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TOPICAL REVIEW

Disturbances in North American boreal forest and Arctic tundra: impacts, interactions, and responses

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Abstract

Ecosystems in the North American Arctic-Boreal Zone (ABZ) experience a diverse set of disturbances associated with wildfire, permafrost dynamics, geomorphic processes, insect outbreaks and pathogens, extreme weather events, and human activity. Climate warming in the ABZ is occurring at over twice the rate of the global average, and as a result the extent, frequency, and severity of these disturbances are increasing rapidly. Disturbances in the ABZ span a wide gradient of spatiotemporal scales and have varying impacts on ecosystem properties and function. However, many ABZ disturbances are relatively understudied and have different sensitivities to climate and trajectories of recovery, resulting in considerable uncertainty in the impacts of climate warming and human land use on ABZ vegetation dynamics and in the interactions between disturbance types. Here we review the current knowledge of ABZ disturbances and their precursors, ecosystem impacts, temporal frequencies, spatial extents, and severity. We also summarize current knowledge of interactions and feedbacks among ABZ disturbances and characterize typical trajectories of vegetation loss and recovery in response to ecosystem disturbance using satellite time-series. We conclude with a summary of critical data and knowledge gaps and identify priorities for future study.

1. Introduction

In the North American Arctic-Boreal Zone (ABZ), climate change and human activity are rapidly and extensively reshaping vegetation dynamics via a range of disturbance processes, resulting in considerable uncertainty in the fate of these ecosystems (Shaw *et al* 2021). Many disturbances (i.e. an event that alters ecosystem composition, structure, function, or the physical environment, Pickett and White 1985) trigger a transient reduction and gradual recovery of vegetation cover and ecosystem function (Liu *et al* 2011, Li *et al* 2021), although there is high variability in the nature and pace of these changes depending on the type and severity of disturbance (Jorgenson *et al* 2015, Gaglioti *et al* 2021) (figure 1). Climate warming is occurring in the ABZ at more than twice the global average rate (Price *et al* 2013, Smith *et al* 2019, Chylek *et al* 2022, Rantanen *et al* 2022), and many disturbance processes are highly sensitive to climate. Consequently, the impact of climate change via disturbance on ABZ vegetation dynamics is expected to increase over the next century (Price *et al* 2013, Gauthier *et al* 2015, Bush and Lemmen 2019, Smith *et al* 2019).

Disturbance-driven loss and subsequent recovery of vegetation partly explain widespread trends in satellite-observed vegetation indices (i.e. 'greening' and 'browning') within the North American ABZ (Ju and Masek 2016, Sulla-Menashe *et al* 2018, Wang and Friedl 2019). Large-scale greening trends across the ABZ are complex (Myers-Smith *et al* 2020), but have generally been interpreted as an increase in ecosystem productivity driven by climatic warming and recovery from disturbance (Bhatt *et al* 2010, Berner *et al* 2020). Meanwhile, areas of browning are generally attributed to vegetation stress from disturbances such as fires, insect outbreaks, warming-induced drought, and increased surface water associated with permafrost degradation (Goetz *et al* 2005, Shur and Jorgenson 2007, Verbyla 2011, Berner and Goetz 2022). Many of these disturbances are increasing in their extent, frequency, and/or severity because of climatic changes and increasing anthropogenic pressures (Jorgenson *et al* 2006, Baltzer *et al* 2021). Understanding the net impact of climate change and its effects on different disturbance regimes is critical for forecasting future ABZ composition, dynamics, ecosystem services, and potential management responses.

As in many other ecosystems, fires have dramatic and extensive impacts on vegetation cover and carbon dynamics in the ABZ, and exceptional warming in this region is intensifying fire regimes (Soja *et al* 2007, Kasischke *et al* 2010, Veraverbeke *et al* 2017, McCarty *et al* 2021, Whitman *et al* 2022). However, the unique characteristics of ABZ ecosystems result in additional types of disturbances that lack analogs in tropical and temperate ecosystems. The wide extent of permafrost (i.e. perennially frozen ground; Gruber 2012) that underlies large parts of the northern high-latitudes makes these ecosystems vulnerable to a unique set of other disturbances (Shur and Jorgenson 2007). For example, thawing permafrost causes ground surface subsidence that can induce persistent changes in hydrology, vegetation, and microtopography in ABZ landscapes with high ground-ice contents (Grosse *et al* 2011, Jones *et al* 2015, Carpino *et al* 2018, Farquharson *et al* 2019, Swanson 2021). Exceptional warming in the ABZ also makes high-latitude forests vulnerable to increasing incidences of drought and insect outbreaks (Volney and Fleming 2000, Hogg *et al* 2008, Kurz *et al* 2008). Natural resource development activities such as oil and gas well exploration and production and logging introduce additional complexity to disturbance regimes (Gauthier *et al* 2015, Shaw *et al* 2021) in various parts of the region (Williams *et al* 2013, Pasher *et al* 2013, Raynolds *et al* 2014, Williams *et al* 2021).

Fire is a key driver of the carbon balance of boreal ecosystems (Harden *et al* 2000, Bond-Lamberty *et al* 2007, Wang *et al* 2021), but the relative importance and impacts of other disturbance types have been less studied (Shaw *et al* 2021). Thus, it remains unclear how much these other disturbance types and their interactions (Buma 2015) impact ABZ ecosystems. In this review, we summarize the existing state of knowledge of major disturbance types in North American ABZ ecosystems and use case studies of Landsat satellite-derived time series of vegetation greenness and moisture indices to illustrate the distinct spatiotemporal characteristics of vegetation loss and recovery associated with each disturbance type. Additionally, we review interactions between disturbances, which are likely to intensify in the future (Buma 2015, Seidl *et al* 2017).

In this review, we focus on 'pulse' disturbances, characterized as generally abrupt, relatively discrete events that rapidly alter ecosystem structure, resources, or the physical environment (Pickett and White 1985). We do not address 'press' disturbances which impact ecosystems slowly over decades and centuries (e.g. long-term warming; Grosse *et al* 2011). We divide major ABZ disturbances into several categories: (a) fire; (b) insects and pathogens; (c) permafrost-related disturbances; (d) anthropogenic disturbances; (e) weather-related disturbances; (f) riverine processes; and (g) ungulate and grazer activity. These disturbance types are not meant to be an exhaustive list of all known disturbances within the North American ABZ, but rather a characterization and discussion of the major climate-sensitive and anthropogenic disturbances within the region that impact vegetation processes. We do not, for example, include coastal erosion, alpine landscapes (e.g. avalanches), or localized geologic settings (e.g. volcanism).

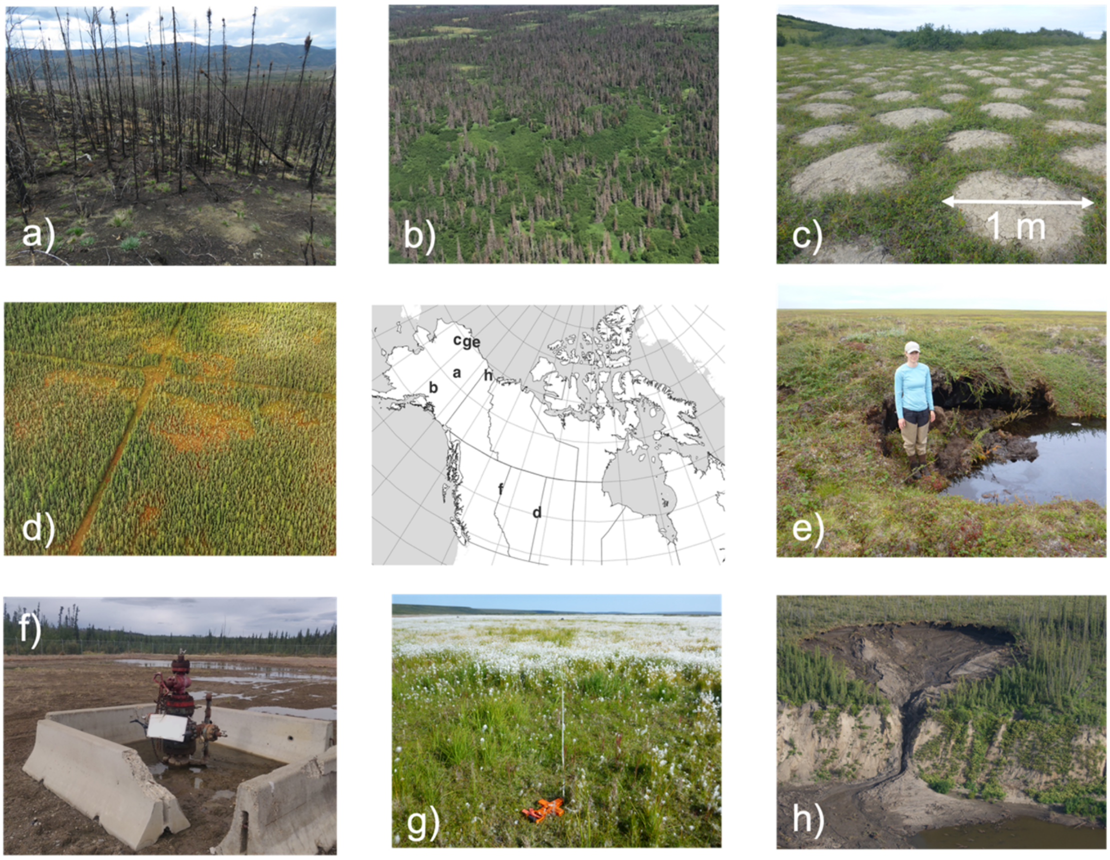

Figure 1. Examples of disturbances and successional responses in North American Arctic and boreal forest ecosystems. (a) Burned (2020) upland black spruce forest in early succession, Interior Alaska; (b) spruce beetle infestation in 2016, south-central Alaska,; Photo by Bruce Cook, reproduced with permission; (c) non-sorted circles arising from cryoturbation, Alaska North Slope; (d) seismic line disturbance cutting across a treed peatland, northern Alberta, Canada; (e) thermokarst after ice-wedge degradation, Alaska North Slope; (f) suspended oil and gas well, drilled in 2006, north-eastern British Columbia, Canada; (g) recently drained lake basin in early succession, Alaska North Slope; (h) thaw slump, Old Crow Flats, Yukon, Canada.

By considering a range of major disturbance types, we seek to answer a set of interrelated questions: *What are the distinct causes of each disturbance type, and how are disturbance regimes (i.e. extent, frequency, and severity) sensitive to climate change and human activity? How does each disturbance type impact vegetation composition, structure, and recovery? How do different disturbance regimes interact with each other?* In doing so, we aim to provide context, identify data and knowledge gaps, and lay the groundwork for future studies that analyze how the full suite of disturbance agents are reshaping the vegetation dynamics of ABZ ecosystems.

2. Methods

This paper discusses the background, outstanding science questions, and data relevant to each of the seven broad disturbance categories. We also introduce case studies showcasing typical vegetation loss and recovery in response to select disturbances evident from remote sensing data.

2.1. Literature survey

Articles referenced in the background (section 3), spatiotemporal characteristics (section 4), and interactions (section 5) sections were selected based on a thematic literature review as well as our own bibliographic lists derived from our active research in these fields. We searched the peer-reviewed literature using terms related to each disturbance category and type and biome (e.g. 'boreal forest windthrow', 'cryoturbation', 'ice-jam flooding'). We emphasized recent (since 2014) papers and studies published on the North American boreal and Arctic ecosystems; however, we included studies from Eurasia to supplement topics where North American studies are lacking and to expand the global relevancy of this review.

2.2. Case studies and datasets

To evaluate patterns of vegetation loss and recovery after different disturbance types we compiled a set of locations ($n = 397$) of known disturbances within the North American ABZ to serve as case studies (figure 2). We compiled locations of known disturbance occurrences based on expert knowledge and field work of the authors as well as published locations in the literature and existing disturbance databases (table S1). For each case study, we analyzed vegetation greenness and moisture changes during and following disturbance using time series of surface reflectance

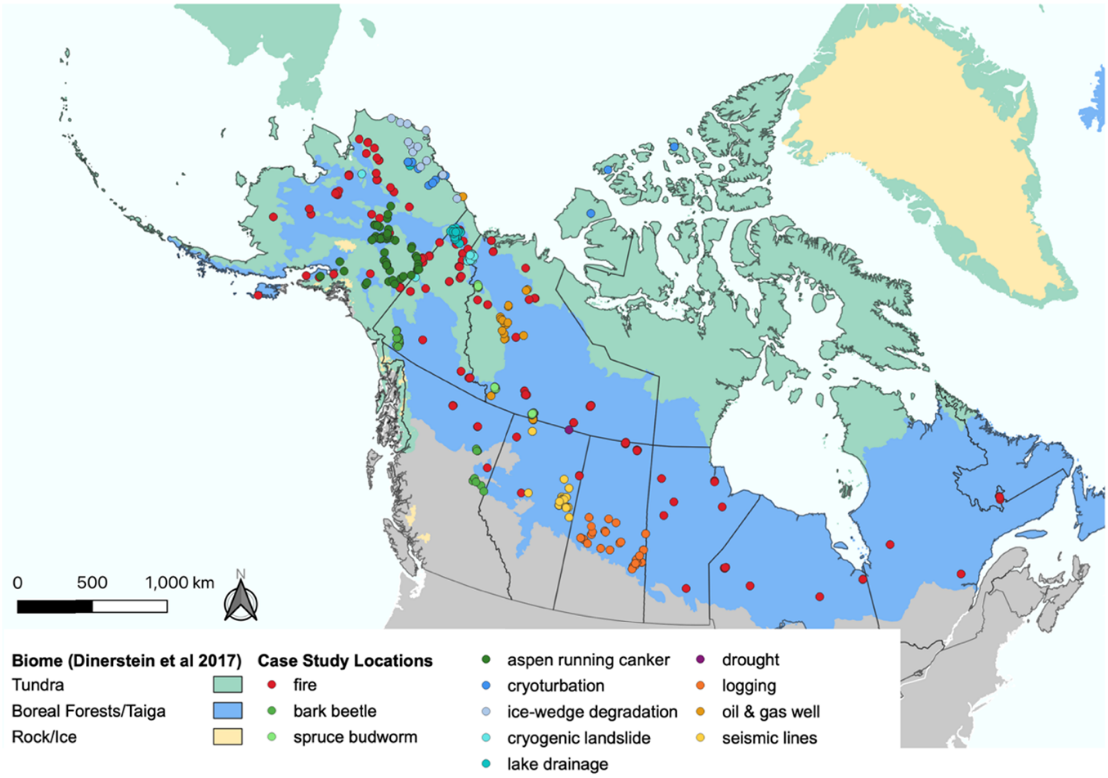

Figure 2. Locations of case study sites for disturbance types in the North American ABZ. Locations for spruce budworm and extreme drought provided by, and is the property of, the Forest Management Division, Department of Environment and Natural Resources, Government of the Northwest Territories.

data from the Landsat series of satellites (1985–2020; Wulder *et al* 2019).

