

Disturbances Increase Net Carbon Emissions in the Arctic-Boreal Zone - An Expert Assessment

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Research Article

Keywords: Arctic, Boreal, Carbon, Disturbance, Expert Assessment, Permafrost

Posted Date: September 18th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11051608/v1>

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Additional Declarations: The authors declare no competing interests.

Abstract

Carbon emissions from disturbances in the Arctic-Boreal Zone (ABZ) are not adequately included in global carbon budgets due to insufficient measurements and model representation. Due to this data gap, we conducted an expert assessment to examine the potential trajectories of multiple disturbance types in the ABZ and their impacts on net carbon fluxes over the next one to three centuries. Across five disturbance categories – anthropogenic (e.g., oil and gas infrastructure), biotic, fire, abrupt permafrost thaw, and weather – experts agreed that the extent, frequency, range, and severity of disturbances will increase for at least the next century. Taken together, our assessment suggests that ABZ disturbances could result in 154–417 TgC yr⁻¹ (median expert estimates) greater net carbon emissions by 2100 relative to 2000–2020 for three climate change mitigation scenarios – global mean temperature increase held below (1) 1.5°C by 2100, (2) 2°C by 2100, and (3) Representative Concentration Pathway (RCP) 8.5 (~ 2.6–4.8°C by 2100 with rising temperatures beyond that). Critically, the experts agreed these impacts will persist long after global net zero anthropogenic emissions are reached, causing continued carbon emissions that are currently unaccounted for. Key research priorities for reducing uncertainty in these estimates were 1) improved spatio-temporal monitoring of ABZ disturbances to quantify their extent and distribution, 2) increased measurements of ecosystem carbon fluxes during and following disturbance events, and 3) incorporation of disturbance processes into models.

1. Introduction

The Arctic-Boreal Zone (ABZ) stores upwards of 1500 Pg of organic carbon in soil and vegetation (Hugelius et al. 2014; Schuur et al. 2015, 2018; Bradshaw and Warkentin 2015; Strauss et al. 2017). Biogeochemical transformation and release of even a portion of this carbon has important implications for global climate (Natali et al. 2021; Harris et al. 2022; Schuur et al. 2022). In addition to incremental changes in carbon fluxes due to gradual top-down thawing of permafrost soils in response to climate change (Schuur et al. 2022; See et al. 2024), pulse disturbance events (i.e., relatively discrete events that disrupt an ecosystem) can perturb carbon fluxes and potentially release additional sequestered carbon (Pickett and White 1985; Foster et al. 2022; Wilkinson et al. 2023; Hugelius et al. 2024; Ramage et al. 2024) that is not accounted for in process-based models or global emissions budgets (Natali et al. 2021). While ecosystems often show resilience to disturbance and can recover quickly (Heliasz et al. 2011; Lund et al. 2017; Parmentier et al. 2018), this resilience is at risk as the frequency and severity of many disturbances are expected to increase as climate change disproportionately warms the ABZ and direct human impacts increase (Wilkinson et al. 2023; Zhang et al. 2024). Although it is challenging to detect and predict disturbances (de Groot et al. 2013; Phoenix and Bjerke 2016), predicting the resulting impact on carbon fluxes is even more challenging, especially given the wide variety of disturbance types, the varied state of research and available data across them, the potential for interactions between disturbance types, and the large uncertainties associated with models. Here, we broadly categorize disturbances in the ABZ as anthropogenic, biotic, fire, abrupt permafrost thaw, and weather disturbances.

Anthropogenic disturbances are directly caused by human activity (e.g. logging, mining, and infrastructure) (Pasher et al. 2013; Becker and Pollard 2016; Foster et al. 2022; Klotz et al. 2023; Povoroznyuk et al. 2023). Anthropogenic disturbances can impact carbon fluxes over decadal scales (Foster et al. 2022) through direct and indirect effects of vegetation removal and succession (Davidson et al. 2021; Foster et al. 2022), soil disturbance (Strack et al. 2018, 2019; Davidson et al. 2020), microclimatic changes (Bayatvarkeshi et al. 2024), and permafrost thaw induced by infrastructure or vegetation removal (Dabros et al. 2018; Schneider von Deimling et al. 2021; Hjort et al. 2022). Although many anthropogenic disturbances are well documented, these data are gathered by a variety of government agencies, private companies, and nongovernmental organizations, and limited efforts exist to compile the data that are available (e.g. Pasher et al. 2013; Williams et al. 2021; Kang et al. 2021).

Biotic disturbances are caused by non-human biotic activity. They include insect outbreaks, extreme mammalian herbivory, fungal pathogens, and ecosystem engineering by beavers (Jepsen et al. 2009; Kautz et al. 2017; Tape et al. 2018; Boyd et al. 2019; Foster et al. 2022). Biotic disturbances can affect large areas (> 10,000 km²) over short periods of a year or two (Kautz et al. 2017). Insect outbreaks are becoming more frequent and severe with climate change due to a number of interacting factors, including increased winter insect survival as minimum temperatures increase (Jepsen et al. 2009), faster reproductive rates, and greater plant stress under drought conditions (Raffa et al. 2008; Bentz et al. 2010; Hansen et al. 2011; Pureswaran et al. 2018; Harvey et al. 2023). Biotic disturbances can impact carbon fluxes through direct effects on vegetation (e.g. reduced photosynthesis, mortality, shifts in succession) (Kautz et al. 2017; Boyd et al. 2019, 2021; Canelles et al. 2021; Foster et al. 2022), changes in soil structure and composition (e.g. vegetation inputs, nutrient inputs, trampling) (Lara et al. 2016; Leroux et al. 2020; Siewert and Olofsson 2021; Meyer et al. 2022), shifts in hydrology and permafrost thaw due to beaver activity (Tape et al. 2018), interactions with other disturbances (Romualdi et al. 2023), and other cascading effects (e.g. changes in albedo) (Macias-Fauria et al. 2020). Although there has been considerable research into many types of biotic disturbances, quantifying and predicting the net carbon impact remains challenging due to high spatial and temporal variability (Kautz et al. 2017), limited measurements of carbon fluxes during disturbance, and potential interactions with other forms of disturbance, particularly wildfire (Talucci and Krawchuk 2019; Talucci et al. 2020).

Fire is an integral part of boreal ecosystems and is becoming increasingly common in tundra (Rocha et al. 2012; Veraverbeke et al. 2017; McCarty et al. 2021; Phillips et al. 2022; Foster et al. 2022; Descals et al. 2022; Scholten et al. 2022; Zheng et al. 2023; Byrne et al. 2024). Annual burned area and fire intensity are increasing in the boreal zone, as lightning and extreme fire weather have increased (Kasischke et al. 2010; Veraverbeke et al. 2017; Hanes et al. 2019; Walker et al. 2020; Chen et al. 2021b; Jain and Flannigan 2021; Ellis et al. 2022; Jain et al. 2022; Descals et al. 2022; Jones et al. 2024). Fire can impact carbon fluxes directly through the combustion of organic matter in soil and vegetation (Walker et al. 2019; Phillips et al. 2022; Zheng et al. 2023; Wilkinson et al. 2023; Potter et al. 2023; Byrne et al. 2024), as well as indirectly through impacts on respiration, photosynthesis, vegetation succession (Johnstone et al. 2010; Morison et al. 2020; Guo et al. 2021; Mack et al. 2021; Bouskill et al. 2022; Kim et al. 2024b; Kelly et al. 2024), and permafrost thaw (Gibson et al. 2018; Holloway et al. 2020). Although mapping efforts for wildfire are more mature than for other ABZ disturbance types, data from Siberia are inadequate and burned area is likely underestimated (Talucci et al. 2022; Clelland et al. 2024). Additionally, bottom-up estimates of combustion emissions rely on uncertain estimates of fuel loads and emission factors, while top-down approaches are only available at coarse resolutions (Potter et al. 2023; Byrne et al. 2024). Finally, carbon impacts caused by overwintering fires, post-fire vegetation trajectories, future fire regime shifts, management decisions, and interactions with

permafrost thaw further complicate predictions of future wildfire-related emissions (McCarty et al. 2021; Treharne et al. 2022; Foster et al. 2022; Kim et al. 2024a).

Abrupt permafrost thaw occurs over years to decades due the melting of ground ice within permafrost, and results in substantial and persistent environmental change (e.g. thermokarst lakes, retrogressive thaw slumps, gas emission craters) (Kokelj and Jorgenson 2013; Foster et al. 2022; Parmentier et al. 2024; Demidov et al. 2024). Rates of abrupt permafrost thaw are increasing with increases in the frequency and intensity of extreme summer temperature and rainfall events (Kokelj et al. 2015; Lewkowicz and Way 2019; Farquharson et al. 2019) and changes in snow cover and surface hydrology (Parmentier et al. 2024). Impacts on carbon fluxes occur through shifts in hydrology, nutrient status, exposure of organic material, and vegetation composition, productivity, and mortality (Abbott et al. 2014; Malhotra and Roulet 2015; Varner et al. 2021; Rodenhizer et al. 2023), often leading to increased greenhouse gas emissions (Turetsky et al. 2020; Varner et al. 2021). Current circumpolar scale spatio-temporal data of ground ice content – a key predictor of abrupt thaw – and abrupt thaw features are available only at coarse scales (Brown et al. 1998; Olefeldt et al. 2016; Obu et al. 2019) or in particular regions (e.g. Runge et al. 2022; Yang et al. 2023). Additionally, there are limited measurements of carbon flux trajectories following thaw, including lateral transport and transformation in water (Olefeldt et al. 2016; Zolkos et al. 2022), and limited data on vegetation trajectories following abrupt thaw (Estop-Aragonés et al. 2018; Rodenhizer et al. 2022).

Weather disturbances are short-duration, extreme weather events (e.g. rain-on-snow, heat waves, windthrow, and frost drought) (Bokhorst et al. 2011; Walsh et al. 2020; Foster et al. 2022) that are increasing with climate warming and increasing weather variability (Hansen et al. 2014; Groisman et al. 2016; Vikhamar-Schuler et al. 2016; Walsh et al. 2020; Jorgenson et al. 2020; Rantanen et al. 2024). Weather disturbances influence carbon fluxes through impacts on vegetation composition, productivity, and mortality; soil organic matter decomposition; soil hydrological and thermal conditions; and permafrost state (Michaelian et al. 2011; Walsh et al. 2020; Williams et al. 2020; Mekonnen et al. 2021; Beel et al. 2021). Improved monitoring networks are needed for weather disturbances (Putkonen et al. 2009; Pan et al. 2018). Additionally, uncertainties in predictions of where, when, and which plants will succumb to weather disturbances pose challenges for understanding the carbon impact of weather disturbances (Virkkala et al. 2019; Foster et al. 2022).

