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Overwintering fires can occur in both peatlands and upland forests with varying ecological impacts

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Climate warming is increasing the prevalence of overwintering 'zombie' fires, which are expected to occur primarily in peatlands, undermining carbon storage through deep burning of organic soils. We visited overwintering fires in Northwest Territories, Canada, and Interior Alaska, United States, and present field measurements of where overwintering fires are burning in the landscape and their impact on combustion severity and forest regeneration. Combustion severity hotspots did not generate overwintering, but peat and woody biomass smouldering both supported overwintering, leading to wintertime smouldering in both treed peatlands and upland forests. These findings create challenges for fire managers and uncertainty about carbon emissions, but forest regeneration was not compromised.

Overwintering or 'zombie' fires ignite in one fire season, smoulder over winter and re-emerge after snowmelt[1]. High-latitude warming[2] that is leading to more large, severe wildfire seasons is also conducive to more overwintering fires[3,4]. The 2023 fire season exemplifies this: extreme hot, dry conditions in Western Canada led to widespread burning (>10 Mha) and unprecedented numbers of overwintering fires (>150) and spring flare-ups, numbers that do not capture the full extent of overwintering fires as many go undetected and unreported because they do not flare up or are too small for detection. Despite growing concerns about the ecological and climate feedbacks of overwintering fires[5,6], we lack in situ information. Here, we evaluate where overwintering fires occur in the landscape, that is, treed peatlands or upland forests. We also investigated the impacts of these fires on combustion severity, postfire tree regeneration and material legacies that affect postfire forest recovery.

Overwintering fires are thought to occur primarily in peatlands where deep, carbon-rich peat can support smouldering combustion belowground for extended periods[1,3] with potential feedbacks on climate warming[1]. However, there are no field-based observations to support this expectation. To evaluate where in the landscape overwintering fires occur and their ecological impacts, we sampled 20 overwintering fire sites, without previous knowledge of the landcover in which they were burning, and nearby single-season fires that burned in the initial ignition year without overwintering. We determined the forest type in which overwintering fires burned (treed peatland versus forested upland) and the main mechanism of smouldering.

Smouldering combustion impacts material legacies, matter present in an ecosystem after disturbance[7]. Smouldering over winter in organic soils should lead to a thinner and less variable residual soil organic layer (SOL) owing to deeper soil combustion[8],

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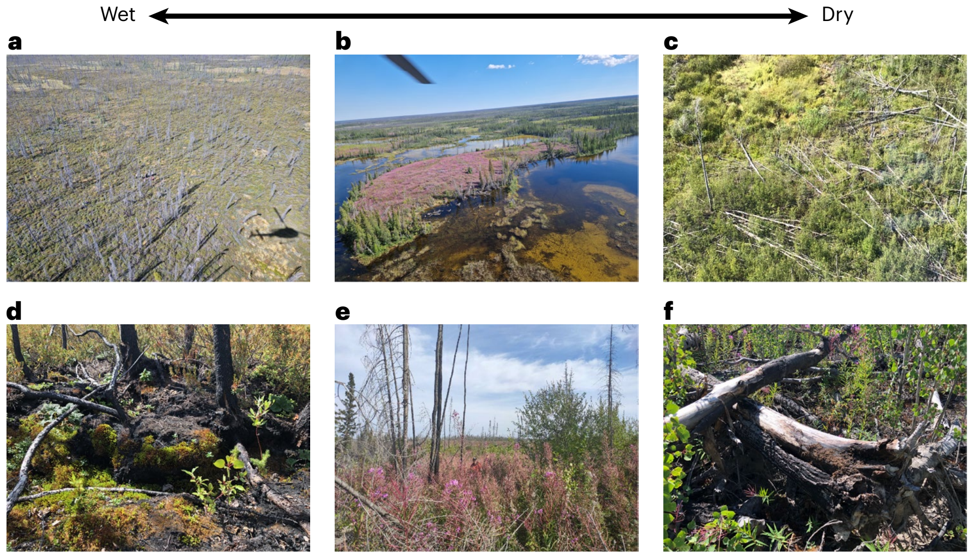

Fig. 1 | Aerial and ground images of landscape conditions in which overwintering fires occurred. a–**f**, Landscape (**a**–**c**) and corresponding ground-based (**d**–**f**) pictures of sites where overwintering fires occurred. These locations ranged from subhygric peatlands (**a**,**d**) to mesic (**b**,**e**) and xeric (**c**,**f**) productive forests. Photo credits: J.L.B. (**a**,**c**,**d**,**f**), S.V. (**b**) and Jason Paul (**e**).

modifying seedbeds[9]. Similarly, extended smouldering should accelerate postfire tree fall because smouldering combusts roots and the organic soil supporting them, owing to lower soil moisture around trees[10]. Dead-fallen versus dead-standing trees alter postfire regeneration conditions (for example, via shading), fuel structure, decomposition and wildlife use[11,12].

Recent boreal wildfires are altering forest composition (for example, conifer to broadleaf) but perhaps more worryingly, undermining regeneration entirely (that is, forest to non-forest)[9]; forests experiencing short-interval fires may be particularly vulnerable[13]. Overwintering fires could exacerbate this loss of resilience through two main mechanisms. First, greater canopy combustion resulting from burning in both the initial and overwintering fire year should reduce seed inputs and seedling establishment[14]. Second, soil heating with prolonged smouldering and subsequent flare-ups should kill seeds and seedlings on the forest floor that would have supported regrowth. These mechanisms should result in poor or failed tree regeneration. Alternatively, deeper burning and exposure of mineral soil seedbeds can improve establishment conditions for many boreal species, particularly faster-growing, broadleaf trees[15], meaning that, if seeds are available, seedling establishment and growth may be higher[9].

The largest number of overwintering fires in Interior Alaska (AK) and southern Northwest Territories (NT) since detection began in 2000[3] occurred following large fire years in 2009 (AK; 1.19 Mha) and 2014 (NT; 2.85 Mha)[16]. Overwintering fire locations[3] in these years were refined using high-resolution (30 m) Landsat images (Hessilt et al., manuscript in preparation); all locations were remote, requiring helicopter access. This led to 15 (AK) and 17 (NT) potential locations within a flight radius of ~150 km for fires overwintering into 2010 (AK) and 2015 (NT) (Extended Data Fig. 1), which were sampled in 2022 (NT) and 2023 (AK). Not all sites could be visited for logistic and safety reasons, leading to 7 and 13 sample sites in AK and NT, respectively. We sampled one site where overwintering and reburning occurred and a nearby, environmentally comparable site which experienced only single-season burning (Methods). Here, we describe landcover types that supported overwintering fires in our sampling domain (Extended Data Fig. 1) and ecological impacts with respect to combustion severity, material legacies and regeneration.