For case study locations derived from individual latitude and longitude points, we extracted Landsat time series within a 100 m buffer surrounding each site to mitigate issues with geospatial accuracy of the case study locations. For case study locations derived from polygons, polygons were first filtered to only include 'severe' impacts (if known), as well as disturbances that occurred between 2001 and 2016 to ensure adequate temporal coverage of pre- and post-disturbance vegetation greenness and wetness. The selected polygons were then randomly sampled ($n = 25$ per disturbance type), and 30 m Landsat pixels were randomly selected within each sampled polygon ($n = 50$ per polygon). For fire disturbance, in order to ensure broad coverage of diverse ecological conditions present within the North American ABZ, ten random points were sampled within each of five random fire polygons per Level II Ecoregion (US EPA 2015).

2.3. Case study analysis

We calculated spectral indices representing land surface greenness (the Normalized Difference Vegetation Index—NDVI; Rouse *et al* 1974, Tucker 1979) and wetness (the Normalized Difference Moisture Index—NDMI; Gao 1996). NDVI is a widely used index that is sensitive to leaf chlorophyll content and is generally correlated with vegetative cover and photosynthetic productivity. However, NDVI is less sensitive to changes in the state of evergreen forests (Jin *et al* 2017), which are the dominant forest type in the ABZ (Gauthier *et al* 2015). NDMI is an index that is sensitive to leaf water content and may reflect more subtle changes in vegetative stress in evergreen trees (Goulden and Bales 2019). While more specific and fine-scale indices may lend more information about, for example, species composition changes following disturbance, the use of NDVI and NDMI allows for broad coverage of the impact of different disturbances on vegetative cover and condition. Changes in NDVI and NDMI thus are interpreted as vegetation loss (e.g. declining NDVI or NDMI) and recovery (e.g. increasing NDVI or NDMI) in response to disturbance.

We developed time series of annual summer maximum greenness and wetness for the case study sites (table S1). For each sampled location, we extracted all available Landsat 5, 7, and 8 surface reflectance data acquired each summer (day-of-year 151–242; 31 May–31 August) from 1985 to 2020 for a total of ~11 000 000 multi-band measurements tallied across all pixels. These data were retrieved from the Landsat Collection 2 surface reflectance dataset (Masek *et al* 2006, USGS 2021), accessed using Google Earth Engine (Gorelick *et al* 2017) and functions provided by the *lsatTS* package (Berner *et al* 2021, accepted) in R (R Core Team 2021). We quality-screened these

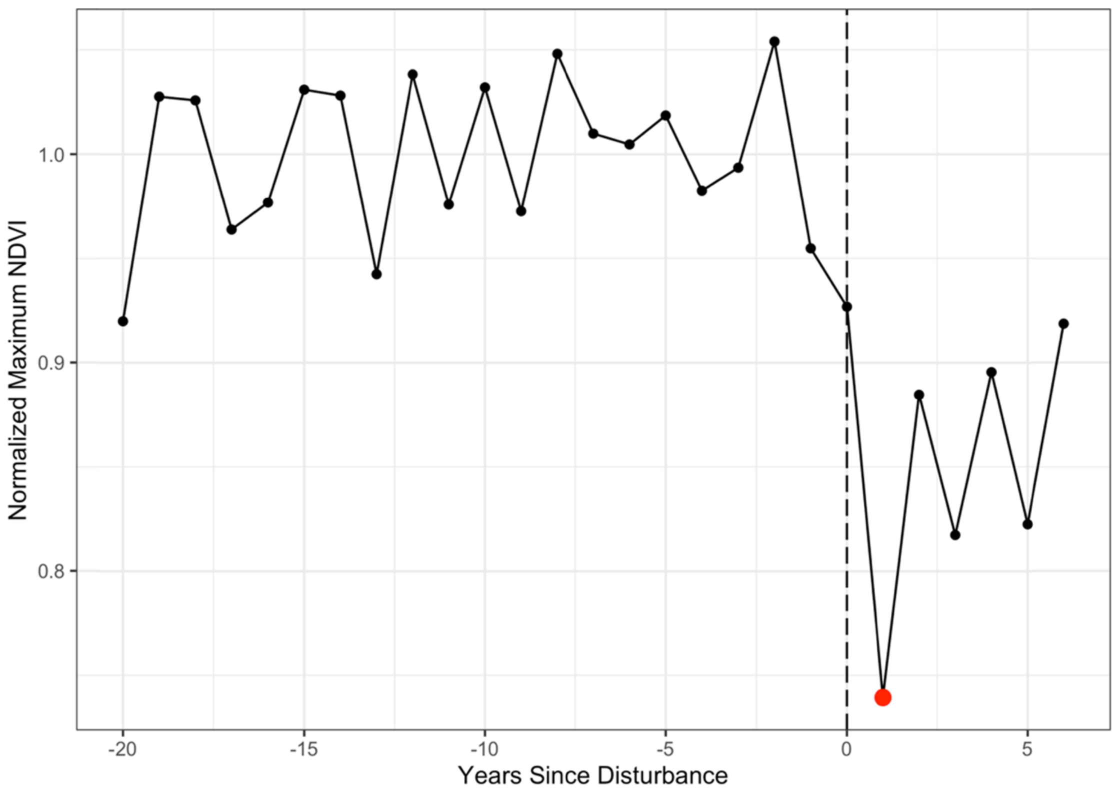

Figure 3. Example normalized maximum growing season NDVI for a site in the Northwest Territories, Canada (67.023°, −123.348°), where the NDVI is normalized to the pre-disturbance mean. A fire occurred in 2014 (dashed line). The red dot corresponds to the year of maximum impact of the fire on NDVI.

surface reflectance measurements based on pixel- and scene-criteria (i.e. scene-wide cloud cover <80%, geometric uncertainty <30 m, and solar zenith angle <60°) and further cross-calibrated them among Landsat sensors using the *lsatTS* package. Cross-sensor calibration is necessary to avoid spurious trends in NDVI and other spectral indices that arise from systematic differences in spectral bands among Landsat sensors (Sulla-Menashe *et al* 2016, Berner *et al* 2021). We calculated annual summer maximum surface greenness (NDVI) and wetness (NDMI) at each sampled location as the maximum summer NDVI or NDMI. Overall, we developed 14 709 annual time series of surface greenness and wetness for recently disturbed pixels across the study domain (table S1).

Because some case study locations were approximate or derived from large aerial survey polygons, not all pixels were located over an actual disturbed area. Therefore, to focus our analyses on pixels that captured disturbance events, we filtered pixels to those that included detectable disturbance impacts on NDVI and NDMI within five years of the known disturbance event, except for cryoturbation and ice-wedge degradation, which occur within landscape mosaics and do not correspond to a single 'event'. Aside from cryoturbation and ice-wedge degradation, disturbances were identified using visual interpretation of each time series and via the Breaks For Additive Season and Trend (BFAST) algorithm in the *bfast* package (Verbesselt and Herold 2012) in R (figure S1). BFAST iteratively estimates abrupt changes (or 'breakpoints') within time series and can be used to analyze seasonal and annual time series of satellite-observed reflectance to detect statistically significant temporal changes (Verbesselt *et al* 2010, Verbesselt and Herold 2012).

Following breakpoint detection, each time series with detected breakpoints was smoothed using the R function *smooth* (Tukey 1977), and inflection points were identified in the smoothed time series. The series was first smoothed to identify 'true' changes in the vegetation index trajectory, rather than those simply due to noise or interannual variability. The inflection point with the minimum (or maximum, for NDVI of lake drainage) spectral index value was identified as the year of full effect from the disturbance on land surface greenness and wetness. The time series before the breakpoint and following any breakpoints detected earlier in the series (e.g. between 1994 and 2014 in figure S1) was used to calculate an average pre-disturbance mean NDVI and NDMI. Each time series was then normalized by its pre-disturbance mean ($NDVI_{norm} = NDVI/NDVI_{mean}$, figure 3). We normalized the time series to better compare within and between disturbances, which occurred in different biomes and bioclimatic regions.

These normalized time series were used as our case study trajectories to evaluate the impact of each disturbance on vegetation as well as the magnitude, direction, and speed of recovery following each disturbance (see section 3).

2.4. Disturbance characteristics and interactions

The major ABZ disturbance types have distinct spatial, temporal, and severity characteristics. To compare the spatial and temporal dynamics among disturbances, we developed several spatiotemporal metrics. *Spatial grain* describes the average extent of an individual disturbance event (e.g. for a wildfire it would be the size of a polygon associated with the outer perimeter of the burn scar, but for insect infestation it might be a single tree or forest stand). *Return interval* refers to the average length of time for the disturbance to reoccur in the same location. *Occurrence timeline* describes the average length of time a disturbance event lasts from initiation to completion (e.g. for wildfire: from ignition to extinction). *Recovery timeline* refers to the average length of time it takes for the vegetation/ecosystem to return to pre-disturbance conditions. Finally, *intensity/impact* refers to the average effect on vegetation and the ecosystem, from vegetation stress to complete vegetation mortality. We determined qualitative values for each of these categories and disturbance types using scientific literature and expert knowledge (see section 4). The metrics were converted into relative numerical scales (table S2) and applied to a principal component analysis (PCA) to understand how the different metrics correlate with one another across the different disturbance types. The PCA was conducted using the R function *prcomp*, with the categorical metrics scaled and centered within the PCA.

The degree to which different disturbance types interact with each other is complex and not well understood, and critical feedbacks between disturbances make their potential impacts difficult to analyze and predict. Therefore, we developed a disturbance interaction matrix based on our literature survey and expert knowledge. This matrix describes the impact (strong/weak positive, strong/weak negative, both, none, or unknown) of a 'driver' disturbance on potential subsequent 'response' disturbances (see section 5). We distinguish 'strong' and 'weak' interactions by their relative effect on ecosystem structure and function, the ubiquity and likelihood of this impact occurring, and the ability of the ecosystem to resist or recover from subsequent response disturbances. For example, we classify the impact of boreal windthrow on subsequent insect and pathogen disturbance as 'strong positive' (figure 20), because this interaction is a well-documented and impactful phenomenon within forested ecosystems (e.g. Malmstrom and Raffa 2000). In contrast, we classify the impact of logging on subsequent windthrow events as 'weak positive' (figure 20), because while forest fragmentation, such as that created by forest harvest, does impart higher susceptibility to windthrow (Meilby *et al* 2001, Peterson 2004), the low probability of windthrow in boreal North America (Bouchard *et al* 2009) reduces the overall impact of this interaction. See section 5 for a further discussion of these interactions.

3. Disturbance agents in North American Arctic and boreal ecosystems

3.1. Fire

3.1.1. Background

Wildfire is the most well-studied disturbance agent in forests of boreal North America, as fires have substantial impacts on human settlements (Kent 2017), subsistence resources (Nelson *et al* 2008), and air quality (Trainor *et al* 2009), in addition to climate (Randerson *et al* 2006, Potter *et al* 2020b) and vegetation (Rogers *et al* 2013, Foster *et al* 2022). Fires in boreal North America are generally high-intensity crown fires that kill most affected trees and consume substantial belowground carbon stocks, in contrast to those in boreal Eurasia or more temperate ecosystems which include a high fraction of lower-severity surface fires that result in relatively low tree mortality (Stocks and Kaufmann 1997, de Groot *et al* 2013, Rogers *et al* 2015). Fire is less common in Arctic tundra but has been increasing in frequency and severity (Hu *et al* 2015, McCarty *et al* 2021), especially in the Beringian region (Racine *et al* 1985, Rocha *et al* 2012, Masrur *et al* 2018, Gaglioti *et al* 2021). Recent increases in boreal and Arctic wildfire activity may indicate fundamental shifts in the causes and impacts of the underlying fire regime, including overwintering fires that smolder during winter months and reappear the following year (Scholten *et al* 2021, Xu *et al* 2022), increased occurrence of lightning ignitions (Veraverbeke *et al* 2017, Chen *et al* 2021c), and long-term shifts in forest composition following these fires (Baltzer *et al* 2021, Mack *et al* 2021). Forest fire records throughout the North American boreal region show an increase in annual burned area and number of large fires since the mid-20th century (Calef *et al* 2015, Hanes *et al* 2019, Walker *et al* 2020b). The majority of projections of future fire regimes suggest increasing fire activity across boreal North America over the 21st century due to climate change (Bachelet *et al* 2005, Amiro *et al* 2009, Chen *et al* 2016, Hope *et al* 2016, Veraverbeke *et al* 2017, Wang *et al* 2020, Phillips *et al* 2022).

Precursors to fire in boreal ecosystems are well understood—an adequate amount of fuel and fuel dryness are required for fires to ignite and spread, in addition to ignition sources such as lightning strikes and anthropogenic activities (Veraverbeke *et al* 2017, Archibald *et al* 2018, Rogers *et al* 2020). In the boreal zone, fires are generally limited by fuel dryness and ignition sources because the characteristically deep organic and moss layers provide ample fuel. Both species composition and litter moisture are influenced by site drainage conditions, with organic-rich soils dominated by fire-prone and flammable species such as black spruce (*Picea mariana*). Conversely, Jack pine (*Pinus banksiana*) and less flammable deciduous species typically occur in well-drained locations with thinner, drier soils (Walker *et al* 2018, 2020b).