While extensive research has highlighted the importance of disturbances to the ABZ carbon cycle, most of this research is case-specific, limiting generalizability. This gap in modeling and empirical research limits the incorporation of ABZ disturbances into carbon cycle models and global emissions budgets. Therefore, we used expert assessment to synthesize the knowledge and opinions of experts into quantitative estimates of the carbon impact of pulse disturbances in the ABZ. Expert assessment has been used in permafrost research to investigate pressing questions for which modeling, field, and laboratory studies are insufficient to answer, as well as to identify future research needs (Schoor et al. 2013; Abbott et al. 2016; Sayedi et al. 2020; Loisel et al. 2021). This approach provides a first-order estimate of additional net carbon emissions caused by ABZ disturbances and identifies key research priorities needed to improve these estimates. We focused on five broad categories of pulse disturbance types: anthropogenic, biotic, fire, abrupt permafrost thaw, and weather disturbances. Using a survey format, we asked experts questions on the different types of ABZ disturbances for (1) estimates of future trajectories of disturbances by 2100 and 2300, (2) estimates of the current and future impact of disturbances on carbon fluxes by 2100 and 2300, and (3) remaining knowledge gaps that can be used to inform future research.

2. Methods

2.1. Arctic-Boreal Carbon Flux Workshop

The expert assessment presented in this work was initiated during an Arctic-Boreal Carbon Flux Upscaling workshop hosted virtually by Woodwell Climate Research Center in October, 2020. This workshop brought together 145 international experts in Arctic-boreal carbon cycling, atmospheric science, remote sensing, ecosystem modeling, and disturbance in order to identify research progress, the largest sources of uncertainty in Arctic-boreal carbon budgets, and future research priorities. The workshop took place over five days and included three core themes: (1) examination of regional carbon dioxide flux models, (2) improving understanding of methane uptake and emissions from terrestrial and aquatic systems, and (3) accounting for the impacts of ecosystem disturbances on carbon fluxes. The need for a disturbance-focused expert assessment was identified during (3), and workshop participants were invited to collaborate and contribute.

2.2. Description of survey

In 2021, surveys were sent to 180 experts on anthropogenic, biotic, fire, abrupt permafrost thaw, and weather disturbances in the ABZ. Experts were identified by inviting attendees of the Arctic-Boreal Carbon Flux Workshop and soliciting recommendations from all workshop organizers and attendees to expand the pool. In gathering expert input, we actively aimed to balance career stage, gender, and geographic area (Table S1).

The survey focused on pulse disturbances, which were defined as any relatively discrete event in time that disrupts ecosystem, community, or population structure and/or a change in resources, substrate availability, or the physical environment (Pickett and White 1985). Each expert was asked to complete the survey based on their area(s) of expertise for one or two types of disturbance. We received 77 completed surveys (Table S1; anthropogenic: 10, biotic: 13, fire: 21, abrupt permafrost thaw: 22, weather: 11). Respondents represented a broad range of career stages, were fairly evenly split between self-identified women and men with no representation of non-binary genders, were predominantly from North America and Europe with little representation from Asia and Russia, and studied a variety of ecosystems and regions across the ABZ (Table S1).

The survey consisted of five questions related to the trajectory of a given disturbance type and its impact on net carbon fluxes by 2100 and 2300 (Table 1; Appendix 1). Experts were asked to (Q1) estimate the net carbon impact of the disturbance for the current period (2000–2020) relative to the pre-industrial period (defined here as prior to 1870); (Q2) estimate the change in disturbance frequency, extent, range, and severity from 2020 to 2100 (and optionally to 2300); (Q3) estimate the change in net carbon impact due to the disturbance by 2100 relative to the current period (and optionally through 2300); (Q4)

evaluate the availability of evidence and the level of consensus about spatial variability of the net carbon impact, the temporal variability of the net carbon impact, the role of primary climate change effects on net carbon impact, and the role of secondary climate change effects on net carbon impact of the disturbance; and (Q5) provide an optional flowchart of the interaction between the disturbance type considered in the survey and the type of disturbance with the most important interaction. All questions considered the entire ABZ, defined as the combined area of the boreal and tundra biomes, taken to be approximately 24 million km² for the purposes of this survey (Dinerstein et al. 2017).

Frequency was defined as how often a discrete disturbance event takes place at a given location, extent was defined as the average area affected by a discrete disturbance event, range was defined as the spatial range over which disturbance events occur, and severity was defined as the carbon release per unit area for a given disturbance event (Appendix 1). Net carbon impact was estimated as a mean annual value over the period concerned in each question in Tg C yr⁻¹ (Appendix 1; Appendix 2). The survey did not separate carbon into the greenhouse gas components, CO₂ and CH₄, and took positive values to reflect net carbon release to the atmosphere and negative values to reflect net carbon uptake. For questions concerning the net carbon impact, experts were asked to provide a lower estimate (5% quantile), upper estimate (95% quantile), and median estimate. For all questions addressing future impacts, three separate climate scenarios were considered: (1) global mean temperature increase held below 1.5°C by 2100, (2) global mean temperature increase held below 2°C by 2100, and (3) Representative Concentration Pathway (RCP) 8.5 (global mean temperature increase of ~ 2.6–4.8°C by 2100 with rising temperatures beyond that date; Collins et al., 2013). Finally, experts were asked to evaluate their expertise and confidence on a 1–5 scale for each question (Fig. S1–S7). The impact of expertise and confidence on answers was investigated to determine if the relative expertise of respondents might influence the results, and no patterns were identified.

Table 1

Survey questions that were sent to the experts. The full survey, with additional context about these questions, is available in Supplemental Materials 2 and 3.

Question	Timescale	Scenarios
1 What is the absolute value of the increase or decrease in the mean annual net carbon impact of anthropogenic disturbance during the present-day period (here defined as 2000–2020) compared to the period prior to anthropogenic warming (i.e. prior to ~1870)? Please give your estimates in Teragrams of carbon per year (TgC yr ⁻¹).	Current	
2a For each of the scenarios 1–3 how would you expect the characteristics of anthropogenic disturbance regimes, as defined in the response table below, to change from the present day period (here defined as 2000–2020) to 2100?	2100	1.5°C 2°C RCP8.5
2b OPTIONAL QUESTION: For each of the scenarios 1–3, and using the same scale defined above, how would you expect the characteristics of anthropogenic disturbance regimes, as defined in the response table below, to change from the present day period (here defined as 2000–2020) to 2300?	2300	1.5°C 2°C RCP8.5
3a For each of the scenarios 1–3 defined in question 2, please estimate the absolute value of the increase or decrease in the mean annual net carbon impact* of anthropogenic disturbance by 2100 compared to the present day period (here defined as 2000–2020). Please respond in Teragrams of carbon per year.	2100	1.5°C 2°C RCP8.5
3b OPTIONAL QUESTION: For each of the scenarios 1–3, please estimate the absolute value of the increase or decrease in the mean annual net carbon impact* of anthropogenic disturbance by 2300 compared to the present day period (here defined as 2000–2020). Please respond in Teragrams of carbon per year.	2300	1.5°C 2°C RCP8.5
4 Please consider the diagram below (Appendix 1). The two axes are labeled 'availability of evidence' and 'consensus', and each quadrant is labeled from '(a): established but incomplete' to '(d): competing explanations', according to these two dimensions. For your reference, a more detailed conceptualisation of each of these quadrants is provided at the end of this question. With reference to this diagram, what is your opinion of the overall state of scientific understanding in relation to the following concepts? Please indicate your responses by marking an 'X' on the diagram below and labeling this with the corresponding question number (see example (v)). i) Spatial variability of the mean annual net carbon impact of anthropogenic disturbance at regional and greater scales during the present day period. ii) Temporal variability of the mean annual net carbon impact of anthropogenic disturbance at annual and longer scales during the present day period. i.e. our ability to separate interannual variation from any longer-term trend, and/or to quantitatively identify 'extreme' values. iii) The role of direct, primary climate change effects (including warming, altered precipitation regimes and soil moisture, and other directly climate-related changes) in driving the mean annual net carbon impact of anthropogenic disturbance at regional and greater scales during the present day period. iv) The role of secondary or downstream climate change effects (such as climate-driven changes in vegetation composition and productivity, animal or pathogen abundance, distribution or activity, or regimes of other disturbance types) in driving the mean annual net carbon impact of anthropogenic disturbance at regional and greater scales during the present day period (here defined as 2000–2020).	Current	
5 Select the disturbance type, using FAQ 6 as a guide, that in your opinion has the greatest influence on the annual net carbon impact of anthropogenic disturbance during the present day period (here defined as 2000–2020). Qualitatively illustrate how this disturbance interacts with anthropogenic disturbance by completing the response flowchart below (Appendix 1). Use solid arrows to indicate causation and dashed arrows to indicate annotation. Label the arrows '+' or '-' to indicate a positive (+) or negative relationship (-). Label the arrows which represent the processes with the greatest impact on the annual net carbon impact of anthropogenic disturbance 1–3, where '1' indicates the process with the greatest impact.	Current	

2.3. Analysis

Answers were collated and inspected to ensure that answers included in the analysis were consistent with the requested units, region, disturbance type, and directionality of flux, among others. In cases where we suspected a discrepancy between the requested information and the information provided, we followed up with individual experts for clarification and adjusted units or removed answers as necessary. We calculated the median and standard deviation across respondents for each of the lower, upper, and median estimates in Q1 and Q3. The median was used rather than the mean to account for skew in the responses. Summary statistics were not calculated for Q2, as the answers were ordinal rather than numerical. The mean and standard deviation were calculated for Q4, as the answers did not display a strong skew.

For Q5, we combined individual flowcharts with the same interacting disturbance types into a single summarized flowchart provided there were at least 5 answers with the same interacting disturbance types. Because respondents provided a flowchart for the most important interacting disturbance type, a greater number of replicates indicates higher agreement that the interaction is an important one. Although the differing number of respondents for each disturbance type also impacted the number of replicate flowcharts, we settled on an n of 5 as sufficient replication to warrant further analysis. First, we aligned node terminology (e.g., plant die-off and vegetation mortality represent the same concept) to ensure that the concepts were represented consistently across respondents. We summed the importance of each relationship (e.g., drought → vegetation mortality) across respondents. Importance was quantified

by the number of times each relationship appeared in a flowchart weighted by respondent labels for the top three most important relationships (1: relationship is included in the flowchart without an importance label, 2: relationship is 3rd most important, 3: relationship is 2nd most important, 4: relationship is most important). If the same relationship was included with the opposite direction of causality (soil moisture → permafrost thaw vs. permafrost thaw → soil moisture), these relationships were counted separately. The combined flowcharts were visualized utilizing arrows to indicate the hypothesized direction of causality, line width to represent the summed importance of each relationship and color to represent the sign of the relationship (all positive, all negative, or mixed across respondents).