Surprisingly, only 2 of the 20 overwintering fires occurred in peatlands (SOL thickness >40 cm) and less than half supported SOL smouldering as a mechanism for overwintering (Fig. 1a,d and Supplementary Table 1). Most overwintering fires occurred in mesic to dry, productive forests with thinner prefire SOL (<29 cm; Fig. 1 and Supplementary Table 1). In many sites, most or all of the SOL had been combusted and smouldering appeared to have been supported by tree roots and boles (Extended Data Fig. 2b,c and Supplementary Table 1). Thus, overwintering fires are not limited to peatlands and are occurring more than expected in productive forests, which represented only ~30% and 15% of unburned landcover area in our sampling domains in AK and NT, respectively (Hessilt et al., manuscript in preparation). Our results suggest that smouldering over winter can be sustained by woody biomass and transmitted through the root system, given that our driest sites had insufficient SOL to sustain combustion. Previous remote-sensing studies provide mixed evidence for the suggested[1,6] colocation of overwintering fires and peatlands[3], which corroborates our field-based findings. We want to emphasize that, because of the limited sample size on which these findings are based, we cannot infer the relative importance of smouldering in peatlands versus uplands in promoting overwintering fire behaviour at the landscape scale.

Our finding that overwintering fires occur across landscape positions has implications for proposed ecological responses. First, the idea that overwintering fires experience deeper burning compared to single-season fires received mixed support; AK sites burned deeper in overwintering fires while NT sites did not (treatment × region $P = 0.0016$; Fig. 2, Extended Data Fig. 3a and Supplementary Table 2). One caveat is that the drier AK sites (four of seven) could not be included in this analysis because we were unable to estimate burn depth owing to a lack of black spruce; this may have exaggerated burn depth differences in AK. The ambiguous support for proposed differences in burn depth is not surprising given that many of our sampled fires occurred in mesic or dry sites with thinner SOL, which cannot support deep burning[17]. Overwintering fires experienced more complete SOL combustion than single-season fires in both regions (treatment $P = 0.0052$; Fig. 2, Extended Data Fig. 3b and Supplementary Table 2). Together, these findings provide some support for deeper and more complete SOL combustion with overwintering. In contrast, we found no evidence of greater aboveground combustion in overwintering fires (treatment $P = 0.2310$; Fig. 2, Extended Data Fig. 3c and Supplementary Table 2). Both single-season and overwintering fires had low aboveground combustion, with fine fuels intact in many sites

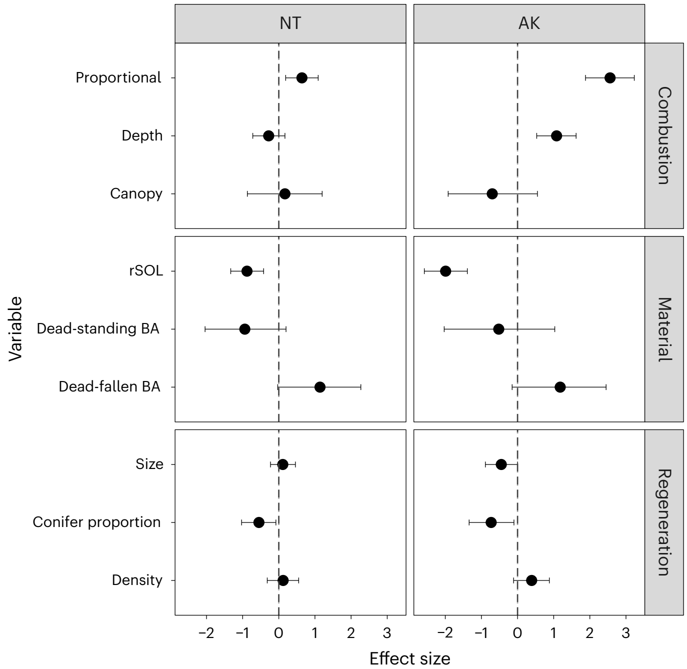

Fig. 2 | Overwintering fire effects on combustion severity, regeneration outcomes and material legacies. Effect sizes (Cohen's *D*; a standardized effect size measuring the difference between two means) and 95% confidence intervals comparing measured variables in overwintering and single-season fire sites in NT ($n = 75$ (nine overwintering and six single-season fire sites with five nested plots per site)) and AK ($n = 66$ (seven overwintering and four single-season fires sites with six nested plots per site)). Negative effect sizes indicate a larger value in single-season compared to overwintering sites while positive values indicate a larger mean value in overwintering compared to single-season sites. Variables are grouped into combustion severity (proportional combustion (%), burn depth (cm) and canopy combustion (unitless)), regeneration outcomes (recruit size (basal diameter in cm), conifer proportion in recruits (unitless) and recruit density (seedlings m^{-2})) and material legacies (rSOL thickness (cm), dead-standing BA (m^2 ha^{-1}) and dead-fallen BA (m^2 ha^{-1})) for ease of viewing. Mean values for all variables are presented in Extended Data Figs. 3, 4 and 6 and linear mixed effects model results are presented in Supplementary Table 2.

(Extended Data Fig. 2a,b). Most overwintering fires occur near fire perimeters (Hessilt et al., manuscript in preparation) where the fire intensity and spread rate will be diminished, reducing aboveground combustion. Our data support this explanation given that our combustion estimates for both single-season and overwintering fires are comparable to or lower than mean combustion rates for single-season fires in these regions[9,17]. Our data thus do not support the notion that overwintering behaviour is supported by hotspots of extreme combustion.

Our results support the idea that overwintering is supported by severe combustion of tree roots and boles. Most overwintering sites experienced near-complete stem fall (Extended Data Fig. 2e,f) whereas most stems remained standing in single-season fires (dead-fallen basal area (BA) treatment $P = 0.0379$; Fig. 2, Extended Data Fig. 4a,b and Supplementary Table 2). In NT, there was evidence of charring on the undersides of downed stems in most overwintering sites (Extended Data Fig. 2b) indicating tree fall in response to over-winter smouldering with subsequent gentle reburning, which charred the stems without consuming fine fuels. Aerial reconnaissance of 2023 overwintering fires showed complete stem fall by spring 2024, corroborating this idea (Extended Data Fig. 5). Postfire residual SOL (rSOL) was reduced in overwintering compared to single-season fires, although this was only marginally significant (treatment $P = 0.0637$; Fig. 2 and Extended Data Fig. 4c); this aligns with our finding of proportionally greater SOL combustion in overwintering fires.