Lightning strikes ignite most fires in the North American ABZ. Lightning ignitions have increased since the mid-20th century due to a warmer and more convective atmosphere (Veraverbeke *et al* 2017, Chen *et al* 2021c). More severe fire weather is also prolonging fire seasons and increasing fire intensity and annual area burned. For example, Kasischke *et al* (2010) found the mean annual area burned in Alaska during the 2000s was 50% greater than any previous decade since the start of the record in 1940, resulting in increased ground-layer combustion and net carbon emissions to the atmosphere (Turetsky *et al* 2011).

Within the North American boreal region, fires create lasting legacies on vegetation, driving changes in soil characteristics, regeneration patterns, and successional trajectories (Johnstone *et al* 2010, Gaglioti *et al* 2021, Mack *et al* 2021). High-severity forest fires that remove much of the organic layer favor regeneration by deciduous and fast-growing pine species, which may maintain dominance under a warming climate (Johnstone *et al* 2011). Field data have also suggested that increased warming and fires may be altering the ability of typically resilient black spruce forests to recover following large fires, leading potentially to a tipping point for boreal vegetation—shifting from evergreen to deciduous or non-forested land cover types (Baltzer *et al* 2021). Alterations to phenological metrics from time series of NDVI and other greenness metrics observed in burned areas in Alaska may also indicate long-term shifts in vegetation cover type and photosynthetic activity at regional scales (Potter 2020a, Madani *et al* 2021).

In the Arctic tundra, our understanding of the drivers of the wildfire regimes is less thorough, due to a combination of factors including lower fire frequency, remoteness, and limited *in-situ* observations. It is commonly believed that lightning (Chen *et al* 2021c, He *et al* 2022), summer temperature, and precipitation (Hu *et al* 2015, Vachula *et al* 2022) are among the primary factors controlling the wildfire regimes in Alaskan tundra. Fire usually favors the recruitment and growth of deciduous shrubs in the tundra. It is therefore an important mechanism for Arctic shrubification (Lantz *et al* 2010b, Jones *et al* 2013, Frost *et al* 2020). Following fire, net ecosystem productivity (NEP) declines because of reduced vegetation productivity and increased ecosystem respiration, with forest ecosystems becoming a carbon source for roughly one to two decades (Amiro *et al* 2010, Liu *et al* 2011, Kurz *et al* 2013). In the tundra, vegetation productivity recovers more quickly, in as little as three years post-fire, though longer term impacts on NEP remain less clear (Gaglioti *et al* 2021). As vegetation and soils recover, NEP increases up to a maximum and then decreases to a steady state, at which point the ecosystem is again carbon neutral or a carbon sink (Goetz *et al* 2012, Song *et al* 2018). Climate change, however, may alter the post-fire NEP response in the future due to species composition shifts, productivity changes, and permafrost thaw (Rocha *et al* 2012, Gibson *et al* 2018, Foster *et al* 2019, Mekonnen *et al* 2019, Baltzer *et al* 2021).

Vegetation responses to fire disturbance can be seen in Landsat-derived trajectories of greenness (NDVI) and wetness (NDMI), as showcased in the average across all fire trajectories ($n = 32$) as well six individual fires (figure 4). The average trajectory shows a rapid decline in normalized NDVI and NDMI immediately following fire, with a moderate recovery rate in the following years (approximately 10 years for NDVI and 15 years for NDMI). Tundra NDVI recovers more rapidly, with NDVI values reaching the pre-disturbance mean within a decade following fire. The NDMI response following fire is more varied for the tundra locations, a pattern which highlights the cascading effects of wildfire on accelerated permafrost thaw and associated changes in soil thermal and moisture regimes, and variability arising from local differences in fire severity and ground ice conditions (Jones *et al* 2015).

3.1.2. Limitations, data needs, and unknowns

Large fire databases are crucial for understanding fire precursors, effects, trends, and dynamics in boreal and Arctic ecosystems. In Alaska and Canada, existing fire history databases provide fire perimeter polygons beginning in the 1940s and 1960s, respectively, and are maintained and updated annually. These databases are some of the longest and most complete large-scale historical fire records available anywhere on the planet (Kasischke *et al* 2002, Stocks *et al* 2002) and they are foundational datasets for investigating regional impacts of post-fire vegetation succession (Rogers *et al* 2013, Potter *et al* 2020b). Despite this, due to the great challenges in mapping wildfires in the high latitudes (e.g. limited availability of Landsat observations during a short growing season and persistent cloud cover; Chen *et al* 2021a, 2021b), omissions of large wildfire events by these wildfire history records still exist, particularly in the tundra (Jones *et al* 2013). Moreover, the fire perimeters themselves become less accurate further back in time, and often contain substantial patches of unburned vegetation (Kasischke *et al* 2002, Walker *et al* 2018, Potter *et al* 2020b). Advances in remote sensing tools enable fires and their impacts to be mapped and tracked at increasingly finer spatiotemporal resolutions (Eidenshink *et al* 2007, Duncan *et al* 2020, Hall *et al* 2020). Field data are also crucial for studying

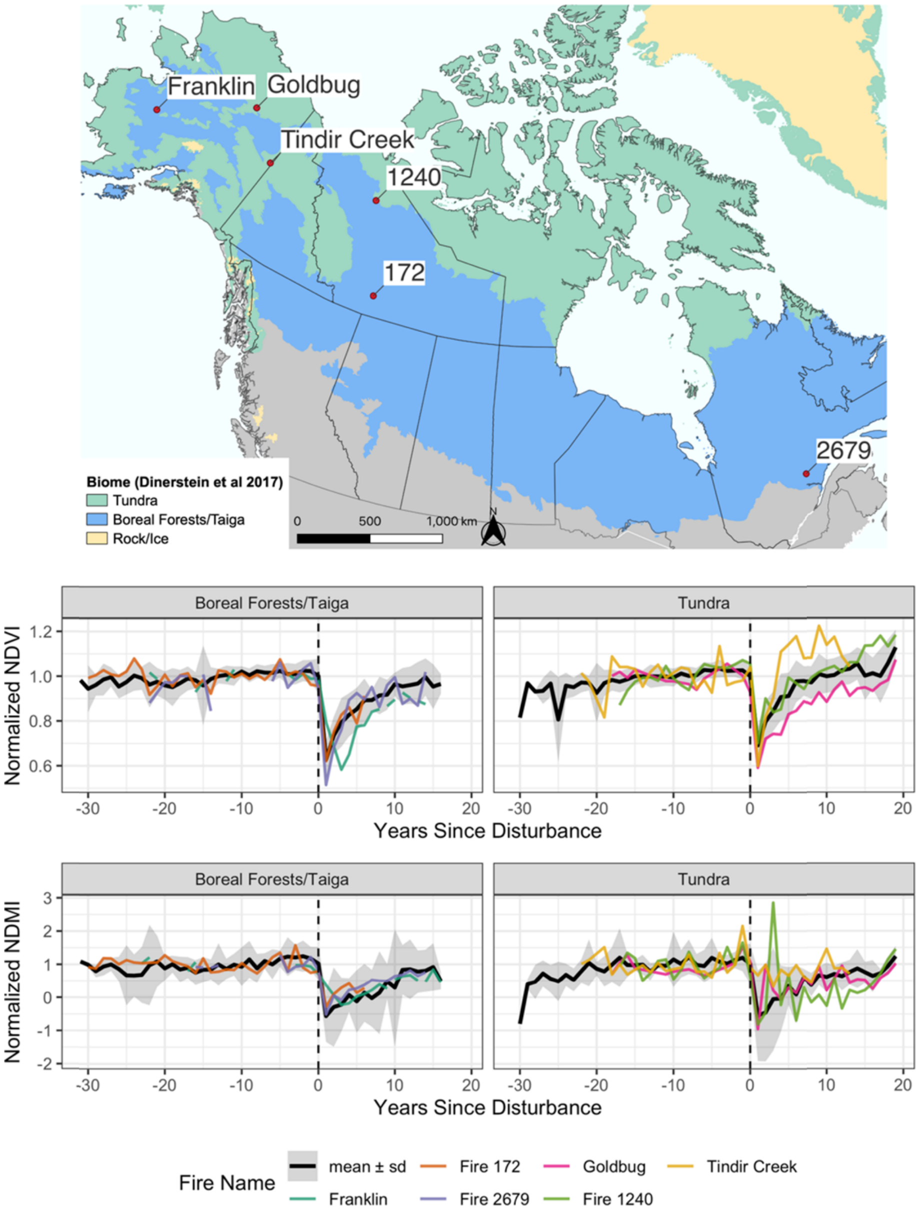

Figure 4. Average ($n = 32$) as well as six individual case study trajectories for fire disturbances in Alaska and Canada showing NDVI and NDMI normalized to the pre-disturbance average value.

fire impacts on carbon stocks and fluxes, vegetation recovery, hydrology, and other ecosystem properties, and a growing number of databases are allowing for meta-analyses of fire impacts (Virkkala *et al* 2018, Walker *et al* 2020a, Virkkala *et al* 2022). However, additional combustion estimates are needed to better understand the interactions between fire weather, fire spread and intensity, and combustion (Walker *et al* 2020b).

Further data are required to elucidate the interactions between wildfire, vegetation, and permafrost in the context of changing climate (Gibson *et al* 2018, Treharne *et al* 2022). Increasing temperatures, changing precipitation, and increases in fire activity will impact vegetation composition and structure, hydrology, and carbon fluxes. Future researchers could utilize a combination of active radar and subsidence data, high spatial and spectral resolution imagery, digital elevation models, and airborne LiDAR and other remote sensing data to observe and analyze these changes. It is also unclear how these changes to vegetation and fuels will interact with future fire regimes. Predicted increases in deciduous fraction and declines in organic layer and other fuels (Foster *et al* 2019, Mekonnen *et al* 2019) may lead to decreasing fire frequency and severity, even as fire weather and fuel drying increases (Parks *et al* 2015). Further, if young stands re-burn following fire, it is unknown how and which species may be able to regenerate as seed banks become depleted and soils become less conducive to seedling establishment (Baltzer *et al* 2021).

From a societal perspective, the increasing frequency of large fires, and necessary increased

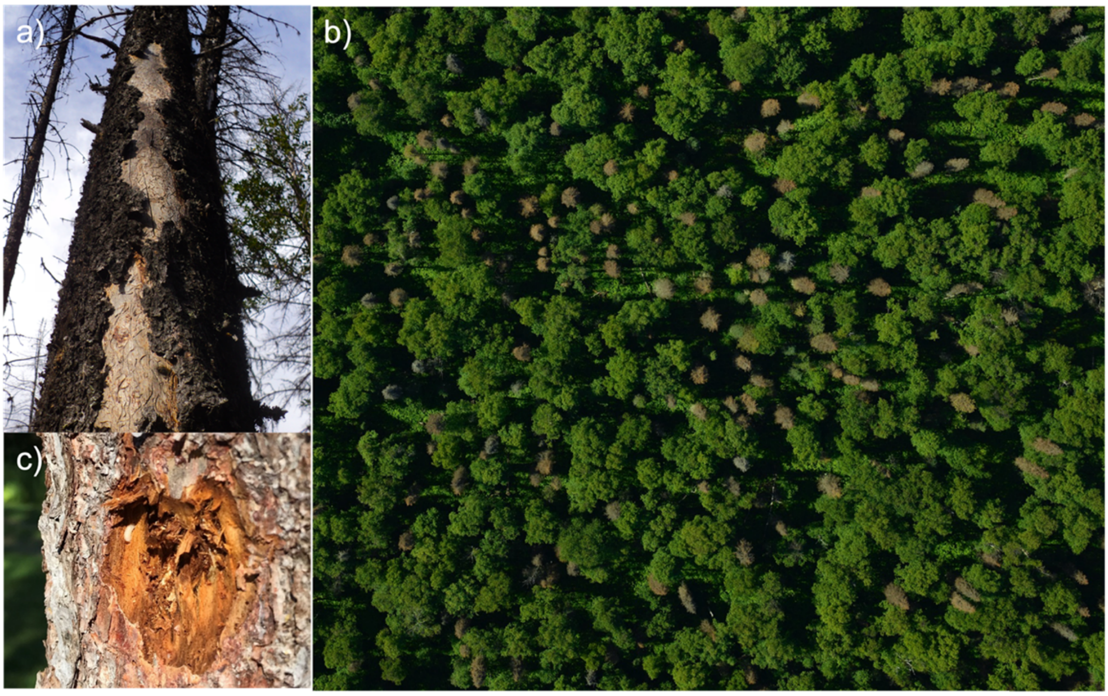

Figure 5. (a) Tree trunk infested with mountain pine beetle, showcasing egg galleries; (b) NASA G-LiHT aerial imagery of white spruce infested with spruce beetle, south-central Alaska (Cook *et al* 2013); (c) spruce beetle larvae within a white spruce trunk.

investments in fire-fighting activities at the wildland-urban interface, will strain the existing fire management budgets and governance structures (Rogers *et al* 2020). More studies are needed linking the influence of management on fire regimes, both historically and in the future, to quantify these relationships and make predictions for the efficacy and costs of fire management efforts (Calef *et al* 2015, Melvin *et al* 2017b, Phillips *et al* 2022).

3.2. Insect outbreaks and pathogens

3.2.1. Background

Biotic disturbances, such as fungal pathogens (e.g. root rots and needle rusts) and insect outbreaks (e.g. bark beetles and defoliators/leaf miners) can cause extensive tree mortality during outbreaks (Holsten *et al* 2008, Kautz *et al* 2016). Fungal pathogens often kill individuals slowly by disrupting water and nutrient transport (Holsten *et al* 1985) and reducing growth. In contrast, episodic insect outbreaks can cause major growth reductions and spatially widespread tree mortality over a few years, at times eclipsing that due to fire. For example, annual forest volume lost due to productivity reduction and mortality from pests and pathogens in Canada was estimated to be 106 million m^3 yr^{-1} between 1982 and 1987, which was three times that lost annually to fire and 70% of volume harvested in Canada nationally during that period (Hall and Moody 1994, Malmstrom and Raffa 2000, Volney and Fleming 2000, Price *et al* 2013). In the 1990s in Alaska, insects cumulatively damaged 1.6–2 million hectares of forest, which was 30% more area than burned during that period (Malmstrom and Raffa 2000).