3. Results

3.1. Future Trajectory of Disturbances

Experts overwhelmingly agreed that the extent, frequency, range, and severity of all disturbance types would increase over both timescales, commensurate with the magnitude of warming (Fig. 1). There were no patterns between expert responses and expertise, career stage or confidence (data not shown). In general, experts expected that the increases in anthropogenic disturbances would be less pronounced (median values $\leq 50\%$ increase across all scenarios) than the increases in other disturbance types. It is possible this is because anthropogenic disturbances are driven directly by human behavior rather than by the effects of climate change. For biotic, fire, permafrost, and weather disturbances, the predicted median change in disturbance by 2100 under RCP8.5 was often $\geq 50\%$, depending on the metric. Median values for the 1.5°C and 2°C scenarios in these categories never exceeded 50%, showing that experts agree that more ambitious climate action could mitigate the increase in disturbances in the ABZ. In many cases, the change in disturbances was expected to be greater by 2300 than by 2100, suggesting that the effects of climate change on disturbances are likely to last for several centuries. Exceptions to this were seen primarily in the anthropogenic and weather disturbances categories. In the anthropogenic category, extent, frequency, severity, and, to a lesser degree, range were expected to decrease slightly between 2100 and 2300. Experts attributed this decrease to changes in human behavior (e.g., logging and mining pressure will peak sometime before 2100). In the weather category, range, severity, frequency, and, to a lesser degree, extent were expected to begin decreasing between 2100 and 2300 under the 1.5°C and 2°C scenarios. A few experts thought that weather disturbances could fall below current levels by 2300. These decreases were attributed to the recovery of the climate system under more ambitious climate change mitigation scenarios. Additionally, under RCP8.5, experts thought that fire severity and extent might begin to decrease between 2100 and 2300 due to a combination of depletion of biomass fuels and vegetation composition changes leading to less fire-prone forests and landscapes.

3.2. Current and Future Carbon Impact of Disturbances

Experts strongly agreed that each of the disturbance types would lead to increased net carbon emissions in the range of 10s to 100s of Tg C yr^{-1} from the ABZ (Fig. 2; Table 2). The sum of the median estimates across all disturbance types was 154 Tg C yr^{-1} for the 1.5°C scenario, 218 Tg C yr^{-1} for the 2°C scenario, and 427 Tg C yr^{-1} for the RCP8.5 scenario. Greater net ecosystem carbon release was expected under scenarios with greater warming, except for anthropogenic disturbances, where scenarios of greater warming were hypothesized to have slightly less elevated net carbon emissions. Net carbon emissions were generally expected to be highest from abrupt permafrost thaw (median estimate of $50\text{--}190 \text{ Tg C yr}^{-1}$ depending on scenario) followed by fire ($25\text{--}100 \text{ Tg C yr}^{-1}$), biotic disturbances ($24\text{--}70 \text{ Tg C yr}^{-1}$), anthropogenic disturbances ($20\text{--}40 \text{ Tg C yr}^{-1}$), and weather disturbances ($15\text{--}47 \text{ Tg C yr}^{-1}$; Table 2). However, there was high variation in net carbon emission estimates among respondents and considerable overlap between disturbance types, particularly when lower and upper estimates are considered. The carbon impact was primarily attributed to both disturbance-related carbon emissions (e.g., combustion during fire or soil respiration during thermokarst) and reductions in gross primary productivity resulting from disturbance to vegetation, although other disturbance-specific mechanisms for carbon uptake and release were mentioned (e.g., fire-induced succession resulting in less flammable forests, hydrologic transport of carbon from permafrost disturbances, or inundation during thermokarst leading to increased methane emissions). Experts agreed that net carbon emissions caused by disturbances will continue well after temperatures begin to decline in the 1.5°C and 2°C mitigation scenarios, but the timeframe over which these emissions will continue varied by disturbance type. However, a few respondents indicated that disturbance could lead to a decrease in net carbon emissions relative to current levels. These responses were split between those who thought this would be due to recovery from disturbance by 2300 and those who thought that increased net carbon uptake might be the direct result of disturbances. For these answers, typically only the lower bound estimate indicated a decrease in net carbon emissions, while the median and upper bound estimates both indicated an increase in net carbon release.

Table 2

Expert opinion on the net carbon impact (Tg C yr^{-1}) of the five disturbance types. The mean, median, standard deviation (SD), and sample size (n) of the estimate, lower estimate, and upper estimate provided for each disturbance type, timescale, and scenario. Positive values indicate net carbon release and negative values indicate net carbon uptake. Note that values for all future scenarios represent changes from current mean annual net carbon budgets. Not all respondents provided a median, upper, and lower estimates, occasionally resulting in different sample sizes across these components of the questions.

				Mean (Tg C yr ⁻¹)			Median (Tg C yr ⁻¹)			SD		n	
Disturbance	Timescale	Scenario	Question	Estimate	Lower	Upper	Estimate	Lower	Upper	Estimate	Lower	Upper	Estimate
Anthropogenic	Current	Current	1	50	24	116	60	20	110	37	23	81	7
	2100	1.5°C	3a	93	71	176	40	15	90	140	120	201	7
		2°C		85	68	181	25	22	125	112	119	171	7
		RCP8.5		47	82	184	20	10	85	55	164	208	6
	2300	1.5°C	3b	315	267	382	70	2	95	464	461	536	3
		2°C		242	201	298	50	3	95	354	346	392	3
		RCP8.5		48	1	83	25	0	50	63	2	104	3
Biotic	Current	Current	1	83	11	145	20	1	25	160	21	305	9
	2100	1.5°C	3a	52	25	77	24	9	34	70	35	101	9
		2°C		90	37	127	28	11	43	160	63	213	9
		RCP8.5		241	-26	512	70	10	70	479	170	1091	9
	2300	1.5°C	3b	315	88	332	315	65	195	262	102	416	2
		2°C		418	156	435	418	68	203	400	214	585	2
		RCP8.5		-175	-642	577	-175	0	225	460	1177	807	2
Fire	Current	Current	1	46	-5	129	53	9	100	94	134	97	17
	2100	1.5°C	3a	52	12	112	25	10	50	75	73	136	19
		2°C		82	28	151	50	15	75	111	97	163	19
		RCP8.5		165	53	305	100	50	150	259	239	376	19
	2300	1.5°C	3b	184	20	462	38	4	55	344	34	1033	8
		2°C		325	155	611	60	33	85	683	343	1375	8
		RCP8.5		619	253	1119	125	55	160	1440	728	2407	8
Permafrost	Current	Current	1	45	-1	126	33	4	100	48	29	103	20
	2100	1.5°C	3a	72	0	198	50	10	135	75	124	183	20
		2°C		119	24	288	80	19	180	103	112	254	20
		RCP8.5		330	65	687	190	73	575	324	243	620	20
	2300	1.5°C	3b	57	-77	190	30	0	100	78	192	182	7
		2°C		118	-31	274	50	10	250	114	179	207	9
		RCP8.5		486	-98	1419	200	100	450	827	617	1945	8
Weather	Current	Current	1	77	48	190	10	2	50	137	104	257	9
	2100	1.5°C	3a	81	51	188	15	7	60	135	104	246	9
		2°C		110	99	259	35	13	70	194	187	360	9
		RCP8.5		179	181	501	47	22	125	266	342	664	9
	2300	1.5°C	3b	82	38	120	14	0	38	146	111	188	4
		2°C		145	50	183	38	0	63	238	100	281	4
		RCP8.5		464	225	615	325	51	525	561	386	696	4

3.3. Disturbance Interactions

There was high agreement on the importance of interactions between (1) fire and abrupt permafrost thaw (8 replicate flowcharts) and (2) fire and weather (9 replicate flowcharts). The flowcharts for the fire and abrupt permafrost thaw interaction had relatively high agreement on the pathways (both nodes and

relationships) through which the two disturbance types impacted each other. There was general agreement that fire increased the likelihood of permafrost disturbances, primarily through reductions in biomass, soil organic layer depth, and albedo, which all result in higher soil temperatures conducive to abrupt permafrost thaw (Fig. 3). For nearly all relationships included in the flowchart, respondents were confident about the sign of the relationship; the one exception was between vegetation and albedo, for which the respondents were split on whether it was positive or negative. Additionally, the directionality was consistent across flowcharts, with respondents indicating that fire increases permafrost disturbances, but no effect of permafrost disturbances on fire was reported. There was relatively low agreement on the interaction pathways between fire and weather, resulting in a flowchart with many relationships that appeared only once in individual flowcharts (Fig. S8). Despite this, there was some agreement that drought causes an increase in fire through its impact on fuel moisture and vegetation.

3.4. State of the Research and Knowledge Gaps

Across most disturbance types, knowledge of the direct effects, spatial variability, and temporal variability of disturbances was rated as “established but incomplete” on average, indicating a fairly low availability of evidence, but fairly high consensus in the evidence that is available (Fig. 4). However, the temporal variability of biotic disturbances was considered “speculative”, and both the spatial variability of fire and the direct effects of weather disturbances were considered “well established”. Overall, there was high variability in responses for direct effects, spatial variability, and temporal variability of disturbances, and mean ratings did not necessarily reflect the quadrant(s) with the largest number of responses. Unsurprisingly, there was high agreement that knowledge of the indirect effects of disturbances is “speculative” in all disturbance types, indicating low availability and consensus of the evidence.