Overwintering did not affect seedling growth (treatment $P = 0.2753$) or regeneration densities (treatment $P = 0.4476$; Fig. 2 and Extended Data Fig. 6a,b). Regeneration was strong across sites (7.7 ± 8.4 seedlings m^{-2}; mean ± s.d.; Extended Data Fig. 6b) and somewhat higher than postfire seedling densities in single-season fires across boreal North America (4.0 ± 11.9 seedlings m^{-2}) (ref. 9), indicating that conditions in overwintering fires do not undermine forest recovery. There were no instances of complete regeneration failure in any overwintering sites. The absence of regeneration failure suggests that overwintering fires are not sufficiently severe to limit forest recovery. There were large regional differences in postfire regeneration composition with AK having lower proportional conifer regeneration than NT (Fig. 2, Extended Data Fig. 6c and Supplementary Table 2), probably owing to a greater prefire deciduous fraction in AK sites. However, both regions saw modest increases in the proportion of deciduous recruits in overwintering compared to single-season fires (treatment $P = 0.0432$; Fig. 2, Extended Data Fig. 6c and Supplementary Table 2). This translated to postfire compositional shifts: prefire, most sites were conifer-dominated, which was not the case postfire (Extended Data Fig. 6d). These findings suggest that the main impact of overwintering fires on forest regeneration is reinforcement of the declining postfire conifer dominance observed in boreal North America[9].

Climate warming is affecting many aspects of the boreal fire regime, including increases in overwintering fires. This is concerning for fire management and ecological function; we have contributed new knowledge to both areas. Relatively low combustion severity suggests that combustion hotspots do not give rise to overwintering. We demonstrated that overwintering fires occur across landscape positions, which create distinct hazards. Prevalent combustion of tree roots and boles leads to falling trees that can endanger fire crews and increase surface fuel buildup enhancing future flammability. Similarly, peat smouldering can create pits disguised under a thin duff veneer. Ecologically, we demonstrated that overwintering fires impact aspects of combustion, material legacies and tree regeneration. However, these effects were moderate and differed somewhat between regions. Given our limited sample size, we consider two important next steps to deepen our understanding of overwintering fires. One priority arising from our work is to further evaluate the landscape distribution of overwintering fires and whether different landscape positions lead to different outcomes in terms of flare-ups and fire growth in the subsequent fire season. A second priority is to evaluate situations where overwintering fires lead to sustained smouldering into the next fire season. Our sites were limited to overwintering fires that re-ignited the following spring, as we used flare-ups for detection. However, fire managers have noted overwintering fires in northwest Canada associated with ongoing smouldering with and without flare-ups (for example, Extended Data Fig. 5). Without significant rain, this could lead to multiyear overwintering fires dominated by smouldering further modifying patterns of burning seasonality. In several years, the many overwintering fires in northwest Canada following the unprecedented 2023 fire season will be instrumental to studies examining these priorities.

Methods

Site description and sampling locations

Two field sampling campaigns were undertaken, one in 2022 in the southern Taiga Plains in NT, Canada, and one in 2023 in Interior Boreal Alaska at sites near Fairbanks (AK), United States (Extended Data Fig. 1). Both regions are home to conifer-dominated forests, black spruce (*Picea mariana*) being the shared dominant tree species, and both experience regular wildfire. These regions both capture considerable variability in parent material, soil development and landcover[18,19]. The year 2014 was a then unprecedentedly large fire season in NT with 2.85 Mha of forested land burning[20]. Similarly, 2009 led to 1.19 Mha of forested land burning in the Alaskan interior[16]. These large fire years both gave rise to the most overwintering fires since MODIS detection began in 2000 (ref. 3), providing the opportunity to evaluate overwintering fire impacts.

In each region, we sampled adjacent overwintering and single-season burn sites. For the overwintering fires, we targeted locations that had burned in the summers of 2009 and 2014, smouldered through the winter months and re-ignited in 2010 and 2015 in AK and NT, respectively. We used previous detections of overwintering fires based on satellite data and reports from fire managers to identify overwintering fires[3]. We increased the accuracy of overwintering fire locations using 30 m Landsat imagery (Hessilt et al., manuscript in preparation). Adjacent to these overwintering sites, we identified single-season burn sites from within portions of the 2009 and 2014 fires that were unaffected by overwintering. The identified single-season sampling location was also evaluated on the ground to ensure comparability in site attributes identified to be important to postfire outcomes such as prefire tree species composition and site drainage[9]. Because all sampling was conducted by helicopter, where proximal overwintering fire sampling locations were environmentally similar, we used a shared single-season fire as the unburned contrast for efficiency in flight time. In AK, a total of seven overwintering fire sites and four single-season fire sites were sampled, while nine overwintering fire sites and six single-season fires sites were sampled in NT (Extended Data Fig. 1). In NT, additional sites were visited but for safety reasons (for example, large, actively falling trees in single-season fires) were deemed unsafe to sample. However, during reconnaissance of these sites we were able to evaluate landscape position, stand type and dominant smouldering mechanism thereby expanding our sample size to 13 overwintering fire sites for the evaluation of these attributes in NT. Although helicopter access limited our sample size owing to the remote nature of the 32 identified overwintering fire locations, we visited 20 (63%). Helicopter sampling reduced the likelihood of biases in drainage conditions that can occur with road access sampling. As such, we consider this representative of overwintering sites in our sampling domain (see above).