Bark beetles, such as the mountain pine beetle (*Dendroctonus ponderosae*) and spruce beetle (*Dendroctonus rufipennis*), kill host trees outright by feeding on the cambium and phloem (figures 5(a) and (c)) and disrupting water transport (Malmstrom and Raffa 2000, Bentz *et al* 2010). These beetles attack trees through 'mass attacks' of many beetles, attracted via massing pheromones released by the beetles (Raffa *et al* 2008). Bark beetle populations typically exist at relatively low levels, punctuated by occurrences of high, epidemic levels due to climate-, disturbance-, or forest structure-related triggers (DeRose *et al* 2013, Seidl *et al* 2016). Young, healthy trees can often defend against low levels of attacking beetles by exuding resin and allelochemicals. However, stressed trees and those experiencing a large number of attacking beetles are more likely to succumb to infestation (DeRose and Long 2012). Thus, conditions that lead to vegetation stress, such as drought, often lead to outbreak events (Sherriff *et al* 2011, Seidl *et al* 2016).

Defoliators and leaf miners feed on the leaves and needles of host plants. In the North American ABZ, these guilds include, for instance, eastern and western spruce budworms (*Choristoneura* spp.), Jack pine budworm (*Choristoneura pinus*), aspen leaf miner (*Phyllocnistis populliella*) (figure 6(a)), and large aspen tortrix (*Choristoneura conflictana*). Outbreaks of these defoliators and miners cause significant tree growth reduction and potentially tree mortality. Removal or damage to needles and leaves

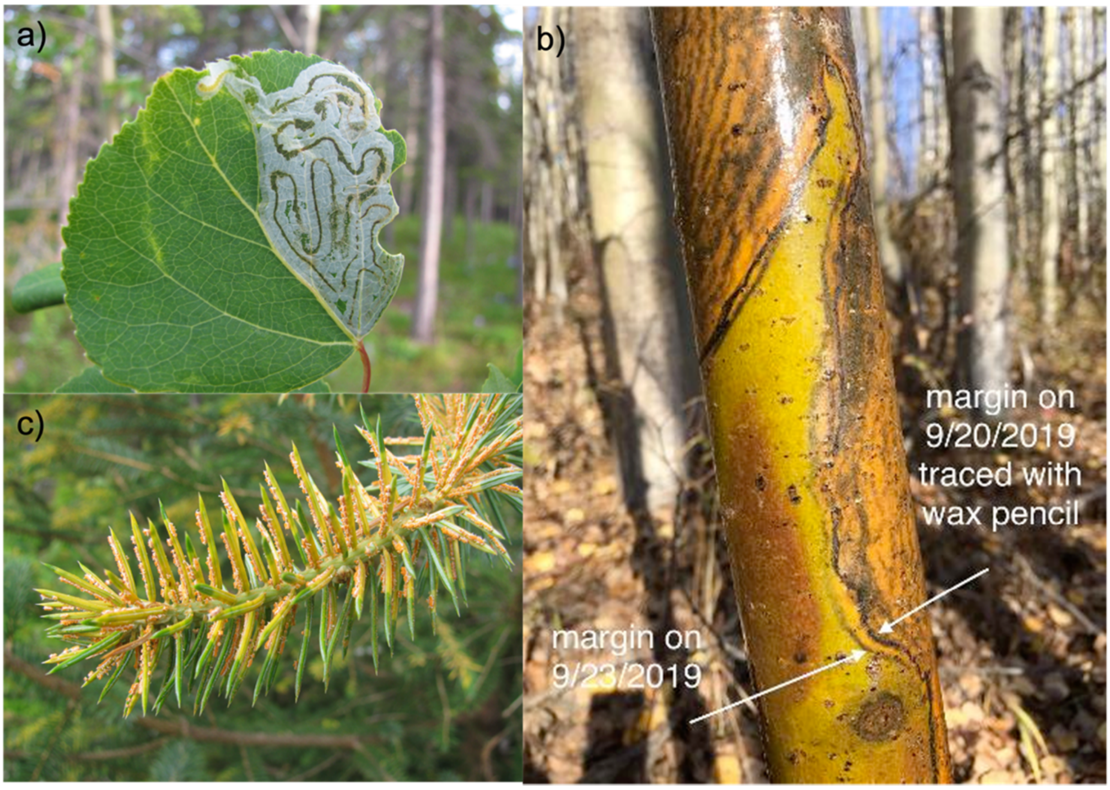

Figure 6. (a) Mines and larvae of an aspen leaf miner, USDA Forest Service photo by Robin Mulvey; (b) advance of an aspen running canker over the course of just three days in 2019, USDA Forest Service photo by Lori Winton; (c) spruce needle rust on a Sitka spruce, USDA Forest Service photo by Robin Mulvey. Photos from the USDA Forest Service public Flickr Page (www.flickr.com/people/194703066@N07/).

disrupts water transport and interferes with photosynthesis, which can kill trees directly or cause physiological stress that predisposes them to death from other factors, such as drought (Malmstrom and Raffa 2000). Recovery from major defoliation and mining depends on the extent of damage and the amount of carbon reserves held in other tissues (Boyd *et al* 2021). Deciduous species generally are more able to re-foliate from leaf damage than evergreen species, even in the same year as defoliation (Krause and Raffa 1996, Holsten *et al* 2008). Evergreen species, however, often have a high rate of mortality following successive years of intense defoliation, potentially leading to species composition shifts post-outbreak.

The most common pathogens in the North American ABZ include root rot (e.g. *Inonotus tomentosus*), heart rot fungi (e.g. *Fomitopsis pinicola*), and needle rusts (e.g. *Chrysomyxa ledicola*; figure 6(c)) (Armstrong and Ives 1995, Holsten *et al* 2008). These pathogens can cause hydraulic impairment by damaging vascular systems, reduce productivity through impacts on needles and leaves, and ultimately lead to plant mortality. Recently, an outbreak of the novel aspen running canker (*Neodothiopora populina*) caused widespread mortality of quaking aspen (*Populus tremuloides*) in interior Alaska (figure 6(b)). Aspen mortality from these infections was exacerbated by ongoing drought as well as an outbreak of aspen leaf miner (Ruess *et al* 2021).

While pathogens frequently affect a wide range of species, insects are often species- or genus-specific in their host requirements (Armstrong and Ives 1995, Holsten *et al* 2008). Hosts that are larger, older, or stressed are generally more susceptible to bark beetles. Thus, areas with high numbers of susceptible hosts are most vulnerable to insect outbreak, with mature, host-dominated stands being the most susceptible (Raffa *et al* 2008, Chapman *et al* 2012, DeRose *et al* 2013, Hart *et al* 2015). These homogenous stands provide a high quality habitat for insects, allowing for self-sustaining populations and sources of large-scale outbreaks (Malmstrom and Raffa 2000, Seidl *et al* 2016). The relatively low biodiversity in ABZ forests thus makes them particularly vulnerable to insect and pathogen outbreaks (Jactel *et al* 2005, Campbell *et al* 2008, Senf *et al* 2017a). Increasing temperatures and drought are thus generally expected to increase the impacts of insects and pathogens in the North American ABZ.

Insect and pathogen outbreak dynamics are affected and compounded by climate and weather by influencing the range and population size of insects and pathogens and altering the vulnerability of plants. For example, warming temperatures can reduce wintertime mortality and accelerate population growth of insects like the spruce beetle (Raffa *et al* 2008, Bentz *et al* 2010, Gray *et al* 2013). Spruce beetles usually have a two-year (semivoltine) life cycle, but

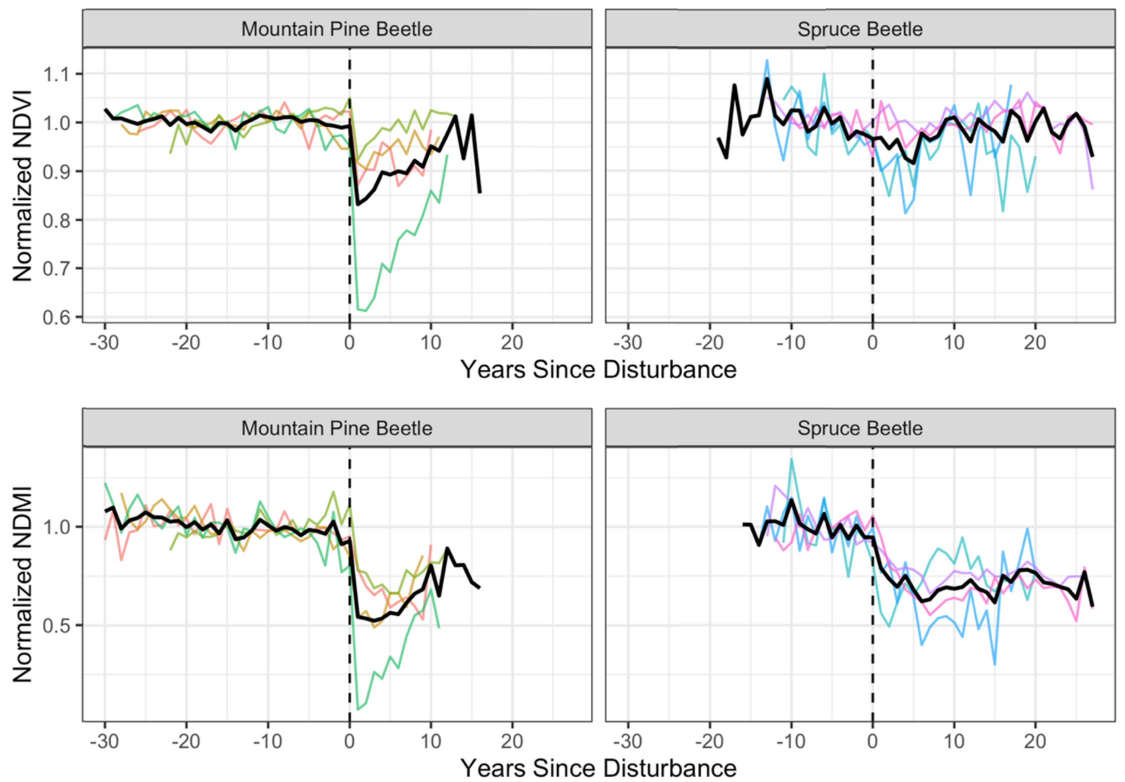

Figure 7. Average (black) and individual (colors) case study trajectories for mountain pine beetle (British Columbia; $n = 4$) and spruce beetle (Yukon Territory; $n = 4$) outbreaks showing NDVI and NDMI normalized to the pre-disturbance average value.

warmer conditions can accelerate larval growth, causing a shift to a one-year (univoltine) life cycle (Hansen *et al* 2011). More beetles with univoltine life cycles drives faster population growth and more severe outbreaks, such as occurred with the expansion of bark beetle outbreaks in British Columbia in the 1970s and 1980s (Bentz *et al* 2010). Host plants also interact with climate through host stress levels. Drought predisposes trees to disease and infestation (Raffa *et al* 2008, McKenzie *et al* 2009, Boyd *et al* 2021, Ruess *et al* 2021), and can be a secondary cause of mortality following defoliation stress (Malmstrom and Raffa 2000). Climate change is predicted to result in range expansion of insect species (de la Giroday *et al* 2012) and increases in outbreak severity and frequency (Raffa *et al* 2008). In Alaska, drought, high vapor pressure deficit, and high temperatures are key contributors to mortality linked with aspen leaf miner and aspen canker (Boyd *et al* 2021, Ruess *et al* 2021).

Because bark beetles tend to affect one or only a few host tree species and preferentially attack larger trees, their outbreaks often result in a shift towards smaller size classes and non-host species (Veblen *et al* 1991, Campbell and Antos 2015, Zeppenfeld *et al* 2015). Productivity often increases in these subsequent stands as non-infested trees are released from suppression (Campbell *et al* 2019). In more homogenous stands, species composition can shift towards early successional species after an outbreak. These impacts can be seen in trajectories of NDVI and NDMI before and during outbreaks (figure 7). Defoliators also tend to impact one or a few species—the eastern spruce budworm (*C. fumiferana*) mostly infests balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*), and infestation-caused mortality often leads to release of seedlings and saplings of host species (Boulanger and Arsenault 2004). Changes in NDVI are generally subtle as outbreaks build, sometimes asynchronously, within individual trees (figure 5(b)), and are usually only visible in moderate-resolution satellites when large areas are impacted (DeRose and Long 2012). This subtle NDVI pattern (figure 7) is especially characteristic of spruce beetle outbreaks, which do not exhibit a characteristic ‘red-stage’ attack as do pine species infested with mountain pine beetle (Coops *et al* 2006). However, NDMI often does decline (figure 7), due to decreases in transpiration and increases in foliar water stress during and following bark beetle outbreaks (Foster *et al* 2017). In contrast, trajectories of NDVI and NDMI during and following spruce budworm infestation in the Northwest Territories (figure 8) have a clearer signal, with some variability across the individual sites, highlighting the impact of infestation severity on the spectral signal. Sites which have a lower infestation severity (e.g. percent defoliation) will have a more subtle signal than sites which had more complete defoliation from spruce budworm infestation (Senf *et al* 2016). The response of NDVI to aspen running canker is

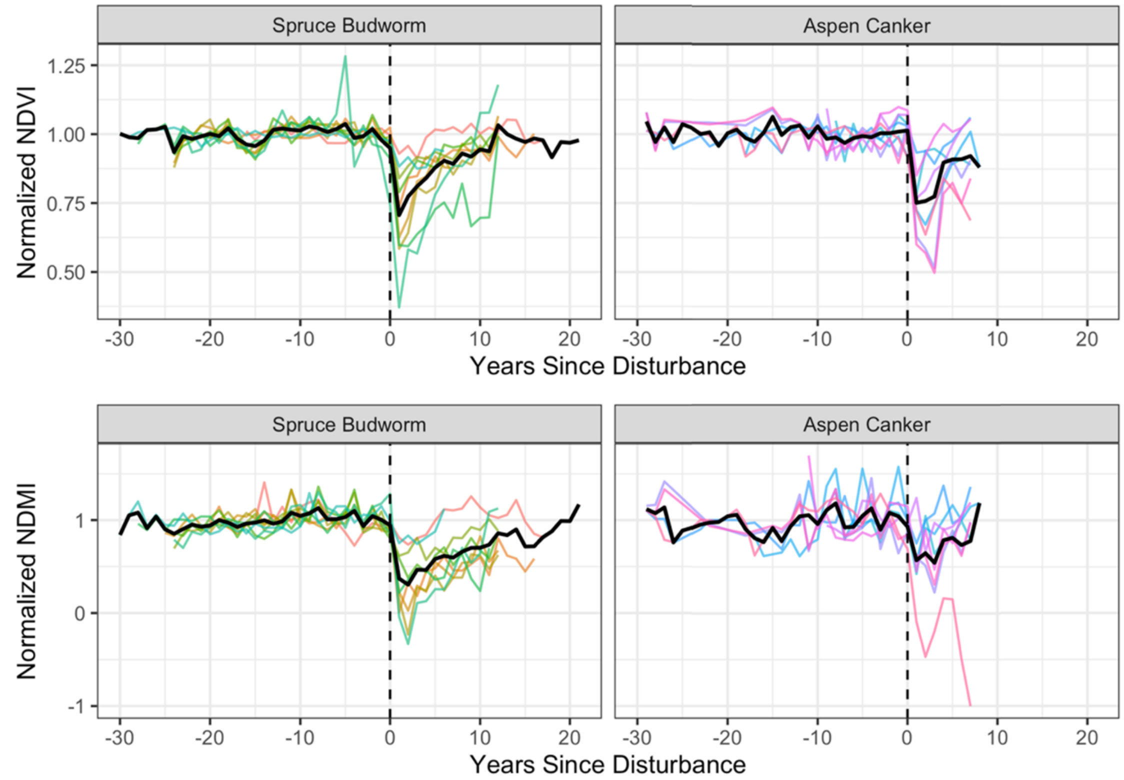

Figure 8. Average (black) and individual (colors) case study trajectories for spruce budworm infestation sites in the Northwest Territories ($n = 9$) and aspen running canker infestation sites in Alaska ($n = 8$) showing NDVI and NDMI normalized to the pre-disturbance average value.

also clear, with limited recovery following the drop in NDVI due to infestation (figure 8). NDMI response is less clear, with some decline following infestation.