4. Discussion

The expert assessment showed strong agreement that increasing disturbances across the ABZ will lead to increases in net carbon emissions on the order of 100s of Tg C yr^{-1} for all disturbances combined by 2100 compared to current emissions. Due to the small number of responses for the 2300 timescale across most disturbance types, we focus on changes in the magnitude of fluxes by 2100. Currently, ABZ disturbances are either not included or are incompletely included in Earth system models (McGuire et al. 2018; Mekonnen et al. 2021; Natali et al. 2021; Schädler et al. 2024). While many vegetation models do include some types of disturbance, not all disturbance types are included and more work is needed to couple them to Earth System Models (Koven et al. 2020; Martín Belda et al. 2022; Heffernan et al. 2024). Thus, expert hypotheses provide the best currently-available insight into future net carbon emissions from these disturbances. Our estimate of 427 Tg C yr^{-1} net emissions under RCP8.5 by 2100 represents a significant increase in predicted carbon emissions from the permafrost region over a previous model synthesis that indicated a slight gain in ecosystem carbon through 2100 and a mean loss of 208 Pg C through 2300 under RCP 8.5 when disturbances are not considered (McGuire et al. 2018). Additionally, our range of $154\text{--}427 \text{ Tg C yr}^{-1}$ summed across all disturbance types is of the same order of magnitude as recent estimates of ABZ net ecosystem exchange (Hugelius et al., 2024; Ramage et al., 2024; Treat, Virkkala et al., 2024) and is one to two orders of magnitude smaller than the estimates for gross primary productivity ($11,344 \text{ Tg C yr}^{-1}$) and ecosystem respiration ($10,397 \text{ Tg C yr}^{-1}$) based on upscaled measurements from undisturbed ecosystems (Virkkala et al. 2021). Based on these comparisons, we can conclude that the experts’ predictions fall within a reasonable range for carbon exchange in the ABZ. Additionally, this indicates that disturbances will play a noteworthy role in modifying net carbon emissions from the ABZ over the next one to three centuries, with the potential for disturbances to flip the region from a carbon sink to a carbon source in the near future.

Experts agreed that net carbon emissions from ABZ disturbances would continue after fossil fuel emissions reach net zero around roughly 2050 (1.5°C scenario) or sometime in the second half of the 21st century (2°C scenario) (Chen et al. 2021a), suggesting that some other method of carbon sequestration will be needed to offset ABZ disturbance emissions to meet a net zero emissions goal. Current emissions reduction goals that do not account for ABZ disturbances are therefore likely to result in significant overshoot without adjustments to account for these additional emissions. Additionally, the few experts who were willing to make predictions out to 2300 expected that net carbon emissions would continue at levels similar to the period 2020–2100, reflecting mechanisms that operate on a much longer timescale than atmospheric carbon levels or even temperature. For example, one respondent in the weather disturbances category highlighted the uncertainty in timescales of vegetation adaptation to new weather conditions, which would in turn closely dictate ecosystem carbon balance (Schuur et al. 2018).

Permafrost and fire disturbances were expected to contribute larger proportions to the total net carbon emissions compared to biotic, anthropogenic, and weather disturbances, although there was considerable overlap between disturbance types due to high variability. Despite this variability, the estimates compare favorably to currently available published values. The estimate of 190 Tg C yr^{-1} net emissions due to abrupt permafrost thaw in 2100 under RCP 8.5 was very similar to the modeled loss of $\sim 20 \text{ Pg C}$ between 2000 and 2100, or $\sim 200 \text{ Tg C yr}^{-1}$, reported in Turetsky et al. (2020). The estimate of $25\text{--}100 \text{ Tg C yr}^{-1}$ net emissions from wildfire by 2100 are somewhat smaller than recent estimates of direct emissions from fire, with an average loss of 79 Tg C yr^{-1} reported for 2001–2019 across a large region in Alaska and northern Canada (Potter et al. 2023), and 647 Tg C lost from the record-setting Canadian fire season of 2023 (Byrne et al. 2024). The region considered in this expert assessment was much larger than either of those studies, but the expert assessment also considers the carbon impact of vegetation recovery over the long-term. Additionally, the expert assessment estimates for fire are similar but somewhat smaller than a recent estimate of net fire emissions in Canada and Alaska by 2050 (Phillips et al., 2022), indicating the expert assessment results for net fire emissions across the entire ABZ may be somewhat conservative. Making comparisons to published data for the other disturbance types is less feasible, as anthropogenic, biotic, and weather disturbances each comprise a wider variety of disturbances and mechanisms that are typically only studied individually.

Respondents did not agree on the exact timing of when ecosystem carbon balance might begin to recover, with varied reasons depending on disturbance type. While most responses indicated continued net carbon emissions from fire by 2300, one respondent hypothesized a decrease in the carbon impact of fire by 2300 due to a biome shift from boreal to northern hardwood forests between 2100 and 2300. A shift from fire-prone tree species such as spruce, pine,

and larch to less fire-prone deciduous species such as aspen and birch has been repeatedly reported as a consequence of increasing burn severity (Johnstone et al. 2010; Beck et al. 2011; Mann et al. 2012; Mekonnen et al. 2019; Holloway et al. 2020; Li et al. 2021; Mack et al. 2021), but there was uncertainty among the experts as to how extensively and over what timeframe this might occur. Similarly, three experts thought the carbon impact of permafrost disturbances would begin to decline by 2300, with two of them hypothesizing large-scale vegetation recovery following abrupt thaw under the 1.5°C and 2°C scenarios and two of them hypothesizing that most areas that are prone to abrupt thaw will already have undergone thermokarst processes by 2300 under RCP8.5. Although abrupt thaw is cyclical, the depletion of near-surface ground ice following abrupt thaw reduces the likelihood of future abrupt thaw until ground ice can reaccumulate (Turetsky et al. 2020), which is far less likely in the warmer Arctic projected for RCP8.5.

Some identified knowledge gaps were consistent across disturbance types, such as the need for (better) spatial data layers of disturbances and more measurements of carbon fluxes. Given the highly episodic nature of disturbances, the most commonly identified knowledge gap was the extent and distribution of disturbances in any given year, highlighting the need for improvements in disturbance mapping. Spatial data layers of disturbances are incomplete, in development, or non-existent for anthropogenic, biotic, permafrost, and weather disturbances, limiting the feasibility of spatial scaling and projecting future extent and distribution. Even for fire, for which the most comprehensive spatial data layers (of burned area) are available (e.g. Clelland et al. 2024), many respondents wanted access to better spatial data layers, particularly in Siberia. Methods to automate mapping of abrupt permafrost thaw disturbances at the circumpolar scale using remotely sensed data are still in development (e.g. Grosse et al. 2008; Nitze et al. 2020, 2021; Lara et al. 2021; Huang et al. 2022; Yang et al. 2023; Chen et al. 2023). Remote sensing data has also been used to track specific biotic disturbances at the regional scale (e.g. Jepsen et al. 2009), but the spatial scale, high temporal variability, and challenge of pinpointing the specific disturbance type currently limit mapping efforts. Another commonly identified knowledge gap across disturbance types was the need for more measurements of post-disturbance carbon fluxes, as well as direct carbon emissions from fire, in order to better quantify fluxes over the trajectory from disturbance to recovery, understand the timeline of carbon cycle recovery, and understand underlying mechanisms. While there is a network of carbon flux measurements across the circumpolar region, measurements that coincide with disturbances are few (Kuhn et al. 2021; Virkkala et al. 2022, 2025; See et al. 2024), limiting understanding of the environmental factors that control carbon fluxes across disturbance types.

The experts identified many disturbance-specific knowledge gaps as well as uncertainties associated with interactions between disturbance types. Predicting future land use was a major source of uncertainty for anthropogenic disturbances. For biotic disturbances, key uncertainties included indirect effects, species interactions, winter processes, and potential changes in forest composition. For fire, key uncertainties included the potential for short-interval reburns to disrupt recovery, successional trajectories, and interactions with permafrost thaw and soil moisture. For permafrost disturbances, uncertainties included post-thaw moisture conditions, the balance between vegetation response and heterotrophic respiration, the size and lability of soil carbon stocks, ground ice distribution, and the interaction with extreme weather events that can initiate thermokarst. Finally, for weather disturbances, key uncertainties included future changes in weather disturbance regimes, carbon impact of the various types of weather disturbances, vegetation recovery and compensatory growth following disturbance, and vegetation range shifts.

5. Conclusion

Based on expert assessment, we conclude that increasing ABZ disturbances are likely to result in substantial increases in net carbon emissions (100s of Tg C yr⁻¹) over the next one to three centuries. Net carbon emissions for most of these disturbances are missing or very uncertain in current Earth system models used to project global climate. These deficiencies likely lead to high uncertainty in climate projections and estimates of remaining anthropogenic carbon budgets. Improving model representations of these disturbances and their impacts on carbon cycling is therefore critical to stay within Paris-aligned global temperature targets. Future research priorities include 1) improving spatial data products of pulse disturbances, 2) increased measurements of carbon fluxes during and following disturbances, and 3) improving the representation of disturbance processes in models for future projections. In the meantime, expert assessment is a useful tool we have available to incorporate the carbon impact of disturbances into global emissions budgets and policy discussions.

Declarations

Funding

This research was funded by the Gordon and Betty Moore Foundation (grant no. 8414) and funding catalyzed by the Audacious Project (Permafrost Pathways) to Susan M. Natali and Brendan M. Rogers. Mathias Göckede acknowledges funding from the European Research Council (ERC synergy project Q-Arctic, grant agreement no. 951288. Juha Aalto acknowledges funding from the Research Council of Finland (decision 342890). Winslow Hansen acknowledges funding from the US National Science Foundation (NSF; OPP-2116863). Elizabeth E. Hoy acknowledges support from the National Aeronautics and Space Administration (NASA) Arctic-Boreal Vulnerability Experiment (ABOVE). Elena A. Kukavskaya was supported by State Assignment Project no. FWES-2024-0040. Mark J. Lara acknowledges funding from NSF (OPP-2311073 and EnvE-1928048). Michael Loranty acknowledges funding from NSF (OPP-1708322). Avni Malhotra was supported by the NASA Terrestrial Ecology Program (project 80NSSC22K1253 to Carnegie Institution and Pacific Northwest National Laboratory) and by the Swiss National Science Foundation (project 200021_215214). Kimberley R. Miner conducted work at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA (80NM0018D0004). Frans-Jan W. Permentier was supported by the Research Council of Norway (project nrs 323945 and 742115). William J. Riley and Zelalem A. Mekonnen were supported by the Office of Science, Regional and Global Model Analysis of the US Department of Energy, Agreement Grant DE-AC02-05CH11231, Reducing Uncertainties in Biogeochemical Interactions through Synthesis Computation Scientific Focus Area (RUBISCO SFA). Tatiana A. Shestakova was supported by the Beatriu de Pinòs Programme of the Government of Catalonia (2020 BP 00126). James D. M. Speed and Hans Tømmervik acknowledge funding from the EU Horizon Europe CHARTER (EU 869471). Maria Strack acknowledges funding from the Canada Research Chairs program (CRC-2019-00299). Ken D. Tape acknowledges funding from the

Author Contributions

H.R. performed the analyses and wrote the original draft. R.T., M.G., M.M., A.-M.V., S.M.N., and B.R. formulated the research goals. S.M.N. and B.R. secured funding. All authors except R.T., M.G., M.M., A.-M.V., and S.M.N. completed the survey. All authors contributed to the writing (review) and conclusions. All authors read and approved the final manuscript.