Field data collection

Sampling methods in the two regions were largely similar but had some site-specific differences outlined below. At each sampled site, site drainage was determined following ref. 21, dominant smouldering type (SOL or tree roots/boles) was determined subjectively on the basis of evidence available on site. Specifically, sites with an existing organic layer were assumed to include peat smouldering as a mechanism of overwintering; fully combusted large roots and hollowed-out tree stems provided evidence of smouldering in woody biomass. A 30×2 m^2 belt transect was then established at each site. Overwintering fires ranged from 1,150 to 113,073 m^2 and sampling transects were fully located within these areas. In NT, where topographic relief was minimal, these transects ran south to north, while in AK transects ran parallel to the slope to avoid slope related gradients. All trees originally rooted within the belt were identified to species, scored as alive/dead and standing/fallen and measured for diameter at breast height (1.37 m). For each stand, standing and fallen BA was calculated from this tree transect. Additionally, combustion was measured on each stem. In NT, we used an ordinal score where each tree was ranked from 0 to 3: 0 = none, alive and no biomass combusted; 1 = low, only needles/leaves consumed; 2 = moderate, all foliage and most fine branches combusted; and 3 = high, most of the aboveground canopy including foliage, branches and bark combusted[20]. In AK, the percentage combustion (0%, 25%, 50%, 75% and 100%) for the stem, coarse branches, fine branches, needles/foliage and cones (if applicable) was recorded; these percentage categories correspond approximately to the ordinal score used in the NT, so data harmonization was trivial. It was not possible to distinguish trees that were fire killed in the original fire versus those that were fire killed during the overwintering fire. Along each belt transect, five (NT) or six (AK) 1×1 m^2 vegetation quadrats were established. Within these quadrats, tree recruits were identified to species, counted and basal diameter measurements made on three representative individuals per species and quadrat. Burn depth was measured using the adventitious root method adjacent to each subplot[17,22]. The black spruce nearest to each subplot was found and the height of the upper three adventitious roots (ARs) from the soil surface was measured. Many of the nearest black spruce trees were fallen, so height of the ARs was measured horizontally from AR to middle of the root ball. The rSOL thickness was also measured from soil cores at every site. It is noteworthy that there was no evidence of moss layer recovery at any sites we visited. *Ceratadon*, an early colonizing moss, was still the dominant moss cover so the rSOL measures should reflect postfire residual rather than a combination of postfire residual and early moss layer recovery. In NT, all measured sites had some black spruce allowing for the use of the adventitious root height method of estimating depth of burn. In AK, the prevalence of paper birch (*Betula neoalaskana*)-dominated stands did not permit this burn depth estimation, so measurements of burn depth and proportional combustion are limited to black spruce-dominated stands (n = 3 of 7). Following NT specific corrections, adventitious root height measurements were corrected to provide burn depth estimates[17]. Burn depth + rSOL provide prefire SOL thickness, allowing the calculation of proportional combustion (burn depth/prefire SOL). Proportional combustion is an important metric when considering regeneration outcomes (high proportional combustion means exposure of underlying mineral soil which promotes broadleaf regeneration[15]) and the potential for legacy carbon loss (if legacy carbon is present, high proportional combustion will ensure its loss[23]).

Data analysis

All analyses were conducted using the R statistical software v.4.0.3 (ref. 24). We had three response variables for each of combustion (burn depth, proportional combustion and canopy combustion), material legacies (rSOL, dead-standing BA and dead-fallen BA) and regeneration (seedling basal diameters, conifer seedling proportion and seedling density). Each of these response variables was modelled individually. All models included two main effects and their interaction: treatment (overwintering versus single-season fire) and region (NT versus AK) as we were interested in evaluating the effect of overwintering fires on these responses and whether regions varied in their response. Except for dead-standing and dead-fallen BA, all variables were modelled using linear mixed effects models (lmer in the lme4 package[25]) with a random intercept for site to account for replicated measurements within site. Linear models were used for the stand-level variables dead-standing BA and dead-fallen BA. Model residuals were visually inspected for normality and homoscedascity. Model P-values were estimated using the Satterthwaite's method in the emmeans package[26]. For ease of visualization of differences between single-season and overwintering fires, Cohen's D effect sizes were calculated for each region separately using cohens_d in the stats package.

Inclusion and ethics statement

The NT portion of this research was authorized under Northwest Territories Scientific Research License no. 17506.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The raw data for NT are available on Borealis[27] while the raw data for AK are available in the National Science Foundation-funded Bonanza Creek Long-Term Ecological Research Data Catalog[28–30].

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Author contributions

J.L.B., M.R.T., S.V., R.O., X.J.W. and M.C.M. conceived the study. J.L.B., X.J.W., S.V., M.C.M., T.D.H. and M.R.T. designed the field sampling. J.L.B., X.J.W., S.V., T.D.H., R.A.-S., M.J.v.G., E.L.O. R.C.S. and M.R.T. collected the field data. J.L.B. analysed the data. J.L.B. wrote the manuscript and all co-authors edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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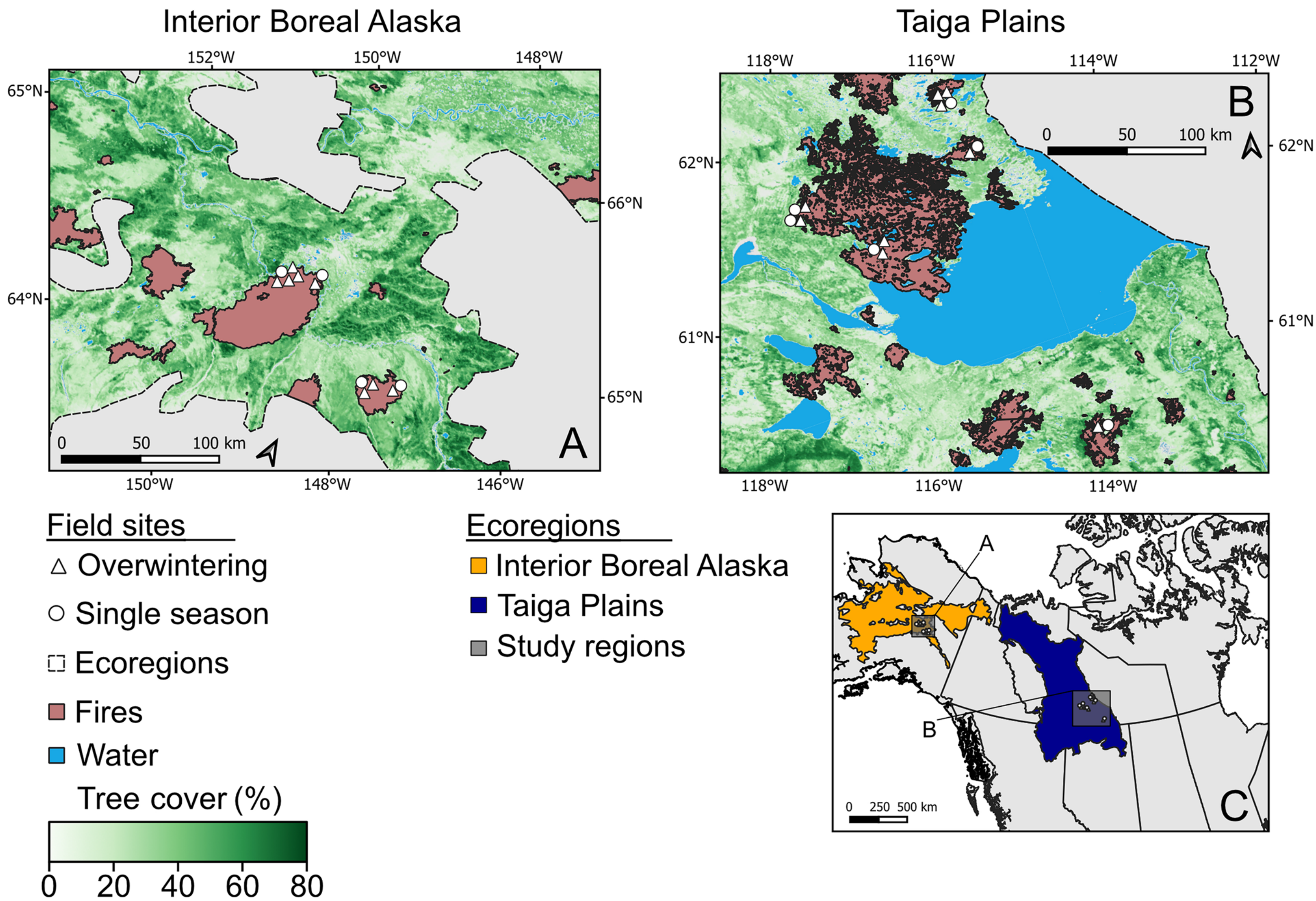