3.2.2. Limitations, data needs, and unknowns

Past insect outbreaks are often identified through dendrochronology and pollen records (Anderson *et al* 2010, Sherriff *et al* 2011). However, these are limited to specific locations, usually where an outbreak is known, resulting in biases in our understanding of their extent and occurrence. Aerial detection surveys that produce polygons of infestation extent and severity are valuable for determining the regional and national impacts of forest pests. However, these polygons are often at a coarse spatial scale with potentially low positional accuracy (Wulder *et al* 2006, Hall *et al* 2016). Detection of recent or ongoing outbreaks using moderate resolution satellite sensors is possible, especially for large, severe outbreaks (Meddens and Hicke 2014, Hall *et al* 2016, Senf *et al* 2016, 2017a). Specialized methods are generally required for each insect type (e.g. bark beetles vs. defoliators). Foliar color changes of conifers infested with bark beetles often progress from green, sometimes to red, and to gray as needles lose moisture and are ultimately shed from the tree. The red and gray stages are easily detectable in multispectral imagery (Coops *et al* 2006), however the green stage is more subtle, making early detection difficult (DeRose *et al* 2011). Despite this difficulty, some studies have had success in using the water-sensitive shortwave infrared wavelengths to detect early moisture stress from green-stage infestations (Foster *et al* 2017).

Accurate and temporally and spatially consistent datasets of infestation/infection status and extent across jurisdictions are crucial for determining the extent and severity of past and ongoing outbreaks, and for predicting future outbreaks (Kautz *et al* 2016, Senf *et al* 2017b). Such large-scale datasets would also aid in generalizing detection methods across wider regions and disturbance agents. Because some major limitations to detecting insect and pathogen disturbance from remotely sensed data include accurately discriminating between these disturbances and other vegetation stressors, due to the exhibition of similar spectral signals (Senf *et al* 2017b), field observations of infestation status that are coincident with remote sensing observations will assist in developing more accurate algorithms for multi-stage detection efforts (Cessna *et al* 2021). Increased availability of different types of remote sensing data, particularly hyperspectral and radar imagery, have the potential to identify changes in forest moisture related to insect and pathogen outbreaks at regional scales and with high spatial detail.

Studies have shown that insects and pathogens are expanding their ranges poleward with increasing temperatures, increasing the area of forest vulnerable to outbreak (de la Giroday *et al* 2012, Pureswaran *et al* 2018). Insects are also beginning to infest novel host species (NRC 2018), and it is unclear how such host species will respond. Such range expansion highlights the need for increased detection and monitoring of outbreaks, as well as the need for predictions of future infestation vulnerability.

3.3. Permafrost-related disturbances

Throughout much of the northern high-latitudes, ecosystems are underlain by permafrost, or soil that remains frozen for more than two years (Gruber 2012). However, with climate change, permafrost ground temperatures are increasing (Biskaborn *et al* 2019) and the active layer—the upper layer of soil that thaws in the summer—is becoming deeper across large areas (Smith *et al* 2022). In addition to the active layer, the physical structure of these soils is being altered across many landscapes in the ABZ due to extensive changes to permafrost status due to warming, and permafrost thaw is expected to increase further in the future, both linearly and abruptly (Kokelj *et al* 2015, Turetsky *et al* 2020). These changes in physical structure can dramatically alter the topography, hydrology, and vegetation, resulting in heterogeneous topography and thermokarst features, especially in ice-rich locations. In this section, we describe several unique disturbances in the ABZ and their associated permafrost-related processes, including cryoturbation, ice-wedge degradation, cryogenic landslides, and lake drainage.

3.3.1. Cryoturbation

Permafrost soils often exhibit warped or broken soil horizons that result from cryoturbation, the frost-based movements of seasonally frozen materials (Bockheim and Tarnocai 1998). Cryoturbation can also create distinctive surficial disturbance features that generate fine-scale spatial heterogeneity in ground conditions and serve as foci for ecological change (Walker *et al* 2011, Frost *et al* 2013, Aalto *et al* 2017). Frost circles are a common form of patterned ground. They occur as approximately circular patches (∼0.5–3 m diameter) of mineral soil that often form geometric mosaics of vegetated and unvegetated microsites at uniform spacing of ∼1–3 m (figure 1(c)).

Frost circles are common in permafrost regions, particularly where surface organic material is lacking and the soil profile is dominated by fine-textured silt or clay (Bockheim *et al* 1998, Peterson and Krantz 2003). The intensity of cryoturbation is strongly affected by soil moisture, soil texture, changes in seasonal temperature, and snow cover (Daanen *et al* 2007, Aalto *et al* 2017). In general, climate warming and increased snow cover dampen cryoturbation by reducing differential frost-heave. Climate warming can also dampen cryoturbation indirectly by promoting vegetation colonization, which stabilizes the soil and results in organic matter accumulation on cryoturbated soils. Species that are fast-growing and/or tolerant of ground surface disturbances are best able to colonize cryoturbated surfaces (Kade *et al* 2005, Sutton *et al* 2006, Frost *et al* 2013). Once cryoturbation is reduced or no longer occurring, the increase in biomass is abrupt and persistent; however, cryoturbation can be renewed if vegetation and organic material are removed by other disturbances (chiefly wildfire).

Cryoturbation can have nonlinear responses to climate change with respect to vegetation cover and biomass, which can be detected in multi-decadal NDVI time series (Frost *et al* 2014). Furthermore, cryoturbation has distinctive spatiotemporal properties as a disturbance agent, because features usually occur as a multitude of 1–3 m microsites within a broad landscape mosaic, and the disturbance acts annually and is not episodic. At our case study locations, both NDVI and NDMI increased over the 30 year Landsat record (figure 9). With respect to NDVI, the warming climate could allow vegetation to colonize previously bare frost circles in cryoturbated landscapes, which would reduce further cryoturbation (Frost *et al* 2013). The NDVI increase could additionally reflect a general background greening (i.e. vegetation increase) of the landscape, as only a fraction is cryoturbated, and the remainder can have nearly complete vegetation cover. For NDMI, the increase in moisture is likely in part due to the moisture content of the colonizing vegetation, but also increased soil moisture beneath the vegetation cover (figure 9).

3.3.2. Ice-wedge degradation

Polygonal ground, encompassing mosaics of ice-wedge polygons (∼5–15 m wide) formed by contraction cracking followed by annual cycles of thawing and refreezing, is widespread and conspicuous in permafrost landscapes (Liljedahl *et al* 2016). Wedge-shaped masses of ice underlie the edges of each polygon (figure 10). Ice-wedge degradation occurs when the uppermost portions of ice wedges thaw, which triggers local ground subsidence, ponding, and persistent changes to vegetation and hydrologic connectivity across the landscape (figure 10). Ice-wedge degradation often results in substantial micro-topographic changes, such as the transition from low-centered to high-centered polygonal landforms.

Polygonal ground is most common in tundra with continuous permafrost, especially areas with fine-textured soils, and patterned landscapes can cover areas as large tens of square kilometers or larger (Lachenbruch 1962). However, ice wedges are also common in discontinuous permafrost regions well into the boreal forest (Kokelj *et al* 2014, Swanson 2016). Extreme warm and wet summers initiate ice-wedge degradation

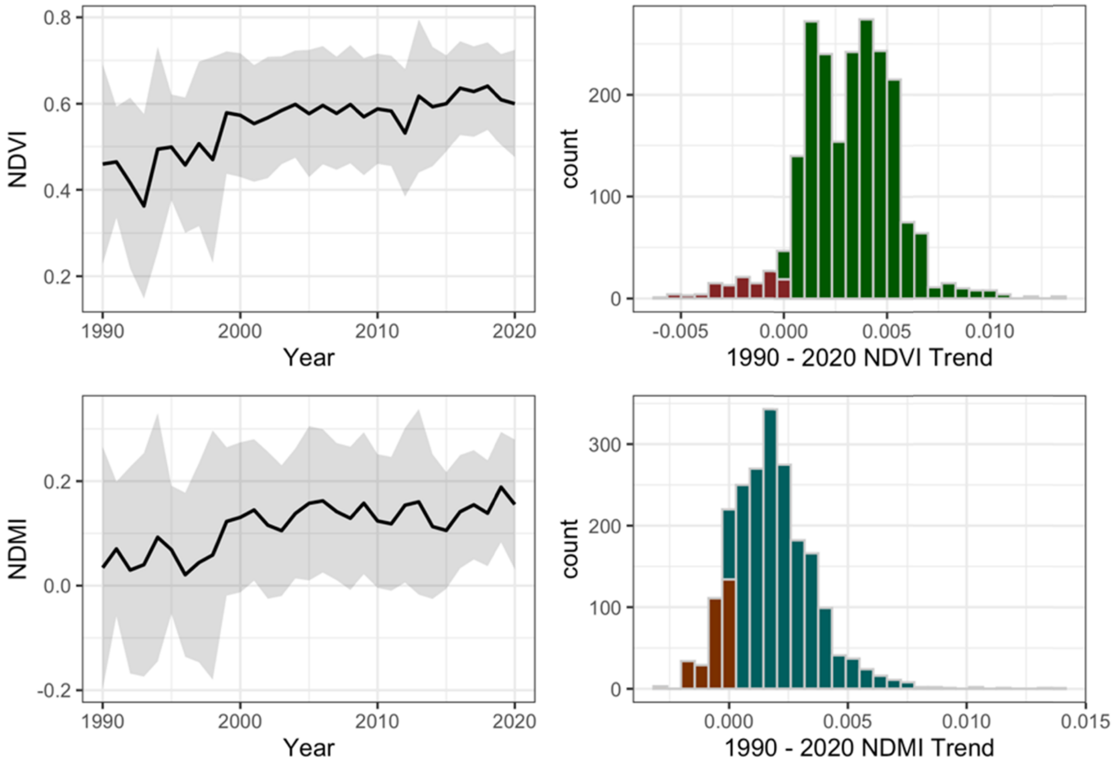

Figure 9. Average trajectories for NDVI and NDMI (left, not normalized) and distributions of trends (right) for NDVI and NDMI at cryoturbation case study pixels ($n = 2129$, across 47 sites) in northern Alaska. Trends were calculated as the slope from linear models fit at each Landsat pixel for the vegetation index. Note that these trajectories were not normalized because cryoturbation is an ongoing disturbance, rather than a single event.

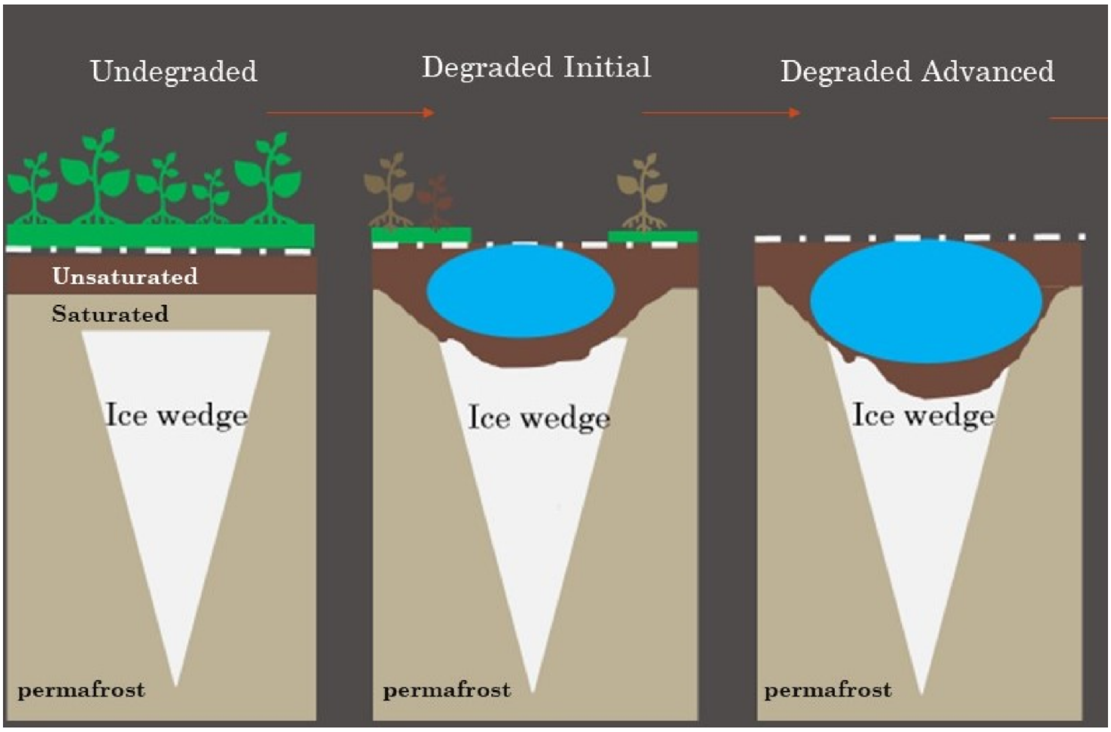

Figure 10. Schematic of ice-wedge degradation showing thawing of ice wedges and associated ponding and vegetation change. Image reproduced with permission from Kelcy Kent.