Data Availability

Survey data and the analysis script are available at https://github.com/HRodenhizer/disturbance_expert_assessment.

References

1. Abbott BW, Jones JB, Schuur EAG, et al (2016) Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment. *Environ Res Lett* 11:034014. <https://doi.org/10.1088/1748-9326/11/3/034014>
2. Abbott BW, Larouche JR, Jones Jr. JB, et al (2014) Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost. *J Geophys Res Biogeosciences* 119:2049–2063. <https://doi.org/10.1002/2014JG002678>
3. Bayatvarkeshi M, Ketcheson S, Weiland L, Strack M (2024) An initial assessment of winter microclimatic conditions in response to seismic line disturbance in a forested peatland. *Hydrol Process* 38:e15243. <https://doi.org/10.1002/hyp.15243>
4. Beck PSA, Goetz SJ, Mack MC, et al (2011) The impacts and implications of an intensifying fire regime on Alaskan boreal forest composition and albedo. *Glob Change Biol* 17:2853–2866. <https://doi.org/10.1111/j.1365-2486.2011.02412.x>
5. Becker MS, Pollard WH (2016) Sixty-year legacy of human impacts on a high Arctic ecosystem. *J Appl Ecol* 53:876–884. <https://doi.org/10.1111/1365-2664.12603>
6. Beel CR, Heslop JK, Orwin JF, et al (2021) Emerging dominance of summer rainfall driving High Arctic terrestrial-aquatic connectivity. *Nat Commun* 12:1448. <https://doi.org/10.1038/s41467-021-21759-3>
7. Bentz BJ, Régnière J, Fettig CJ, et al (2010) Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *BioScience* 60:602–613. <https://doi.org/10.1525/bio.2010.60.8.6>
8. Bokhorst S, Bjerke JW, Bowles FW, et al (2008) Impacts of extreme winter warming in the sub-Arctic: growing season responses of dwarf shrub heathland. *Glob Change Biol* 14:2603–2612. <https://doi.org/10.1111/j.1365-2486.2008.01689.x>
9. Bokhorst S, Bjerke JW, Street LE, et al (2011) Impacts of multiple extreme winter warming events on sub-Arctic heathland: phenology, reproduction, growth, and CO₂ flux responses. *Glob Change Biol* 17:2817–2830. <https://doi.org/10.1111/j.1365-2486.2011.02424.x>
10. Bouchard M, Pothier D, Ruel J-C (2009) Stand-replacing windthrow in the boreal forests of eastern Quebec. *Can J For Res* 39:481–487. <https://doi.org/10.1139/X08-174>
11. Bouskill NJ, Mekonnen Z, Zhu Q, et al (2022) Microbial contribution to post-fire tundra ecosystem recovery over the 21st century. *Commun Earth Environ* 3:1–15. <https://doi.org/10.1038/s43247-022-00356-2>
12. Boyd MA, Berner LT, Doak P, et al (2019) Impacts of climate and insect herbivory on productivity and physiology of trembling aspen (*Populus tremuloides*) in Alaskan boreal forests. *Environ Res Lett* 14:085010. <https://doi.org/10.1088/1748-9326/ab215f>
13. Boyd MA, Berner LT, Foster AC, et al (2021) Historic declines in growth portend trembling aspen death during a contemporary leaf miner outbreak in Alaska. *Ecosphere* 12:e03569. <https://doi.org/10.1002/ecs2.3569>
14. Bradshaw CJA, Warkentin IG (2015) Global estimates of boreal forest carbon stocks and flux. *Glob Planet Change* 128:24–30. <https://doi.org/10.1016/j.gloplacha.2015.02.004>
15. Brown J, Ferrians OJJ, Heginbottom JA, Melnikov ES (1998) Circum-Arctic map of permafrost and ground-ice conditions. Circum-Pacific Map Series CP-45. Revised February 2001.
16. Byrne B, Liu J, Bowman KW, et al (2024) Carbon emissions from the 2023 Canadian wildfires. *Nature* 633:835–839. <https://doi.org/10.1038/s41586-024-07878-z>
17. Canelles Q, Aquilué N, James PMA, et al (2021) Global review on interactions between insect pests and other forest disturbances. *Landsc Ecol* 36:945–972. <https://doi.org/10.1007/s10980-021-01209-7>
18. Chen D, Rojas M, Samset BH, et al (2021a) Framing, Context, and Methods. Cambridge University Press, Cambridge, UK and New York, NY, USA
19. Chen Y, Cheng X, Liu A, et al (2023) Tracking lake drainage events and drained lake basin vegetation dynamics across the Arctic. *Nat Commun* 14:7359. <https://doi.org/10.1038/s41467-023-43207-0>
20. Chen Y, Romps DM, Seeley JT, et al (2021b) Future increases in Arctic lightning and fire risk for permafrost carbon. *Nat Clim Change* 19
21. Clelland AA, Marshall GJ, Baxter R, et al (2024) Annual and Seasonal Patterns of Burned Area Products in Arctic-Boreal North America and Russia for 2001–2020. *Remote Sens* 16:3306. <https://doi.org/10.3390/rs16173306>

22. Collins M, Knutti R, Arblaster J, et al (2013) Long-term Climate Change: Projections, Commitments and Irreversibility. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
23. Dabros A, Pyper M, Castilla G (2018) Seismic lines in the boreal and arctic ecosystems of North America: environmental impacts, challenges, and opportunities. *Environ Rev* 26:214–229. <https://doi.org/10.1139/er-2017-0080>
24. Davidson SJ, Goud EM, Franklin C, et al (2020) Seismic Line Disturbance Alters Soil Physical and Chemical Properties Across Boreal Forest and Peatland Soils. *Front Earth Sci* 8:. <https://doi.org/10.3389/feart.2020.00281>
25. Davidson SJ, Goud EM, Malhotra A, et al (2021) Linear Disturbances Shift Boreal Peatland Plant Communities Toward Earlier Peak Greenness. *J Geophys Res Biogeosciences* 126:e2021JG006403. <https://doi.org/10.1029/2021JG006403>
26. de Groot WJ, Flannigan MD, Cantin AS (2013) Climate change impacts on future boreal fire regimes. *For Ecol Manag* 294:35–44. <https://doi.org/10.1016/j.foreco.2012.09.027>
27. Demidov V, Verkulich S, Ekeykin A, et al (2024) Thaw slump development and other rapid permafrost disturbances in Hollendardalen Valley, Svalbard. *Polar Sci* 101122. <https://doi.org/10.1016/j.polar.2024.101122>
28. Descals A, Gaveau DLA, Verger A, et al (2022) Unprecedented fire activity above the Arctic Circle linked to rising temperatures. *Science* 378:532–537. <https://doi.org/10.1126/science.abn9768>
29. Dinerstein E, Olson D, Joshi A, et al (2017) An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* 67:534–545. <https://doi.org/10.1093/biosci/bix014>
30. Dvornikov YA, Leibman MO, Khomutov AV, et al (2019) Gas-emission craters of the Yamal and Gydan peninsulas: A proposed mechanism for lake genesis and development of permafrost landscapes. *Permafr Periglac Process* 30:146–162. <https://doi.org/10.1002/ppp.2014>
31. Ellis TM, Bowman DMJS, Jain P, et al (2022) Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Glob Change Biol* 28:1544–1559. <https://doi.org/10.1111/gcb.16006>
32. Estop-Aragónés C, Cooper MDA, Fisher JP, et al (2018) Limited release of previously-frozen C and increased new peat formation after thaw in permafrost peatlands. *Soil Biol Biochem* 118:115–129. <https://doi.org/10.1016/j.soilbio.2017.12.010>
33. Farquharson LM, Romanovsky VE, Cable WL, et al (2019) Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian high Arctic. *Geophys Res Lett* 46:6681–6689. <https://doi.org/10.1029/2019GL082187>
34. Foster AC, Wang JA, Frost GV, et al (2022) Disturbances in North American boreal forest and Arctic tundra: impacts, interactions, and responses. *Environ Res Lett* 17:113001. <https://doi.org/10.1088/1748-9326/ac98d7>
35. Gibson CM, Chasmer LE, Thompson DK, et al (2018) Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nat Commun* 9:3041. <https://doi.org/10.1038/s41467-018-05457-1>
36. Groisman PY, Bulygina ON, Yin X, et al (2016) Recent changes in the frequency of freezing precipitation in North America and Northern Eurasia. *Environ Res Lett* 11:045007. <https://doi.org/10.1088/1748-9326/11/4/045007>
37. Grosse G, Morgenstern A, Lantuit H (2008) Distribution of thermokarst lakes and ponds at three yedoma sites in Siberia. 6
38. Guo M, Li J, Yu F, et al (2021) Estimation of post-fire vegetation recovery in boreal forests using solar-induced chlorophyll fluorescence (SIF) data. *Int J Wildland Fire* 30:365–377. <https://doi.org/10.1071/WF20162>
39. Hanes CC, Wang X, Jain P, et al (2019) Fire-regime changes in Canada over the last half century. *Can J For Res* 49:256–269. <https://doi.org/10.1139/cjfr-2018-0293>
40. Hansen BB, Isaksen K, Benestad RE, et al (2014) Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic. *Environ Res Lett* 9:114021. <https://doi.org/10.1088/1748-9326/9/11/114021>
41. Hansen EM, Bentz BJ, Powell JA, et al (2011) Prepupal diapause and instar IV developmental rates of the spruce beetle, *Dendroctonus rufipennis* (Coleoptera: Curculionidae, Scolytinae). *J Insect Physiol* 57:1347–1357. <https://doi.org/10.1016/j.jinsphys.2011.06.011>
42. Harris LI, Richardson K, Bona KA, et al (2022) The essential carbon service provided by northern peatlands. *Front Ecol Environ* 20:222–230. <https://doi.org/10.1002/fee.2437>
43. Harvey JA, Tougeron K, Gols R, et al (2023) Scientists' warning on climate change and insects. *Ecol Monogr* 93:e1553. <https://doi.org/10.1002/ecm.1553>
44. Heffernan E, Epstein H, Declan McQuinn T, et al (2024) Comparing assumptions and applications of dynamic vegetation models used in the Arctic-Boreal zone of Alaska and Canada. *Environ Res Lett* 19:093003. <https://doi.org/10.1088/1748-9326/ad6619>
45. Heliasz M, Johansson T, Lindroth A, et al (2011) Quantification of C uptake in subarctic birch forest after setback by an extreme insect outbreak. *Geophys Res Lett* 38:. <https://doi.org/10.1029/2010GL044733>
46. Hjort J, Streletskiy D, Doré G, et al (2022) Impacts of permafrost degradation on infrastructure. *Nat Rev Earth Environ* 3:24–38. <https://doi.org/10.1038/s43017-021-00247-8>
47. Holloway JE, Lewkowicz AG, Douglas TA, et al (2020) Impact of wildfire on permafrost landscapes: A review of recent advances and future prospects. *Permafr Periglac Process* 31:371–382. <https://doi.org/10.1002/ppp.2048>
48. Huang L, Lantz TC, Fraser RH, et al (2022) Accuracy, Efficiency, and Transferability of a Deep Learning Model for Mapping Retrogressive Thaw Slumps across the Canadian Arctic. *Remote Sens* 14:2747. <https://doi.org/10.3390/rs14122747>
49. Hugelius G, Ramage J, Burke E, et al (2024) Permafrost Region Greenhouse Gas Budgets Suggest a Weak CO₂ Sink and CH₄ and N₂O Sources, But Magnitudes Differ Between Top-Down and Bottom-Up Methods. *Glob Biogeochem Cycles* 38:e2023GB007969. <https://doi.org/10.1029/2023GB007969>