Extended Data Fig. 1 | Sampling locations within single season and overwintering fires. Locations of sampling in the Interior Boreal Alaska ecoregion of Alaska (**A**) and the Taiga Plains ecoregion of Northwest Territories (**B**). Fire perimeters for 2009 (AK)[28] and 2014 (NT)[29] within the sampling region are shown in brown. Delimitations of ecoregions are provided in panel C and follow the US EPA classification (US EPA: Ecoregions of North America [data], https://www.epa. gov/eco-research/ecoregions-north-america (last access: 15 May 2024), 2015). Green shading in A and B represent Landsat-based tree cover product from 2008 for AK and 2013 for NT[30].

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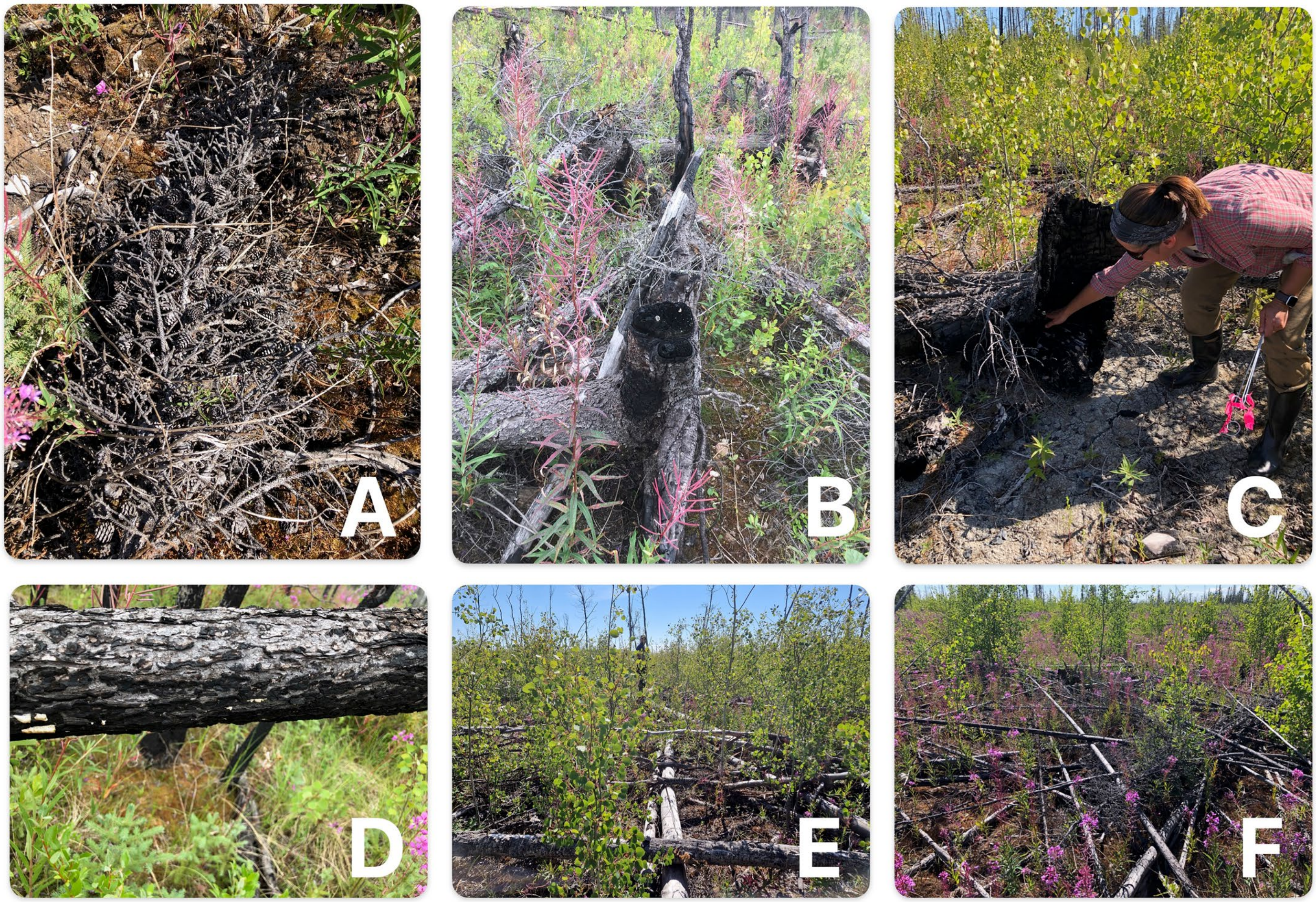

Extended Data Fig. 2 | Ground conditions in overwintering fires. Indication of low severity burning as evidenced by intact fine fuels (**A**) and light combustion on the underside of downed trees (**D**). Evidence of woody biomass smouldering as exemplified by complete combustion of large roots (**B**), boles (**C**) and frequent occurrences of complete stem fall, which was not evident in single season pairs (**E**, **F**). Photo credits: J. Baltzer (**A**,**B**, **D**-**F**), M. Turetsky (**C**).