(Jorgenson *et al* 2006, 2015, Liljedahl *et al* 2016). Long periods of time (i.e. millennia) without additional disturbances are required to develop large ice wedges, so the terrain affected by ice-wedge degradation has historically supported 'climax' vegetation communities—usually tussock tundra or needleleaf

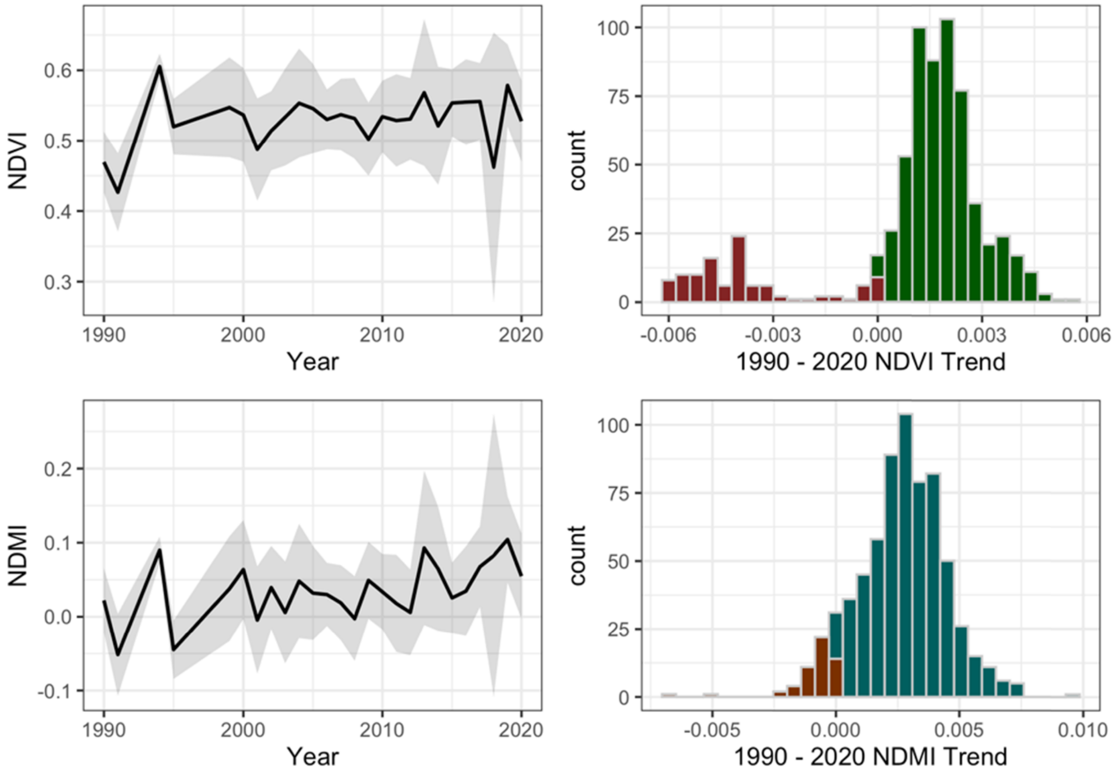

Figure 11. Average trajectories for NDVI and NDMI (left, not normalized) and distributions of trends (right) for NDVI and NDMI at ice-wedge degradation case study pixels ($n = 679$, across 15 sites) in northern Alaska. Trends were calculated as the slope from linear models fit at each Landsat pixel for the vegetation index. Note that these trajectories were not normalized because ice-wedge degradation is an ongoing disturbance, rather than a single event.

woodlands in boreal forest settings (Billings and Peterson 1980).

Local and regional variability in the timing and extent of ice-wedge degradation arises from differences in surficial materials and ground-ice content, disturbance history (natural and anthropogenic), regional climate gradients, and regional differences in the timing and magnitude of recent extreme warm summers (Raynolds *et al* 2014, Kanevskiy *et al* 2017, Frost *et al* 2018a, Farquharson *et al* 2019). This variability in ice-wedge degradation contributes to variability in patterns of tundra vegetation change (e.g. tundra greening or browning). Once thaw begins, the resultant subsidence forms small, flooded pits and troughs along the polygon margins. These pits and troughs pock-mark the landscape, kill existing vegetation that is adapted to mesic conditions (i.e. a mechanism for tundra browning) (Lara *et al* 2018), and support the colonization of hydrophytic vegetation (e.g. wetland sedges and mosses). Secondary impacts can affect large areas because the generation of pits and troughs creates new hydrologic flowpaths that alter soil hydrology and the distribution of surface water (Koch *et al* 2018). Over time (usually a matter of years to a decade), most pits and troughs become colonized by wetland vegetation, and surface water extent declines due to the development of an organic mat (i.e. a mechanism for tundra greening) (Wolter *et al* 2016).

Successional processes after ice-wedge degradation could explain in part the increasing NDVI trajectories in ice-wedge polygon landscapes (figure 11). However, this increase is likely also being driven by a general background greening of the tundra landscape in response to climate warming (Berner *et al* 2020, Myers-Smith *et al* 2020), as the affected microsites comprise only a fraction of the broader polygonal landscape. The distribution of NDVI dynamics includes numerous pixels with strong 'browning' signals, probably due to extensive ice wedge degradation and increasing surface water (Jorgenson *et al* 2022). The increasing NDMI (figure 11) over time in these landscapes is likely being driven by the increasing surface water due to the development of pits and troughs.

3.3.3. *Cryogenic landslides*

Climate-induced thawing of permafrost-affected hillslopes can trigger a variety of abrupt and gradual disturbances involving the mass movement of soils, collectively termed 'cryogenic landslides.' These landslides can result in losses of vegetation, followed by the development of successional vegetation on retransported materials. Different forms of cryogenic landslides vary with respect to their spatial extent and temporal characteristics, and thus the pattern and rate of ecological succession after disturbance. These subtypes include (a) active-layer detachments, (b) frozen debris lobes, and (c) retrogressive thaw slumps.

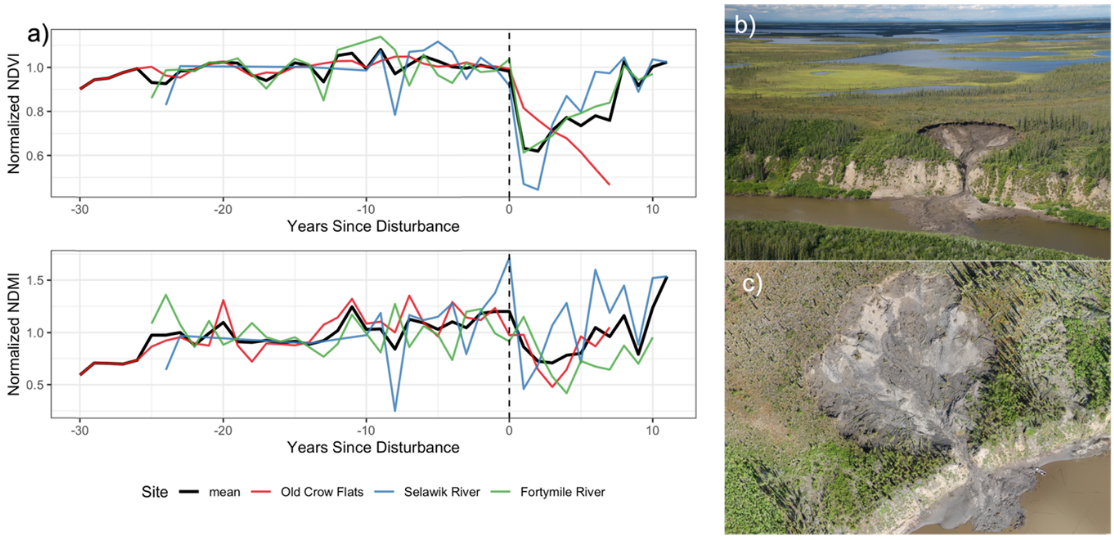

Figure 12. (a) Case study trajectories for average ($n = 3$) and individual thaw slumps in Alaska (Selawik River) and the Yukon Territory (Old Crow Flats; Fortymile River); (b) thaw slump in Old Crow Flats; Reproduced from Turner *et al* (2021). CC BY 4.0. (c) Aerial drone view of thaw slump in Old Crow Flats. Reproduced from Turner *et al* (2021). CC BY 4.0.

Active-layer detachment slides are relatively small, local slope failures that develop after warm, wet summers, such that saturated active-layer soils slide abruptly over the permafrost table (Leibman 1995, Ermokhina and Myalo 2012, Verdonen *et al* 2020). Future climate warming and associated permafrost degradation, as well as increases in triggers such as extreme warm summer periods, increases in rainfall, and forest fires, could increase their frequency (Lewkowicz and Harris 2005). Frozen debris lobes are slow-moving, lobate permafrost features consisting of soil, rock, organic material, and ice that move down permafrost-affected slopes via shear along their bases (Darrow *et al* 2015, 2016, Simpson *et al* 2016). The distribution and dynamics of frozen debris lobes are comparatively poorly known.

Retrogressive thaw slumps are thermokarst slope disturbances that contribute large volumes of materials downslope to lakes, drainage networks, and coastal zones (Burn and Lewkowicz 1990, Lantuit and Pollard 2008). Initiation of retrogressive thaw slumps depends on local geomorphological conditions and meteorology. Fluvial erosion along riverbanks or coastal zones can initiate slope failures, promoted by extended warm and wet conditions (Burn and Lewkowicz 1990). Following an initial slope failure, exposure of ice-rich permafrost enables thaw slump development, which can persist for many years while the areal size of the thaw slumps can expand to tens of hectares. For example, the thaw slump shown in figures 12(b) and (c) expanded from 0.63 ha immediately after the detachment failure in 2016 to 1.04 hectares three years later (Turner *et al* 2021).

The frequency and size of retrogressive thaw slumps can be highly variable within and among landscapes. The largest thaw slumps in North America have been observed in the Richardson Mountains and Peel Plateau regions, NWT, Canada (Lacelle *et al* 2015). This region, which includes the Mackenzie Delta, has experienced an increase in occurrences of thaw slumps in response to wet summer conditions (Lantz and Kokelj 2008, Kokelj *et al* 2015). Zwieback *et al* (2018) also found an increase in thaw slumps on the Tuktoyaktuk Peninsula, northwest of the Mackenzie Delta, Canada, and the Bykovsky Peninsula, Russia, associated with available energy and late-season rainfall. Many coastal areas have seen an increase in thaw slump activity, including Banks Island (Lewkowicz and Way 2019). Interactions with marine environments, including thermo-abrasion from waves and ice, can have a strong influence on thaw slump activity along coastlines (Günther *et al* 2013).

Cryogenic landslides impact terrestrial and aquatic ecosystems and atmospheric feedbacks. Within lake and river aquatic environments, biogeochemical cycling can be impacted by the liberated sediment and solutes, which are typically rich in nutrients and ions. However, the downstream impacts, on nutrient concentrations, for example, can be highly variable (Frey and McClelland 2009, Harms *et al* 2014, Lafrenière *et al* 2017, Mu *et al* 2017) and depend on local geomorphic conditions including relief, ice content, permafrost extent, and parent material (Tank *et al* 2020). These complex relations present uncertainties for associated impacts on local and downstream ecology. Vegetation can efficiently colonize stabilized areas of cryogenic landslides (Turner *et al* 2021). Habitat characteristics associated with landslide age and vegetation composition also have an influence on wildlife (Cray and

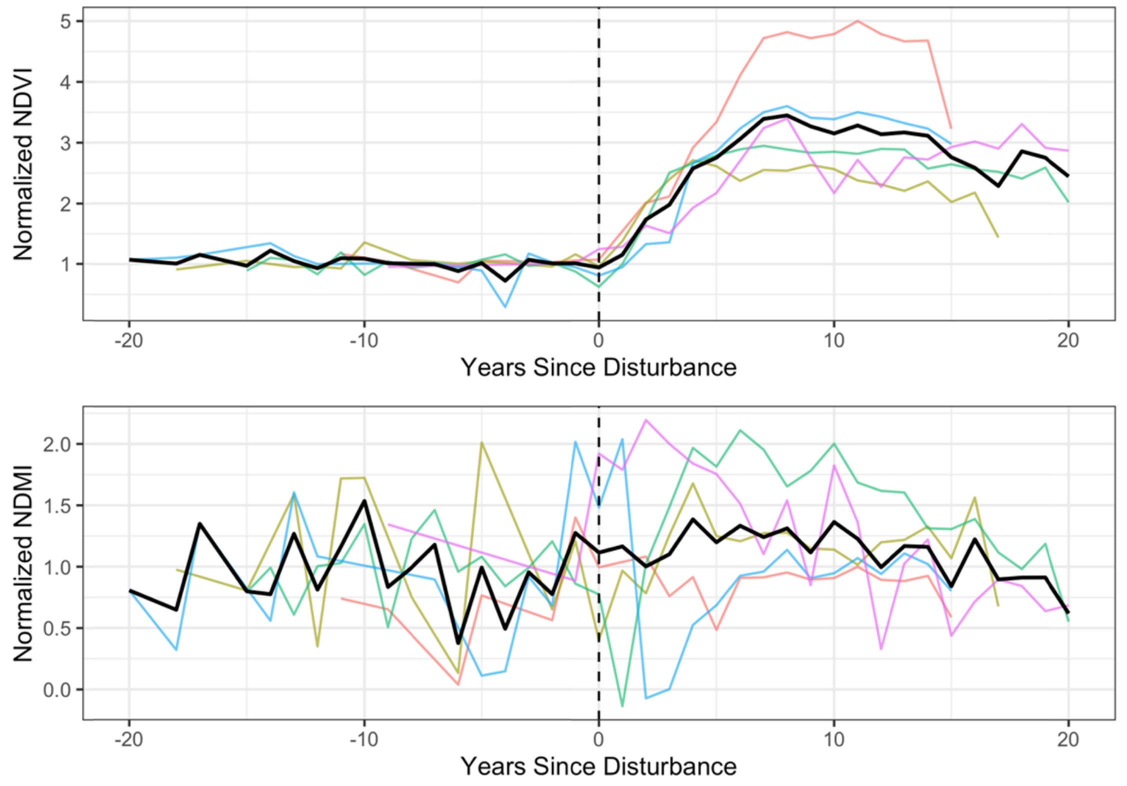

Figure 13. Average (black) and individual (colors) case study trajectories for lake drainage disturbance sites in Alaska and the Yukon Territory ($n = 5$) showing NDVI and NDMI normalized to the pre-disturbance average value.

