0.03**
	Stand Age	-1.07 ± 0.53	-2.04	0.04**

Results are shown for modelling the presence of legacy C (0 = no, 1 = yes) as a function of pre-fire SOL depth (in centimetres) and stand age at the time of fire (years). The X^2-test statistic is presented for Firth's biased model and a *Z*-value for the other models.
*$P < 0.1$; **$P < 0.05$.