50. Hugelius G, Strauss J, Zubrzycki S, et al (2014) Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences* 11:6573–6593. <https://doi.org/10.5194/bg-11-6573-2014>
51. Jain P, Barber QE, Taylor SW, et al (2024) Drivers and Impacts of the Record-Breaking 2023 Wildfire Season in Canada. *Nat Commun* 15:6764. <https://doi.org/10.1038/s41467-024-51154-7>
52. Jain P, Castellanos-Acuna D, Coogan SCP, et al (2022) Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nat Clim Change* 12:63–70. <https://doi.org/10.1038/s41558-021-01224-1>
53. Jain P, Flannigan M (2021) The Relationship between the Polar Jet Stream and Extreme Wildfire Events in North America. *J Clim* 34:6247–6265. <https://doi.org/10.1175/JCLI-D-20-0863.1>
54. Jepsen JU, Hagen SB, Høgda KA, et al (2009) Monitoring the spatio-temporal dynamics of geometrid moth outbreaks in birch forest using MODIS-NDVI data. *Remote Sens Environ* 113:1939–1947. <https://doi.org/10.1016/j.rse.2009.05.006>
55. Johnstone JF, Chapin FS, Hollingsworth TN, et al (2010) Fire, climate change, and forest resilience in interior Alaska This article is one of a selection of papers from The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. *Can J For Res* 40:1302–1312. <https://doi.org/10.1139/X10-061>
56. Jones MW, Veraverbeke S, Andela N, et al (2024) Global rise in forest fire emissions linked to climate change in the extratropics. *Science* 386:eadl5889. <https://doi.org/10.1126/science.adl5889>
57. Jorgenson MT, Douglas TA, Liljedahl AK, et al (2020) The roles of climate extremes, ecological succession, and hydrology in repeated permafrost aggradation and degradation in fens on the Tanana Flats, Alaska. *J Geophys Res Biogeosciences* 125:. <https://doi.org/10.1029/2020JG005824>
58. Kang M, Brandt AR, Zheng Z, et al (2021) Orphaned oil and gas well stimulus—Maximizing economic and environmental benefits. *Elem Sci Anthr* 9:00161. <https://doi.org/10.1525/elementa.2020.20.00161>
59. Kasischke ES, Verbyla DL, Rupp TS, et al (2010) Alaska's changing fire regime — implications for the vulnerability of its boreal forests This article is one of a selection of papers from The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. *Can J For Res* 40:1313–1324. <https://doi.org/10.1139/X10-098>
60. Kautz M, Meddens AJH, Hall RJ, Arneeth A (2017) Biotic disturbances in Northern Hemisphere forests – a synthesis of recent data, uncertainties and implications for forest monitoring and modelling. *Glob Ecol Biogeogr* 26:533–552. <https://doi.org/10.1111/geb.12558>
61. Kelly J, Kljun N, Cai Z, et al (2024) Wildfire impacts on the carbon budget of a managed Nordic boreal forest. *Agric For Meteorol* 351:110016. <https://doi.org/10.1016/j.agrformet.2024.110016>
62. Kim I-W, Timmermann A, Kim J-E, et al (2024a) Abrupt increase in Arctic-Subarctic wildfires caused by future permafrost thaw. *Nat Commun* 15:7868. <https://doi.org/10.1038/s41467-024-51471-x>
63. Kim JE, Wang JA, Li Y, et al (2024b) Wildfire-induced increases in photosynthesis in boreal forest ecosystems of North America. *Glob Change Biol* 30:e17151. <https://doi.org/10.1111/gcb.17151>
64. Klotz LA, Sonnentag O, Wang Z, et al (2023) Oil and natural gas wells across the NASA ABoVE domain: fugitive methane emissions and broader environmental impacts. *Environ Res Lett* 18:035008. <https://doi.org/10.1088/1748-9326/acbe52>
65. Kokelj SV, Jorgenson MT (2013) Advances in thermokarst research: Recent advances in research investigating thermokarst processes. *Permafr Periglac Process* 24:108–119. <https://doi.org/10.1002/ppp.1779>
66. Kokelj SV, Tunnicliffe J, Lacelle D, et al (2015) Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. *Glob Planet Change* 129:56–68. <https://doi.org/10.1016/j.gloplacha.2015.02.008>
67. Koven CD, Knox RG, Fisher RA, et al (2020) Benchmarking and parameter sensitivity of physiological and vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) at Barro Colorado Island, Panama. *Biogeosciences* 17:3017–3044. <https://doi.org/10.5194/bg-17-3017-2020>
68. Kuhn MA, Varner RK, Bastviken D, et al (2021) BAWLD-CH₄: a comprehensive dataset of methane fluxes from boreal and arctic ecosystems. *Earth Syst Sci Data* 13:5151–5189. <https://doi.org/10.5194/essd-13-5151-2021>
69. Lara MJ, Chen Y, Jones BM (2021) Recent warming reverses forty-year decline in Catastrophic lake drainage and hastens Gradual lake drainage across northern Alaska. *Environ Res Lett*. <https://doi.org/10.1088/1748-9326/ac3602>
70. Lara MJ, Johnson DR, Andresen C, et al (2016) Peak season carbon exchange shifts from a sink to a source following 50+ years of herbivore exclusion in an Arctic tundra ecosystem. *J Ecol* 105:122–131. <https://doi.org/10.1111/1365-2745.12654>
71. Leroux SJ, Wiersma YF, Wal EV (2020) Herbivore Impacts on Carbon Cycling in Boreal Forests. *Trends Ecol Evol* 35:1001–1010. <https://doi.org/10.1016/j.tree.2020.07.009>
72. Lewkowicz AG, Way RG (2019) Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. *Nat Commun* 10:1329. <https://doi.org/10.1038/s41467-019-09314-7>
73. Li X-Y, Jin H-J, Wang H-W, et al (2021) Influences of forest fires on the permafrost environment: A review. *Adv Clim Change Res* S1674927821000010. <https://doi.org/10.1016/j.accre.2021.01.001>
74. Loisel J, Gallego-Sala AV, Amesbury MJ, et al (2021) Expert assessment of future vulnerability of the global peatland carbon sink. *Nat Clim Change* 11:70–77. <https://doi.org/10.1038/s41558-020-00944-0>
75. Lund M, Raundrup K, Westergaard-Nielsen A, et al (2017) Larval outbreaks in West Greenland: Instant and subsequent effects on tundra ecosystem productivity and CO₂ exchange. *Ambio* 46:26–38. <https://doi.org/10.1007/s13280-016-0863-9>