Pollard 2019). Atmospheric impacts include climate change feedbacks that stem from microbial decomposition of parent material and subsequent emission of greenhouse gasses (CO_2 and CH_4; Schuur *et al* 2015, Turetsky *et al* 2020, Miner *et al* 2022).

3.3.4. Lake drainage

Thermokarst lakes are formed when permafrost degradation results in subsidence of the land, which subsequently fills with water. These features are abundant across ice-rich permafrost terrain and are highly sensitive to climate conditions (Jones *et al* 2022). Though thermokarst lakes may remain stable for centuries, the shorelines are highly susceptible to erosion and expansion, the rate of which can be strongly influenced by dominant fetch and shoreline ground-ice content as well as climate (Roy-Léveillée and Burn 2010). When shoreline expansion progresses into low-lying areas or invades the boundaries of other thermokarst lakes, they can drain and experience near-complete water loss within days. Additional mechanisms that trigger drainage events can include drainage across an ice-wedge network, headward erosion along adjacent streams or coastal boundaries, and bank overflow when established outflow channels are blocked by snow and ice (Mackay 1981, 1988, Brewer *et al* 1993, Marsh and Neumann 2001, Hinkel *et al* 2007, Wolfe and Turner 2008, Jones and Arp 2015). Drainage can also occur incrementally through partial tapping by a stream and the development of open talik systems beneath the lake (Yoshikawa and Hinzman 2003).

Thermokarst lake drainage events represent drastic landscape transitions. Newly exposed lacustrine deposits serve as seedbeds for colonizing vegetation and can quickly develop continuous vegetation cover (e.g. *Eriophorum russeolum, Carex aquatilis*, and *Senecio congestus*) within the first few years following drainage depending on local conditions (Ovenden 1986, Mackay and Burn 2002, Shur and Jorgenson 2007, Lantz 2017). For example, willow (*Salix spp.)* encroached within 30.8% of the former 12 km^2 lakebed of Zelma Lake in Old Crow Flats, Yukon (Turner *et al* 2022). After a lake drainage event, the aquatic environment of the remaining water body can become highly dynamic for several years following drainage as biogeochemical properties are strongly influenced by weather and pluvial runoff across the exposed lakebed (Tondu *et al* 2017). Lake water biogeochemical properties stabilize as shrubs encroach, which enhances snowpack depth and snowmelt input (Turner *et al* 2022). The increasing NDVI in our lake drainage case study trajectories (figure 13) suggests encroachment of shrub vegetation. NDMI likely does not change because encroaching vegetation at these point locations are inundated with water.

Catchment hydrologic and vegetation characteristics typically do not return to pre-drainage conditions (Bandara *et al* 2020) and can thus exert long-term influence on carbon cycling. Drained lake basins can effectively sequester atmospheric carbon as peat accumulates (Fuchs *et al* 2019), though peat and carbon accumulation may eventually decrease (Bockheim *et al* 2004, Jones *et al* 2012, Fuchs *et al* 2019). Drained lake basins can remain dry for millennia (Hinkel *et al* 2003, Shur and Jorgenson 2007), and succession and ground-ice development may lead to variable species composition depending on local conditions.

Changes in the frequency of thermokarst lake drainage events have been highly variable among permafrost landscapes in Alaska (Jones *et al* 2011, Swanson 2019, Nitze *et al* 2020, Jones *et al* 2020a) and northwestern Canada (Lantz and Turner 2015). However, increasing temperatures and rainfall and associated increase in energy fluxes to permafrost will likely increase the vulnerability of thermokarst lakes to drainage (Turetsky *et al* 2020). In addition, lake drainage can be accompanied by the formation or expansion of other water bodies as observed in Siberia (Karlsson *et al* 2012, Polishchuk *et al* 2015, Nitze *et al* 2020), Alaska (Chen *et al* 2014), and the Tuktoyaktuk Peninsula (Marsh *et al* 2009, Olthof *et al* 2015). While the overall surface water area has remained stable in many of these regions, the spatial redistribution of water bodies suggests that these lake-rich landscapes are in a state of climate-driven transition (Rowland *et al* 2010, Pastick *et al* 2019). Ongoing research and monitoring will build our understanding of the short and long-term consequences for ecology, hydrology, and carbon cycling.

3.3.5. Limitations, data needs, and unknowns

Broadly, the study of permafrost-related disturbances would benefit from remote sensing studies which leverage higher-resolution sensors. Many of these disturbances at the individual scale can be quite small (e.g. frost circles, <3 m in diameter), and thus medium resolution satellites such as Landsat or Sentinel may miss small-scale changes in surface geology and vegetation driven by thermokarst processes. Additionally, more studies are needed to understand vegetation colonization and succession on newly available land created by permafrost-related disturbances.

Although frost circles are common across the entire Arctic climate gradient, the small size of individual features makes them difficult to detect, even in imagery with submeter spatial resolution. As a result, their distribution has not been mapped or constrained except at local scales. Such mapping of cryoturbated surfaces would be highly desirable, especially in the Low Arctic, where they are at risk of becoming less active (Aalto *et al* 2017). At present, areas that support dense frost circles can only be predicted based on coarse-scale maps of surficial geology and generalized soil texture. Whereas individual features may be challenging to identify, it may be possible to distinguish cryoturbated landscapes based on landscape-scale average spatial features.

There are numerous unknowns regarding the dynamics of ice-wedge degradation and potential re-stabilization, and the extent to which they are occurring. Ice wedges are generally insulated by a mat of vegetation and accumulating snow in the winter, and it is still unclear what weather conditions induce ice wedge melting and what might drive heterogeneity in degradation among ice wedges. It is also unclear what factors drive vegetation succession following ice-wedge degradation and the development of surface water ponds and troughs. One factor could be the availability of nutrients such as nitrogen and phosphorus (Beermann *et al* 2015, Herndon *et al* 2020), however only a few studies have attempted to address changes in nutrient concentrations following ice-wedge degradation (Norby *et al* 2019). Finally, the rates of accumulation of organic matter in degraded ice wedges and their potential for stabilization are still poorly understood. Field studies of ice wedge dynamics utilize space-for-time substitution, examining ice wedges at different stages of degradation (Jorgenson *et al* accepted) as opposed to assessing the dynamics of individual ice wedges over time.

There has been substantial progress on our capacity to gauge the extent of ice-wedge degradation utilizing high-resolution remote sensing and machine learning techniques (Witharana *et al* 2020, 2021). Whereas these studies and associated applications can map ice-wedge polygon networks across extensive areas of land, and even potentially estimate the fraction of land that contains ice wedges versus polygon centers, there is still work to be done to distinguish among the different stages of degradation.

There have been many studies that have documented the detection of cryogenic landslides (e.g. Barnhart and Crosby 2013, Balser *et al* 2014, Swanson and Nolan 2018), however, detection of the frequency of relatively small landslides may be difficult using medium resolution imagery (e.g. Landsat). Thus, large-scale mapping of these disturbances is difficult because the size of individual thaw slumps can be characteristically different depending on the region, and because high-resolution imagery at large scales is both cost prohibitive and difficult to work with.

Lake drainage events and associated impacts are complex and require additional research, especially where drainage frequency is increasing. Our ability to identify where and when thermokarst lake drainage will occur in the future must be refined. Existing data archives (e.g. Landsat 5–8, Sentinel-2) provide resources needed for identifying locations of past drainage and associated changes in land cover of larger lakes. While many studies have successfully utilized products from these sensors, the availability of scenes can be limited for any given year according to the timing of cloud-free conditions and the spatial resolution may not be adequate for detection of small-scale surface area change (e.g. <30 m resolution) or for smaller water bodies. Broader coverage of high-resolution (optical, radar and elevation) products will improve these analyses and enhance detection of landscape responses to drainage and geomorphological characteristics (e.g. the proximity of lakes to low-lying areas) that make lakes vulnerable to drainage.

3.4. Anthropogenic disturbances

The North American ABZ has experienced extensive industrial activity and development in the last half-century (Schneider 2002, Pasher *et al* 2013). These disturbances include flooding for hydroelectricity, timber harvest, and other natural resource development (e.g. mining, oil, and natural gas), including associated infrastructure such as pipelines, roads, and seismic lines for resource exploration. Additional highly localized disturbances in this region include landfills and dumps for disposal of domestic and industrial waste. These disturbances do not always fully remove or eliminate vegetation and soil, but often result in highly fragmented landscapes, leading to significant changes in ecosystem composition, structure, and function (Pasher *et al* 2013). As climate continues to change, northward expansion of agricultural areas is expected in southern regions of the ABZ, resulting in lasting removals of natural vegetative cover (King *et al* 2018). Although the cumulative area disturbed by the combined activities is vast, the impact of past and present natural resource development on ABZ ecosystem function (e.g. carbon cycling; Strack *et al* 2019, Schmidt *et al* 2022) and services (Pickell *et al* 2014) has often been overshadowed by fire and insect outbreak due in part to data limitations.

3.4.1. Logging

Forest harvest activities are major disturbances in Canadian forests (Gauthier *et al* 2015), with 35%–40% of the Canadian boreal forest under industrial harvest and management (Burton *et al* 2003, Venier *et al* 2014). Industrial-scale forest management and economic activity have been an important component of the southern and eastern Canadian boreal forest since the 1800's (Venier *et al* 2014). For example, the Canadian forest products industry harvested over 710 000 hectares (∼143 million m^3) of forest in 2020 (National Forestry Database 2020). In these higher productivity and more easily accessible southern and eastern regions, coniferous evergreen species (e.g. spruce, fir and pine) and aspen dominate the landscape and are utilized for lumber, pulp, and paper (Burton *et al* 2003, Venier *et al* 2014). In comparison, timber harvest is less extensive in the Alaskan boreal forest (Potapov *et al* 2008), where managed forests are generally concentrated in areas with high-value sawtimber species, adequate road access, and proximity to milling facilities—mostly in southeastern Alaska (Morimoto and Juday 2018) and episodically within the interior.

Clear-cutting is the most common silvicultural method used in the boreal forest (Haggstrom and Kelleyhouse 1996, Burton *et al* 2003, Cyr *et al* 2009). It was initially justified as an adequate replication of stand-replacing natural wildfire (Bergeron *et al* 2002); however, post-treatment belowground conditions (e.g. soil depth, nutrient content) can substantially differ from those following wildfire (Simard *et al* 2001), ultimately impacting post-disturbance successional trajectories in unique ways (Nguyen-Xuan *et al* 2000). Additionally, the coarse woody debris left after wildfire generates habitat for songbirds and other species, but is largely absent from post-harvest landscapes (Morissette *et al* 2002). Finally, post-treatment planting can increase regrowth compared to post-fire regrowth (Dieleman *et al* 2020). This is evident in the NDVI and NDMI time series for our logging case studies (figure 14), which in general show a faster initial recovery than those for fire (figure 4), and aligns with prior research (White *et al* 2017). However, it should be noted that other work has found the opposite result wherein post-fire forests recover slightly more quickly than harvested areas (Bartels *et al* 2016).

Traditional clear-cutting results in even-aged forest stands, as all trees are either harvested or disturbed due to harvesting activity, with only a small fraction left to stand as a seed source. Consequently, intensively managed landscapes often yield an even distribution of tree ages across the managed area, with no or few stands older than the harvest rotation time (Bergeron *et al* 2002). When the rotation time is shorter than the fire frequency, the resulting stands will be less diverse in terms of stand structure and species composition than stands that grow for longer periods and allow tree replacement or fires to kill a population of trees. Long fire intervals (e.g. 200+ years) allow for shifts in canopy dominance and forest age structure as a result of forest successional processes (Bergeron *et al* 2002). Thus, biodiversity concerns for highly managed areas have arisen, particularly in southern and eastern Canada (Boucher *et al* 2009, Venier *et al* 2014).