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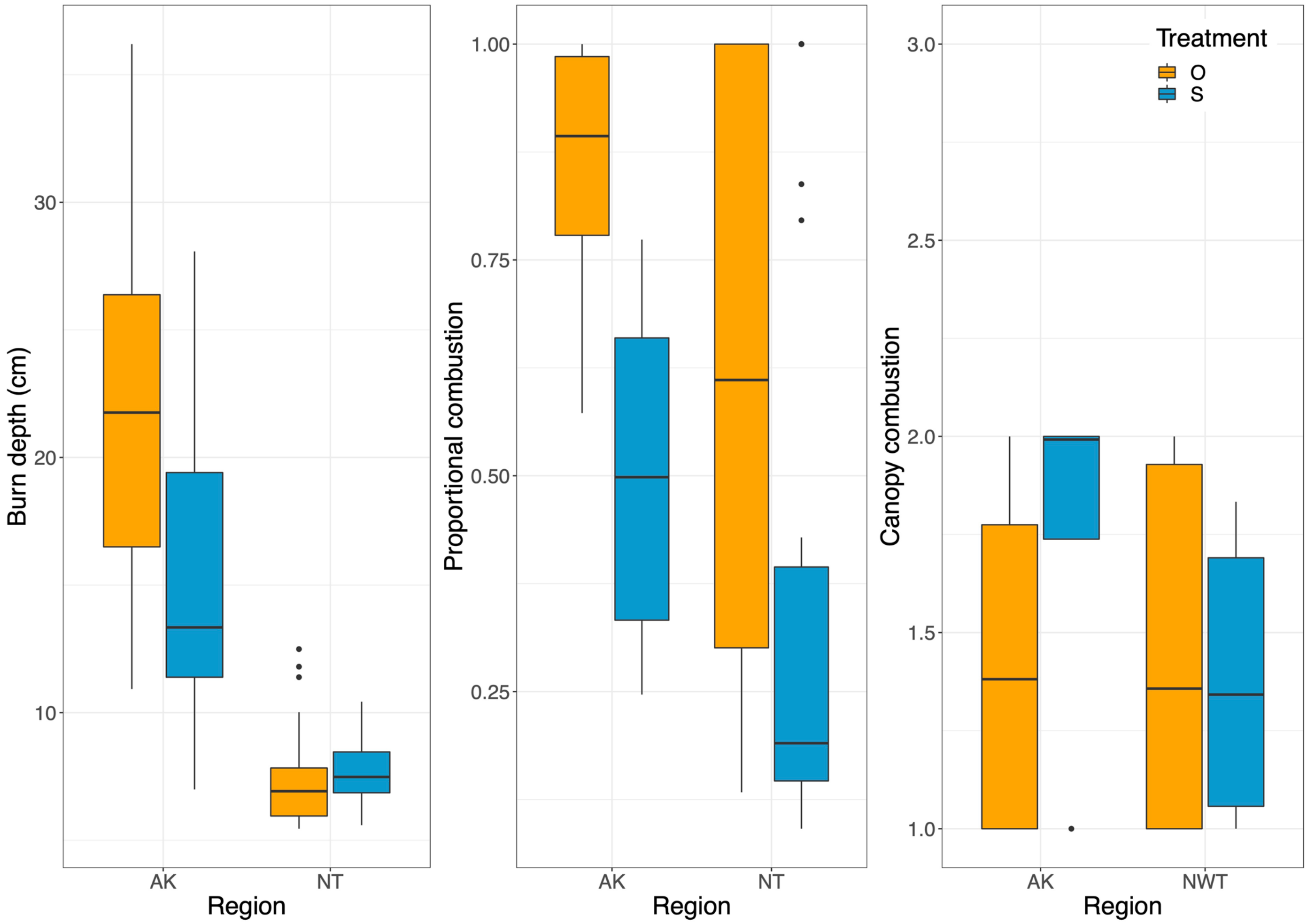

Extended Data Fig. 3 | Comparison of combustion variables between overwintering (O) and single season (S) fires in the Northwest Territories (NT) and Alaska (AK). Boxplots showing distribution of combustion variables; plots include median, 1st and 3rd data quartiles and outliers. Canopy combustion is an ordinal score where each tree was ranked from 0 to 3; 0 = none, alive and no biomass combusted; 1 = low, only needles/leaves consumed; 2 = moderate, all foliage and majority of fine branches combusted; 3 = high, most of the aboveground canopy including foliage, branches, and bark combusted. Model results are presented in Supplementary Table 2. Samples sizes for burn depth and proportional combustion were as follows: NT, n = 75 (9 overwintering and 6 single season fire sites with 5 nested plots per site] and AK, n = 66 (7 overwintering and 4 single season fires sites with 6 nested plots per site). Canopy combustion was measured at the stand level meaning n = 15 for NT and n = 11 for AK.