76. Macias-Fauria M, Jepson P, Zimov N, Malhi Y (2020) Pleistocene Arctic megafaunal ecological engineering as a natural climate solution? *Philos Trans R Soc B Biol Sci* 375:20190122. <https://doi.org/10.1098/rstb.2019.0122>
77. Mack MC, Walker XJ, Johnstone JF, et al (2021) Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. *Science* 372:280–283. <https://doi.org/10.1126/science.abf3903>
78. Malhotra A, Roulet NT (2015) Environmental correlates of peatland carbon fluxes in a thawing landscape: do transitional thaw stages matter? *Biogeosciences* 12:3119–3130. <https://doi.org/10.5194/bg-12-3119-2015>
79. Mann DH, Rupp TS, Olson MA, Duffy PA (2012) Is Alaska's Boreal Forest Now Crossing a Major Ecological Threshold? *Arct Antarct Alp Res* 44:319–331. <https://doi.org/10.1657/1938-4246-44.3.319>
80. Martín Belda D, Anthoni P, Wårlind D, et al (2022) LPJ-GUESS/LSMv1.0: a next-generation land surface model with high ecological realism. *Geosci Model Dev* 15:6709–6745. <https://doi.org/10.5194/gmd-15-6709-2022>
81. McCarty JL, Aalto J, Paunu V-V, et al (2021) Reviews and syntheses: Arctic fire regimes and emissions in the 21st century. *Biogeosciences* 18:5053–5083. <https://doi.org/10.5194/bg-18-5053-2021>
82. McGuire AD, Lawrence DM, Koven C, et al (2018) Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proc Natl Acad Sci* 115:3882–3887. <https://doi.org/10.1073/pnas.1719903115>
83. Mekonnen ZA, Riley WJ, Grant RF, Romanovsky VE (2021) Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate. *Environ Res Lett* 16:024008. <https://doi.org/10.1088/1748-9326/abc444>
84. Mekonnen ZA, Riley WJ, Randerson JT, et al (2019) Expansion of high-latitude deciduous forests driven by interactions between climate warming and fire. *Nat Plants* 5:952–958. <https://doi.org/10.1038/s41477-019-0495-8>
85. Meyer N, Xu Y, Karjalainen K, et al (2022) Living, dead, and absent trees—How do moth outbreaks shape small-scale patterns of soil organic matter stocks and dynamics at the Subarctic mountain birch treeline? *Glob Change Biol* 28:441–462. <https://doi.org/10.1111/gcb.15951>
86. Michaelian M, Hogg EH, Hall RJ, Arsenault E (2011) Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Glob Change Biol* 17:2084–2094. <https://doi.org/10.1111/j.1365-2486.2010.02357.x>
87. Morison MQ, Petrone RM, Wilkinson SL, et al (2020) Ecosystem scale evapotranspiration and CO₂ exchange in burned and unburned peatlands: Implications for the ecohydrological resilience of carbon stocks to wildfire. *Ecohydrology* 13:e2189. <https://doi.org/10.1002/eco.2189>
88. Natali SM, Holdren JP, Rogers BM, et al (2021) Permafrost carbon feedbacks threaten global climate goals. *Proc Natl Acad Sci* 118:e2100163118. <https://doi.org/10.1073/pnas.2100163118>
89. Nitze I, Cooley SW, Duguay CR, et al (2020) The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska: fast-forward into the future. *The Cryosphere* 14:4279–4297. <https://doi.org/10.5194/tc-14-4279-2020>
90. Nitze I, Heidler K, Barth S, Grosse G (2021) Developing and Testing a Deep Learning Approach for Mapping Retrogressive Thaw Slumps. *Remote Sens* 13:4294. <https://doi.org/10.3390/rs13214294>
91. Obu J, Westermann S, Bartsch A, et al (2019) Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km² scale. *Earth-Sci Rev* 193:299–316. <https://doi.org/10.1016/j.earscirev.2019.04.023>
92. Olefeldt D, Goswami S, Grosse G, et al (2016) Circumpolar distribution and carbon storage of thermokarst landscapes. *Nat Commun* 7:13043. <https://doi.org/10.1038/ncomms13043>
93. Pan CG, Kirchner PB, Kimball JS, et al (2018) Rain-on-snow events in Alaska, their frequency and distribution from satellite observations. *Environ Res Lett* 13:075004. <https://doi.org/10.1088/1748-9326/aac9d3>
94. Parmentier F-JW, Nilsen L, Tømmervik H, et al (2024) Rapid Ice-Wedge Collapse and Permafrost Carbon Loss Triggered by Increased Snow Depth and Surface Runoff. *Geophys Res Lett* 51:e2023GL108020. <https://doi.org/10.1029/2023GL108020>
95. Parmentier F-JW, Rasse DP, Lund M, et al (2018) Vulnerability and resilience of the carbon exchange of a subarctic peatland to an extreme winter event. *Environ Res Lett* 13:065009. <https://doi.org/10.1088/1748-9326/aabff3>
96. Pasher J, Seed E, Duffe J (2013) Development of boreal ecosystem anthropogenic disturbance layers for Canada based on 2008 to 2010 Landsat imagery. *Can J Remote Sens* 39:42–58. <https://doi.org/10.5589/m13-007>
97. Phillips CA, Rogers BM, Elder M, et al (2022) Escalating carbon emissions from North American boreal forest wildfires and the climate mitigation potential of fire management. *Sci Adv* 8:eabl7161. <https://doi.org/10.1126/sciadv.abl7161>
98. Phoenix GK, Bjerke JW (2016) Arctic browning: extreme events and trends reversing arctic greening. *Glob Change Biol* 22:2960–2962. <https://doi.org/10.1111/gcb.13261>
99. Pickett STA, White PS (1985) *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, Inc., San Diego, CA
100. Potter S, Cooperdock S, Veraverbeke S, et al (2023) Burned area and carbon emissions across northwestern boreal North America from 2001–2019. *Biogeosciences* 20:2785–2804. <https://doi.org/10.5194/bg-20-2785-2023>
101. Povoroznyuk O, Vincent WF, Schweitzer P, et al (2023) Arctic roads and railways: social and environmental consequences of transport infrastructure in the circumpolar North. *Arct Sci* 9:297–330. <https://doi.org/10.1139/as-2021-0033>
102. Pureswaran DS, Roques A, Battisti A (2018) Forest Insects and Climate Change. *Curr For Rep* 4:35–50. <https://doi.org/10.1007/s40725-018-0075-6>
103. Putkonen J, Grenfell TC, Rennert K, et al (2009) Rain on Snow: Little Understood Killer in the North. *Eos Trans Am Geophys Union* 90:221–222. <https://doi.org/10.1029/2009EO260002>
104. Raffa KF, Aukema BH, Bentz BJ, et al (2008) Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *BioScience* 58:501–517. <https://doi.org/10.1641/B580607>

105. Ramage J, Kuhn M, Virkkala A-M, et al (2024) The Net GHG Balance and Budget of the Permafrost Region (2000–2020) From Ecosystem Flux Upscaling. *Glob Biogeochem Cycles* 38:e2023GB007953. <https://doi.org/10.1029/2023GB007953>
106. Rantanen M, Kämäräinen M, Luoto M, Aalto J (2024) Manifold increase in the spatial extent of heatwaves in the terrestrial Arctic. *Commun Earth Environ* 5:1–8. <https://doi.org/10.1038/s43247-024-01750-8>
107. Rocha AV, Loranty MM, Higuera PE, et al (2012) The footprint of Alaskan tundra fires during the past half-century: implications for surface properties and radiative forcing. *Environ Res Lett* 7:044039. <https://doi.org/10.1088/1748-9326/7/4/044039>
108. Rodenhizer H, Belshe F, Celis G, et al (2022) Abrupt permafrost thaw accelerates carbon dioxide and methane release at a tussock tundra site. *Arct Antarct Alp Res* 54:443–464. <https://doi.org/10.1080/15230430.2022.2118639>
109. Rodenhizer H, Natali SM, Mauritz M, et al (2023) Abrupt permafrost thaw drives spatially heterogeneous soil moisture and carbon dioxide fluxes in upland tundra. *Glob Change Biol* 29:6286–6302. <https://doi.org/10.1111/gcb.16936>
110. Romualdi DC, Wilkinson SL, James PMA (2023) On the limited consensus of mountain pine beetle impacts on wildfire. *Landsc Ecol* 38:2159–2178. <https://doi.org/10.1007/s10980-023-01720-z>
111. Runge A, Nitze I, Grosse G (2022) Remote sensing annual dynamics of rapid permafrost thaw disturbances with LandTrendr. *Remote Sens Environ* 268:112752. <https://doi.org/10.1016/j.rse.2021.112752>
112. Sayedi SS, Abbott BW, Thornton BF, et al (2020) Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment. *Environ Res Lett* 15:124075. <https://doi.org/10.1088/1748-9326/abcc29>
113. Schädel C, Rogers BM, Lawrence DM, et al (2024) Earth system models must include permafrost carbon processes. *Nat Clim Change* 1–3. <https://doi.org/10.1038/s41558-023-01909-9>
114. Schneider von Deimling T, Lee H, Ingeman-Nielsen T, et al (2021) Consequences of permafrost degradation for Arctic infrastructure – bridging the model gap between regional and engineering scales. *The Cryosphere* 15:2451–2471. <https://doi.org/10.5194/tc-15-2451-2021>
115. Scholten RC, Coumou D, Luo F, Veraverbeke S (2022) Early snowmelt and polar jet dynamics co-influence recent extreme Siberian fire seasons. *Science* 378:1005–1009. <https://doi.org/10.1126/science.abn4419>
116. Schuur EAG, Abbott BW, Bowden WB, et al (2013) Expert assessment of vulnerability of permafrost carbon to climate change. *Clim Change* 119:359–374. <https://doi.org/10.1007/s10584-013-0730-7>
117. Schuur EAG, Abbott BW, Commane R, et al (2022) Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic. *Annu Rev Environ Resour* 33
118. Schuur EAG, McGuire AD, Romanovsky VE, et al (2018) Ch. 11: Arctic and boreal carbon. In: Cavallaro N, Shrestha G, Birdsey R, et al. (eds) *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. U.S. Global Change Research Program, Washington, D.C., pp 428–468
119. Schuur EAG, McGuire AD, Schädel C, et al (2015) Climate change and the permafrost carbon feedback. *Nature* 520:171–179. <https://doi.org/10.1038/nature14338>
120. See CR, Virkkala A-M, Natali SM, et al (2024) Decadal increases in carbon uptake offset by respiratory losses across northern permafrost ecosystems. *Nat Clim Change* 14:853–862. <https://doi.org/10.1038/s41558-024-02057-4>
121. Siewert MB, Olofsson J (2021) UAV reveals substantial but heterogeneous effects of herbivores on Arctic vegetation. *Sci Rep* 11:19468. <https://doi.org/10.1038/s41598-021-98497-5>
122. Strack M, Hayne S, Lovitt J, et al (2019) Petroleum exploration increases methane emissions from northern peatlands. *Nat Commun* 10:2804. <https://doi.org/10.1038/s41467-019-10762-4>
123. Strack M, Softa D, Bird M, Xu B (2018) Impact of winter roads on boreal peatland carbon exchange. *Glob Change Biol* 24:e201–e212. <https://doi.org/10.1111/gcb.13844>
124. Strauss J, Schirrmeister L, Grosse G, et al (2017) Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability. *Earth-Sci Rev* 172:75–86. <https://doi.org/10.1016/j.earscirev.2017.07.007>
125. Talucci AC, Krawchuk MA (2019) Dead forests burning: the influence of beetle outbreaks on fire severity and legacy structure in sub-boreal forests. *Ecosphere* 10:e02744. <https://doi.org/10.1002/ecs2.2744>
126. Talucci AC, Loranty MM, Alexander HD (2022) Siberian taiga and tundra fire regimes from 2001–2020. *Environ Res Lett* 17:025001. <https://doi.org/10.1088/1748-9326/ac3f07>
127. Talucci AC, Matosziuk LM, Hatten JA, Krawchuk MA (2020) An added boost in pyrogenic carbon when wildfire burns forest with high pre-fire mortality. *Fire Ecol* 16:21. <https://doi.org/10.1186/s42408-020-00081-1>
128. Tape KD, Jones BM, Arp CD, et al (2018) Tundra be dammed: Beaver colonization of the Arctic. *Glob Change Biol* 24:4478–4488. <https://doi.org/10.1111/gcb.14332>
129. Treharne R, Rogers BM, Gasser T, et al (2022) Identifying Barriers to Estimating Carbon Release From Interacting Feedbacks in a Warming Arctic. *Front Clim* 3:716464. <https://doi.org/10.3389/fclim.2021.716464>
130. Turetsky MR, Abbott BW, Jones MC, et al (2020) Carbon release through abrupt permafrost thaw. *Nat Geosci* 13:138–143. <https://doi.org/10.1038/s41561-019-0526-0>
131. Varner RK, Crill PM, Frolking S, et al (2021) Permafrost thaw driven changes in hydrology and vegetation cover increase trace gas emissions and climate forcing in Stordalen Mire from 1970 to 2014. *Philos Trans R Soc Math Phys Eng Sci* 380:20210022. <https://doi.org/10.1098/rsta.2021.0022>
132. Veraverbeke S, Rogers BM, Goulden ML, et al (2017) Lightning as a major driver of recent large fire years in North American boreal forests. *Nat Clim Change* 7:529–534. <https://doi.org/10.1038/nclimate3329>