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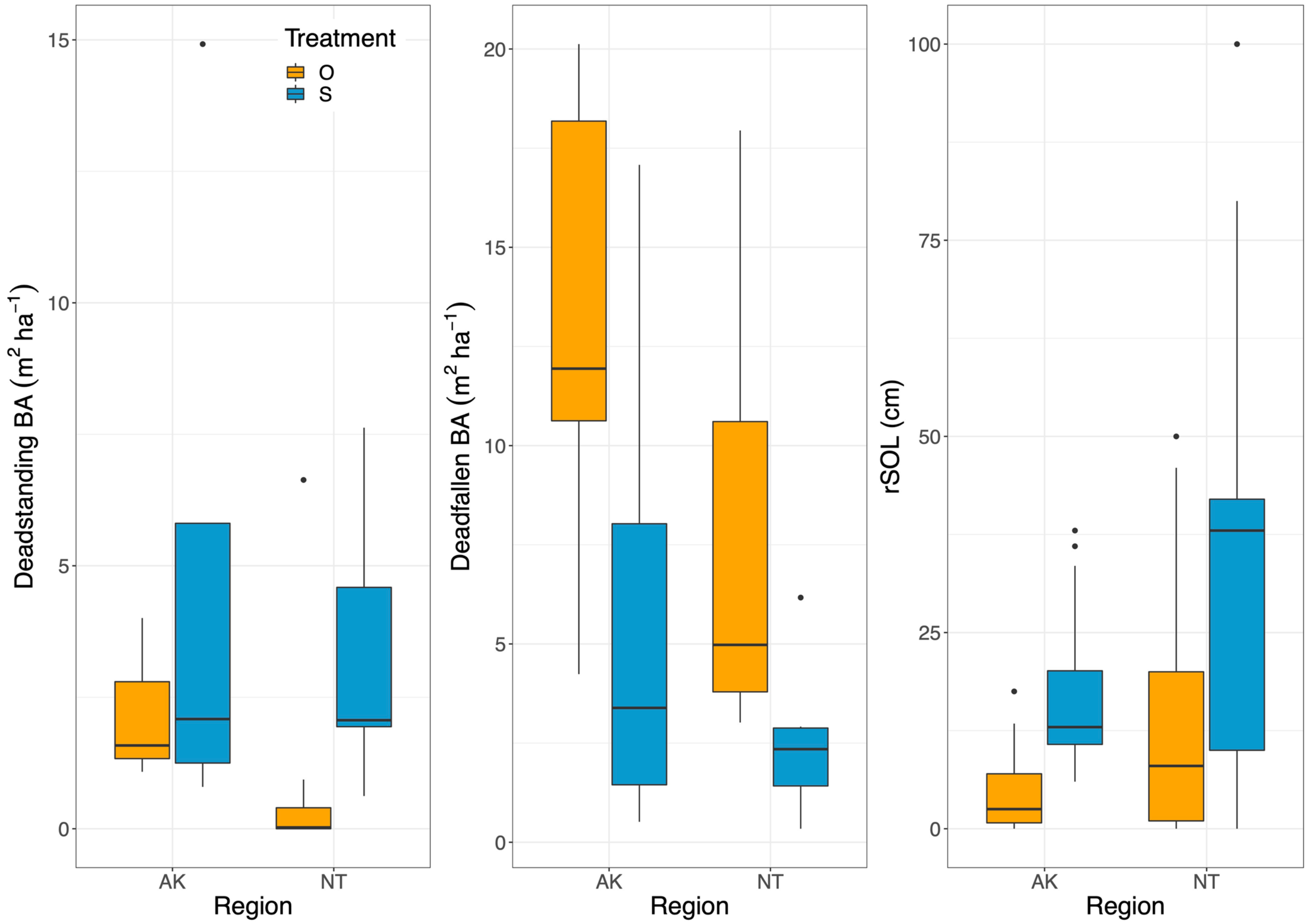
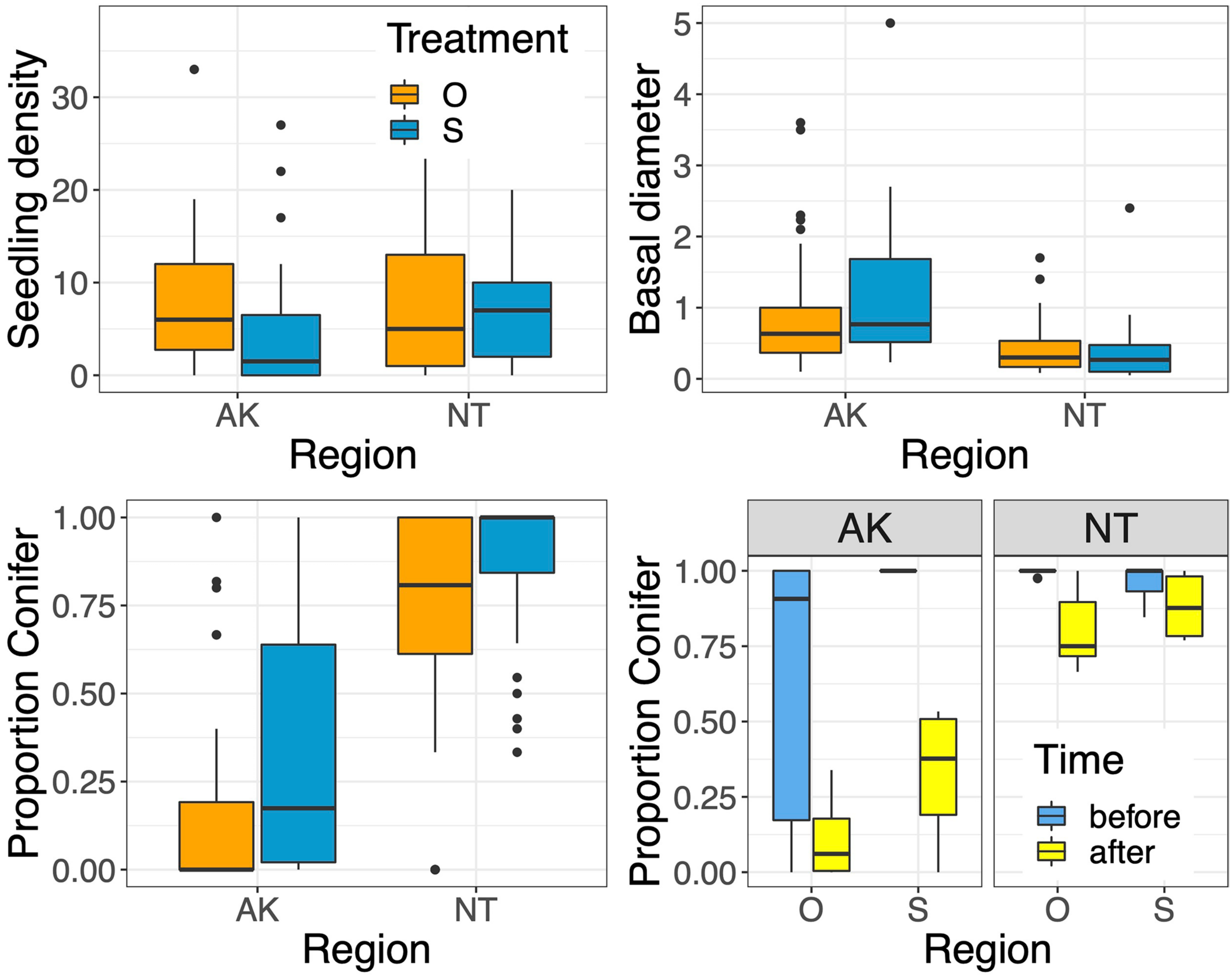


Extended Data Fig. 4 | Comparison of material legacy variables between overwintering (O) and single season (S) fires in the Northwest Territories (NT) and Alaska (AK). Boxplots showing distribution of material legacy variables; plots include median, 1st and 3rd data quartiles and outliers. Model results are presented in Supplementary Table 2. Samples sizes for residual soil organic layer thickness (rSOL) were as follows: NT, n = 75 (9 overwintering and 6 single season fire sites with 5 nested plots per site] and AK, n = 66 (7 overwintering and 4 single season fires sites with 6 nested plots per site). Deadstanding and deadfallen basal area (BA) were measured at the stand level meaning n = 15 for NT and n = 11 for AK.

 https://doi.org/10.1038/s41559-024-02630-2

Extended Data Fig. 5 | Aerial image of an overwintering fire that ignited in 2023 and continues to smoulder without a flare-up as of July 2024. This overwintering fire is at the perimeter of SS022 near Fort Smith, NT. Note the trail of downed stems leading to the current smouldering hotspot. Photo credit: Duane Sinclair, Government of the Northwest Territories Environment and Climate Change.