133. Vikhamar-Schuler D, Isaksen K, Haugen JE, et al (2016) Changes in Winter Warming Events in the Nordic Arctic Region. *J Clim* 29:6223–6244. <https://doi.org/10.1175/JCLI-D-15-0763.1>
134. Virkkala A, Aalto J, Rogers BM, et al (2021) Statistical upscaling of ecosystem CO₂ fluxes across the terrestrial tundra and boreal domain: Regional patterns and uncertainties. *Glob Change Biol* gcb.15659. <https://doi.org/10.1111/gcb.15659>
135. Virkkala A-M, Abdi AM, Luoto M, Metcalfe DB (2019) Identifying multidisciplinary research gaps across Arctic terrestrial gradients. *Environ Res Lett* 14:124061. <https://doi.org/10.1088/1748-9326/ab4291>
136. Virkkala A-M, Natali SM, Rogers BM, et al (2022) The ABCflux database: Arctic–boreal CO₂ flux observations and ancillary information aggregated to monthly time steps across terrestrial ecosystems. *Earth Syst Sci Data* 14:179–208. <https://doi.org/10.5194/essd-14-179-2022>
137. Virkkala A-M, Rogers BM, Watts JD, et al (2025) Wildfires offset the increasing but spatially heterogeneous Arctic–boreal CO₂ uptake. *Nat Clim Change* 15:188–195. <https://doi.org/10.1038/s41558-024-02234-5>
138. Walker XJ, Baltzer JL, Cumming SG, et al (2019) Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* 572:520–523. <https://doi.org/10.1038/s41586-019-1474-y>
139. Walker XJ, Rogers BM, Veraverbeke S, et al (2020) Fuel availability not fire weather controls boreal wildfire severity and carbon emissions. *Nat Clim Change* 10:1130–1136. <https://doi.org/10.1038/s41558-020-00920-8>
140. Walsh JE, Ballinger TJ, Euskirchen ES, et al (2020) Extreme weather and climate events in northern areas: A review. *Earth-Sci Rev* 209:103324. <https://doi.org/10.1016/j.earscirev.2020.103324>
141. Webb H, Fuchs M, Abbott BW, et al (2025) A Review of Abrupt Permafrost Thaw: Definitions, Usage, and a Proposed Conceptual Framework. *Curr Clim Change Rep* 11:7. <https://doi.org/10.1007/s40641-025-00204-3>
142. Wilkinson SL, Andersen R, Moore PA, et al (2023) Wildfire and degradation accelerate northern peatland carbon release. *Nat Clim Change* 13:456–461. <https://doi.org/10.1038/s41558-023-01657-w>
143. Williams JP, Regehr A, Kang M (2021) Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States. *Environ Sci Technol* 55:563–570. <https://doi.org/10.1021/acs.est.0c04265>
144. Williams M, Zhang Y, Estop-Aragónés C, et al (2020) Boreal permafrost thaw amplified by fire disturbance and precipitation increases. *Environ Res Lett* 15:114050. <https://doi.org/10.1088/1748-9326/abbeb8>
145. Yang Y, Rogers BM, Fiske G, et al (2023) Mapping retrogressive thaw slumps using deep neural networks. *Remote Sens Environ* 288:113495. <https://doi.org/10.1016/j.rse.2023.113495>
146. Zhang Y, Wang JA, Berner LT, et al (2024) Warming and disturbances affect Arctic-boreal vegetation resilience across northwestern North America. *Nat Ecol Evol* 1–12. <https://doi.org/10.1038/s41559-024-02551-0>
147. Zheng B, Ciais P, Chevallier F, et al (2023) Record-high CO₂ emissions from boreal fires in 2021. *Science* 379:912–917. <https://doi.org/10.1126/science.ade0805>
148. Zolkos S, Fiske G, Windholz T, et al (2021) Detecting and Mapping Gas Emission Craters on the Yamal and Gydan Peninsulas, Western Siberia. *Geosciences* 11:21. <https://doi.org/10.3390/geosciences11010021>
149. Zolkos S, Tank SE, Kokelj SV, et al (2022) Permafrost Landscape History Shapes Fluvial Chemistry, Ecosystem Carbon Balance, and Potential Trajectories of Future Change. *Glob Biogeochem Cycles* 36:. <https://doi.org/10.1029/2022GB007403>

Figures

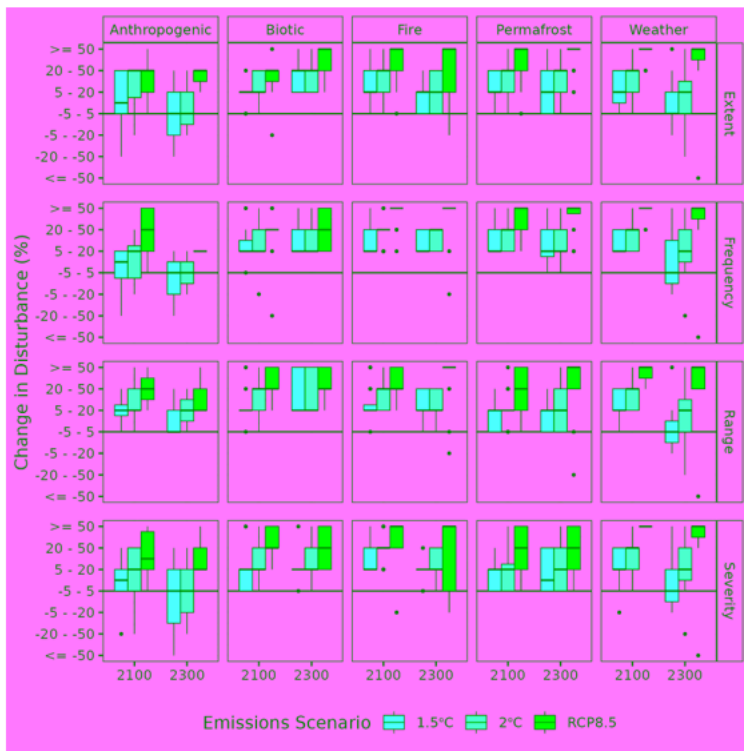


Figure 1

Expert estimates for future change in disturbance prevalence (separated into extent, frequency, range, and severity) relative to the current time period (2000-2020) for different disturbance types and emissions pathways.

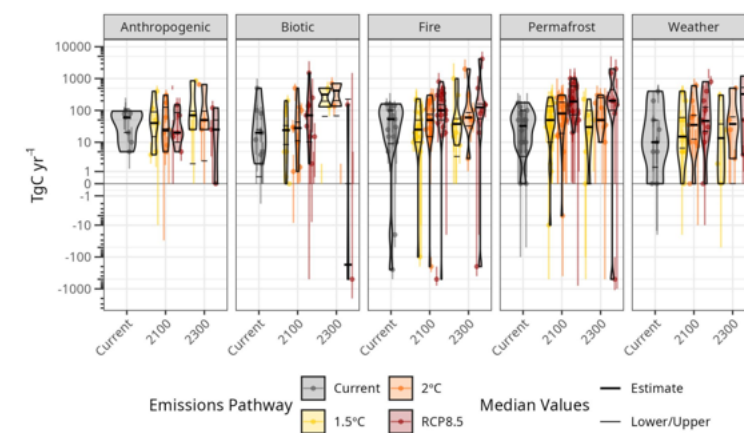


Figure 2

Expert estimates for carbon impact of disturbances. The current time period represents 2000-2020, while the 2100 and 2300 time periods represent the average annual change in carbon impact relative to the current period for 2020-2100 or 2020-2300. Points (median estimate) and error bars (lower and upper estimate) represent individual responses, while the horizontal lines represent median values across respondents. Note the logarithmic scale for y-axes.

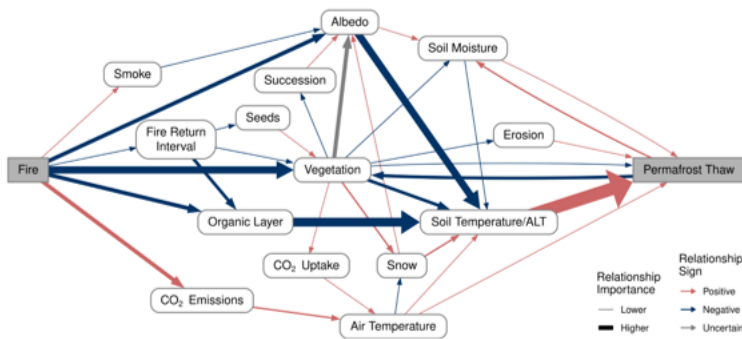


Figure 3

Flowchart of expert-informed interacting relationships between fire and permafrost. Direction of causality is indicated with the direction of the arrows. Blue arrows indicate a negative relationship, red arrows indicate a positive relationship, and gray arrows indicate disagreement among respondents about the sign of the relationship. The sign of the relationship is indicative of a specific arrow, not an entire path. For example, fire causes a reduction in the organic layer thickness and a thicker organic layer keeps soil temperature lower, such that when combined, fire causes an increase in soil temperature. Relationship importance is indicated by arrow width, reflecting both the number of times the relationship appeared in individual flowcharts and the level of importance individuals attributed to it.

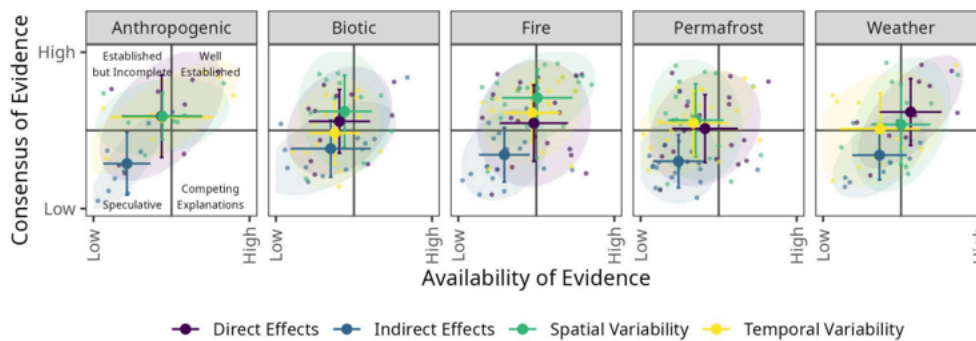


Figure 4

Expert opinion on the state of the research (mean $\pm$ std. dev.) for direct effects of disturbances on net carbon emissions, indirect effects of disturbances on net carbon emissions, spatial variability, and temporal variability of disturbances. Individual responses and the 80% density regions (multivariate normal estimation) are shown in the background. Full descriptions of each quadrant are provided in Appendix 1.

Supplementary Files

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- [Appendix1.docx](#)
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