Extended Data Fig. 6 | Comparison of regeneration variables between overwintering (O) and single season (S) fires in the Northwest Territories (NT) and Alaska (AK). Boxplots showing distribution of regeneration variables including seedling density (seedlings m^{-2}), basal diameter (m^2 ha^{-1}), and relative abundance of conifers (proportion conifer; unitless). Samples sizes for all of these variables were as follows: NT, n = 75 (9 overwintering and 6 single season fire sites with 5 nested plots per site] and AK, n = 66 (7 overwintering and 4 single season fires sites with 6 nested plots per site). In the fourth panel, Time indicates whether the proportion conifer value is for pre-fire (before) or post-fire (after). In this plot site-level means were used as the pre-fire composition is at the site level meaning n = 15 for NT and n = 11 for AK. Plots include median, 1st and 3rd data quartiles and outliers. Model results are presented in Supplementary Table 2.

nature portfolio

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Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☐	☒	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	NA
Data analysis	Standard R scripts were used and all are specified in the text.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The raw data for NT are available on Borealis while the raw data for AK will be available on the NSF-funded Bonanza Creek Long-Term Ecological Research Data Catalog (DOI pending).

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	*Use the terms sex (biological attribute) and gender (shaped by social and cultural circumstances) carefully in order to avoid confusing both terms. Indicate if findings apply to only one sex or gender; describe whether sex and gender were considered in study design; whether sex and/or gender was determined based on self-reporting or assigned and methods used. Provide in the source data disaggregated sex and gender data, where this information has been collected, and if consent has been obtained for sharing of individual-level data; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex- and gender-based analyses where performed, justify reasons for lack of sex- and gender-based analysis.*
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Population characteristics	*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."*
Recruitment	*Describe how participants were recruited. Outline any potential self-selection bias or other biases that may be present and how these are likely to impact results.*
Ethics oversight	*Identify the organization(s) that approved the study protocol.*

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We visited overwintering fires in Northwest Territories, Canada and Interior Alaska, USA and present field measurements of where overwintering fires are burning in the landscape and their impact on combustion severity and forest regeneration. In AK, a total of seven overwintering fire sites and four single-season fire sites were sampled while nine overwintering fire sites and six single-season fires sites were sampled in NT. In NT, additional sites were visited but for safety reasons were deemed unsafe to sample. However, during reconnaissance we were able to evaluate landscape position, stand type, and dominant smoldering mechanism thereby expanding our sample size to 13 overwintering fire sites for the evaluation of these attributes in NT. At each site, 30m x 2m belt transects were established pre-fire stand structure and composition and canopy combustion severity were quantified. Additionally, 5 (NT) or 6 (AK) locations along the transect were sampled for regeneration and soil combustion severity. This led to a nested design and a hierarchical analysis approach with sample plots nested within sites.
Research sample	Two field sampling campaigns were undertaken, one in 2022 in the southern Taiga Plains in Northwest Territories, Canada (NT) and one in 2023 in Interior Boreal Alaska at sites near Fairbanks (AK). These regions both capture considerable variability in parent material, soil development and land cover. 2014 was a then unprecedentedly large fire season in NT with 2.85M ha of forested land burning. Similarly, 2009 led to 1.19M ha of forested land burning in the Alaskan interior. These large fire years both gave rise to the largest number of overwintering fires since MODIS detection began in 2000 providing the opportunity to evaluate overwintering fire impacts.
Sampling strategy	We sampled 60% of all available overwintering fire locations that arose from the 2009 (AK) and 2014 (NT). This was as much as could be accomplished given reliance on helicopters for sampling and safety limitations (e.g., actively falling trees) that negated sampling some sites.
Data collection	Data collection was conducted using ipads. Data recorder varied but teams were consistent for different parts of the measurement protocols.
Timing and spatial scale	Data collection occurred over a 2-week period in NT in 2022 and AK in 2023. Each sampling location was visited one time and all data collection completed during the visit. The timing of the sampling was a function of available funding and helicopter support.

Data exclusions	No data were excluded from analyses.
Reproducibility	Repeating the study was not possible given the tremendous cost and logistical challenges of data collection in remote northern regions. However, we did undertake the study in two distinct regions in northwestern North America which is a form of reproduction.
Randomization	Not applicable.
Blinding	Not applicable

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	The regions sampled in both the Northwest Territories and Alaska are home to conifer dominated forests, black spruce (Picea mariana) being the shared dominant tree species, and experience regular wildfire.
Location	Sampling occurred in the southern Taiga Plains (Northwest Territories) and Interior Boreal Alaska. Specific locations are provided in ED Figure 1.
Access & import/export	The NT portion of this research was authorized under Northwest Territories Scientific Research License #17506. There is no comparable licensing requirement for AK. In terms of accessing sites, all locations were helicopter access only.
Disturbance	There was no disturbance caused by our sampling methods. These are all non-destructive sampling methods.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern
☐	☒	Plants

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Dual use research of concern

Policy information about dual use research of concern

Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

No	Yes	
☒	☐	Public health
☒	☐	National security
☒	☐	Crops and/or livestock
☒	☐	Ecosystems
☒	☐	Any other significant area

Experiments of concern

Does the work involve any of these experiments of concern:

No	Yes	
☒	☐	Demonstrate how to render a vaccine ineffective
☒	☐	Confer resistance to therapeutically useful antibiotics or antiviral agents
☒	☐	Enhance the virulence of a pathogen or render a nonpathogen virulent
☒	☐	Increase transmissibility of a pathogen
☒	☐	Alter the host range of a pathogen
☒	☐	Enable evasion of diagnostic/detection modalities
☒	☐	Enable the weaponization of a biological agent or toxin
☒	☐	Any other potentially harmful combination of experiments and agents

Plants

Seed stocks	Not applicable - field based observations of plant communities
Novel plant genotypes	Not applicable - field based observations of plant communities
Authentication	Not applicable - field based observations of plant communities