While clear-cut or group selection harvests predominate areas with high value stands or in areas where managers are attempting to mimic fire, approaches such as partial harvest and individual tree selection in mixed or deciduous stands often allow for individuals with a range of ages to coexist and the promotion of certain forest types (Gauthier *et al* 2009). Such harvesting practices can help increase diverse forest structural attributes, particularly in stands that are even-aged following prior harvest practices (Bose *et al* 2015). Comparatively, selective harvest is less impactful on total stand biomass than even-aged selection or fire, and thus has a more nuanced signal

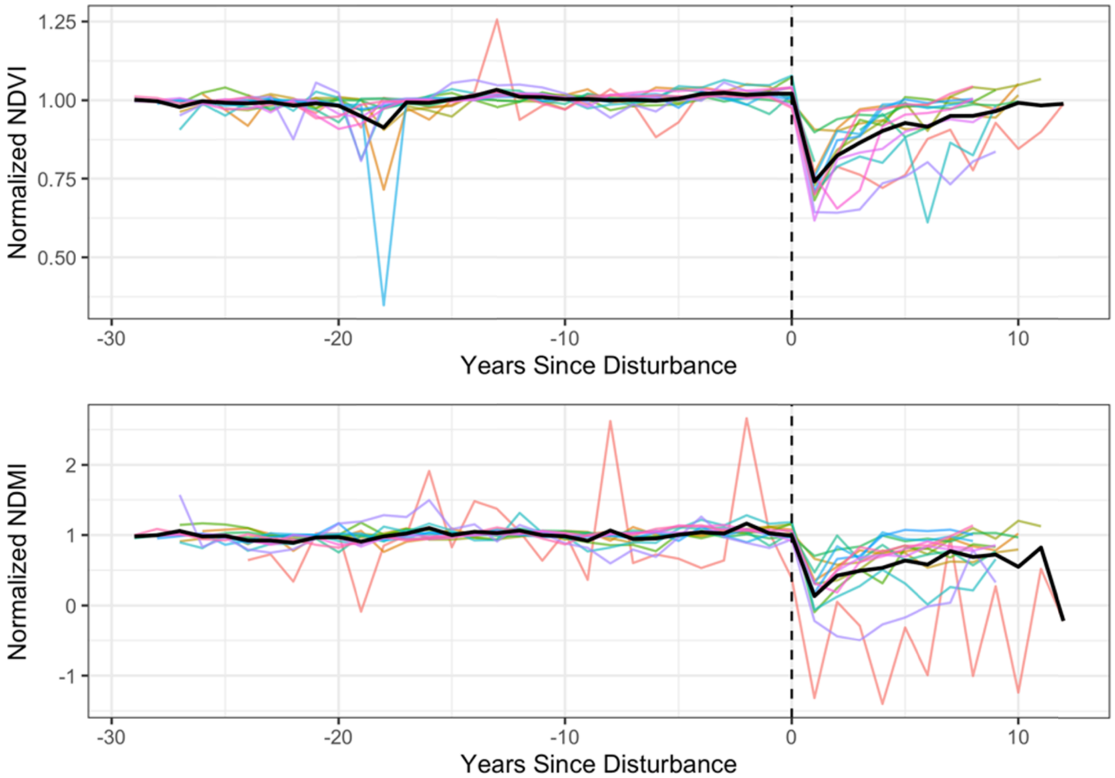

Figure 14. Average (black) and individual (colors) case study trajectories for logging disturbance sites in Saskatchewan ($n = 14$) showing NDVI and NDMI normalized to the pre-disturbance average value.

from remotely sensed data. Notably, many selective harvest practices, particularly those which promote specific species or are considered variable retention that retain structural elements of the stand, have been examined for impacts on avian (Schieck *et al* 2000), vertebrate (Vanderwel *et al* 2009), understory plant (Macdonald and Fenniak 2007), and beetle (Wu *et al* 2020) communities. While group selection and clear-cutting are most common throughout the boreal forests of the North American ABZ, harvest for the purpose of maintaining biodiversity or transitioning forest types for fire management (Astrup *et al* 2018) also occurs throughout the region. These different harvesting techniques and the degree to which outcomes can vary from technique to technique are an important component of the impact of forest management on boreal vegetation and soils, and warrants further study, especially in the context of ongoing shifts in climate and fire regimes that impact regeneration patterns.

3.4.2. Oil and gas well production

Oil and gas well production in the North American ABZ can be traced back a century to the still-active Norman Wells drilled in the 1920s in the Northwest Territories (Bone and Mahnic 1984). In British Columbia, the first commercial gas well was drilled along the Peace River in 1947 and the first discovery of oil in Alaska occurred in 1957. The density of wells in the ABZ is typically less than 1 km^{-2}, however some locations can be as dense as 3 km^{-2} or higher (Warrack *et al* 2021).

Over its long history, oil and gas exploration and the associated production technology, practices, and regulations have evolved (King and King 2013, Kang *et al* 2016). Depending on the type of well (e.g. conventional oil, unconventional gas), intent of the well (e.g. production, exploration, injection), geology (including depth and formation properties), and other factors, the resulting disturbance to the surrounding vegetation can be highly variable in terms of size, shape, and form, with the area of influence ranging from tens to hundreds of square meters. The disturbance also varies temporally throughout the life cycle of the well from site preparation to plug and abandonment (Burnham *et al* 2012, Allen *et al* 2013).

For both exploratory and development (or production) wells, well site preparation includes constructing a well pad and access roads. The lengths of new access roads for well sites in the Wayne National Forest in Ohio are 8–30 km (USFS 2004), but the lengths of new access roads needed in the ABZ may be much longer (Pasher *et al* 2013, Wilkinson *et al* 2021). The well pad involves clearing land so that the drill rigs can be brought in. Wells meant for producing oil and gas are first cased with steel piping and cemented, and then the inside of the innermost casing is connected with the host rock containing oil and/or gas. These activities remove vegetation, degrade soils, result in loss of seed and bud stores (Pickell *et al* 2015), and

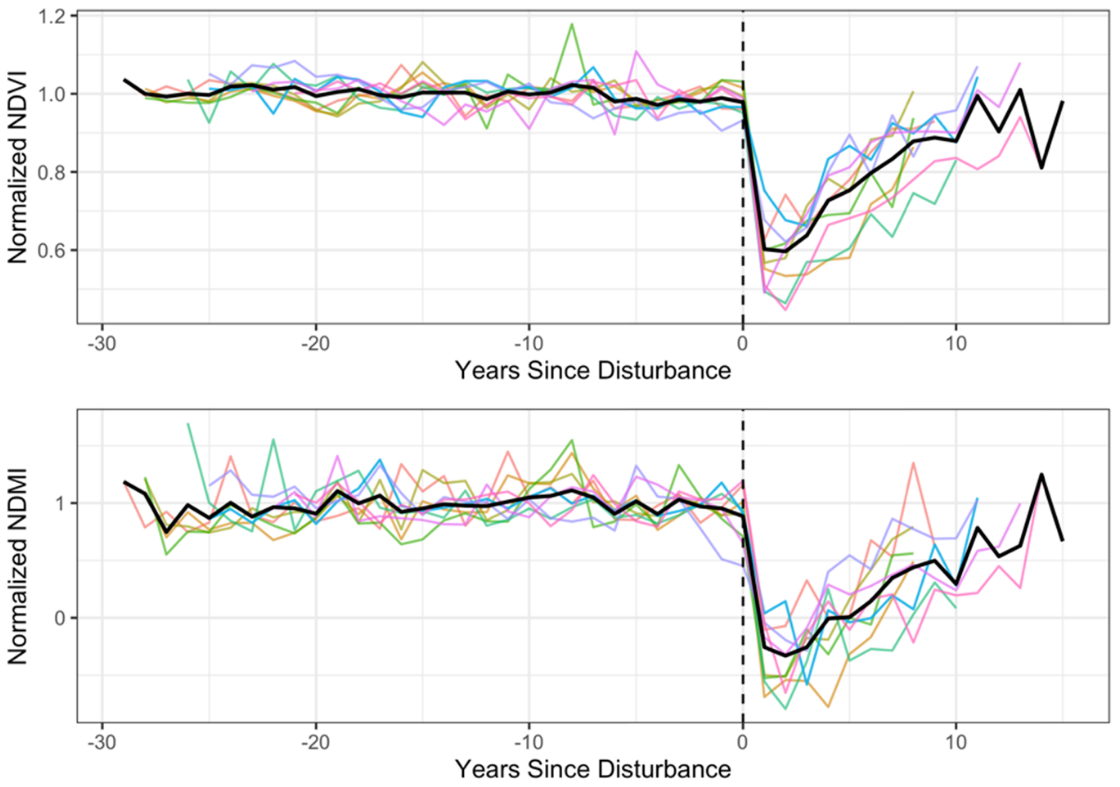

Figure 15. Average (black) and individual (colors) case study trajectories for oil and gas well sites ($n = 10$) showing NDVI and NDMI normalized to the pre-disturbance average value.

lead to overall biodiversity and habitat loss (McDaniel and Borton 2002, Butt *et al* 2013, Northrup and Wittemyer 2013). Due to the impacts of well production on soil nutrients, hydrology, and seed sources, regeneration on well sites is slower than that following fire or forest harvest (Osko and MacFarlane 2001). Forest succession and regrowth and overall landscape recovery can thus take decades following oil and gas activity (Powers *et al* 2015, Chowdhury *et al* 2017). NDVI and NDMI responses to oil and gas wells (figure 15) show a clear decline in both vegetation moisture and greenness, with recovery lasting longer than ten years.

The production life of a well is highly variable, with some wells remaining in production for decades and others being abandoned after only a few years. Nevertheless, all wells are eventually abandoned and, according to modern regulations, must be plugged and the well site restored (Kang *et al* 2019). In Alberta and British Columbia, site restoration involves removing surface infrastructure and re-vegetating the land to pre-development conditions (Kang *et al* 2021). However, some wells have not been plugged and abandoned according to these regulations and have not had the surface restored.

3.4.3. Seismic lines

The largest anthropogenic disturbance across much of boreal and Arctic North America are seismic lines (Jorgensen *et al* 2010, Strack *et al* 2019), which are long linear clearings cut across forests and wetlands for oil and gas exploration (figures 1(d) and 16(a), (b)). Seismic exploration for underground sources of oil and natural gas involves drilling a series of holes 6–20 m deep along the lines and analyzing the reflection of sound waves generated from either explosives detonated at the site or truck-mounted surface vibrators (EMR 2006). Originally, these lines (previously known as legacy or 2D lines) were cleared using heavy machinery to cut through heavily forested areas (Dabros *et al* 2018), creating lines up to 10 m wide. Individual length varies but combined create a vast network; Strack *et al* (2019) estimated 345 000 km of seismic lines crossing peatlands in Alberta alone. This type of clearing results in the complete removal of the aboveground woody vegetation (Filicetti *et al* 2019) and significant soil and peat compaction, causing the water table to be much closer to the ground surface (Davidson *et al* 2020b). These changes in soil characteristics and hydrological conditions can alter understory vegetation composition, including shifts from feather moss-shrub dominated understories to complete cover by sedges (e.g. *Carex aquatilis*) in fen peatlands, or sphagnum moss (*Sphagnum* spp.) in bog peatlands (Deane *et al* 2020, Davidson *et al* 2021). In recent decades, there has been a move towards a method called ‘low-impact’ seismic lines, created using lighter-weight machinery and by hand and allowing for minimal disturbance to the ground-surface (Dabros *et al* 2018). These lines are narrower (1–5 m) than legacy lines but they are far more abundant on the landscape, creating a dense grid-like network of disturbances and can still create substantial changes to both tree cover (van Rensen *et al* 2015) and understory vegetation communities (Davidson *et al* 2021).

Although the creation of some seismic lines occurred almost 40–50 years ago, tree recovery and regeneration in many of these locations is slow and often fails. For example, Lee and Boutin (2006) estimated that after 35 years, approximately 65% of seismic lines crossing forests in Canada's boreal plains remained free of woody vegetation. Yet, our mechanistic understanding of how seismic testing influences vegetation recovery is limited. For example, in wetland locations, mechanical flattening of localized topography can result in a water table closer to the ground surface, leading to unfavorable conditions for black spruce (*Picea mariana)* seedlings to regenerate (Lee and Boutin 2006, Caners and Lieffers 2014). Furthermore, the post-disturbance understory vegetation communities, often dominated by hydrophilic species such as sedges and sphagnum mosses, may outcompete slow growing tree saplings (Davidson *et al* 2020b). In addition to the initial disturbance, continued use of these linear features for hunting, recreational sports, and further resource extraction activities can hinder tree recovery (van Rensen *et al* 2015). This poor recovery can be seen in our Landsat case studies of vegetation response to seismic lines (figure 16). There is a substantial drop in NDVI and NDMI at both upland and peatland seismic line sites following disturbance given trees are actively removed, and NDMI recovery is slow.

3.4.4. Limitations, data needs, and unknowns

Recent progress has been made to identify and map annual forest disturbance from logging across the North American ABZ based on the Landsat data archive spanning 1984–2014 (Zhang *et al* 2022). Between 1987 and 2012, 10.8% of the Alaska and western Canada experienced disturbance, with 1.4% attributed to logging. However, state and provincial forestry records are still an essential data source for understanding the scale and impact of logging and validating satellite detection of forest management, especially for lower-impact forestry practices that may be challenging for remote sensing approaches to detect. Such long-term data (e.g. polygons dating back to the 1960s, and GeoPDFs dating back to the 1800s in Saskatchewan, Canada) are crucial for studies of the impact of forest management on the North American boreal forest. However, many of these records are difficult to obtain. Similarly, data and records of seismic lines are not readily available across all Canadian provinces.

There are limited studies on land disturbances caused by oil and gas well production and exploration with only a few recent studies that are based in the contiguous U.S. (Raynolds *et al* 2014, Nallur *et al* 2020, Chomphosy *et al* 2021). Though databases with information on wells (i.e. intent, type, age, etc) are developed and maintained by numerous state, provincial, and territorial governments as well as the U.S. Bureau of Land Management for wells on federal lands, they can be incomplete (e.g. completely missing wells or incomplete information on well depth and age, etc). Nevertheless, these databases have been compiled for Canada and the U.S. to understand oil and gas well distribution, methane emissions, and other environmental impacts (Kang *et al* 2021, Williams *et al* 2021). Commercial databases are also available (e.g. GeoScout), however, they are not likely to contain information on the size of well pads and land disturbances. There is research on using machine learning and high-resolution imagery to detect active oil and gas well pads, which may provide data on well pad sizes and shapes (Bartsch *et al* 2020). Overall, there is a need for improved oil and gas well databases and information on well pads to understand the full extent of impacts.

3.5. Weather-related disturbances

Though anthropogenic-driven climate change is likely to have longer-term 'press' disturbance effects on ABZ vegetation, a handful of weather-related disturbances can affect vegetation markedly in the short-term, including rain-on-snow events, heat waves and extreme drought, and windthrow. Such disturbances can impact boreal and tundra vegetation, nutrient, and hydrology dynamics.

3.5.1. Rain-on-snow

Rain-on-snow events, or more broadly wet surface snow conditions (Pan *et al* 2018), are driven by a range of physical processes, though most often are caused by wintertime rain events that result in a wet snow surface (Singh *et al* 2000). Wet snow conditions can cause flooding and paludification in ABZ ecosystems, accelerate permafrost thawing, and decrease vegetation productivity (Rennert *et al* 2009, Bjerke *et al* 2014, Jeong and Sishama 2018). In mountainous regions rain-on-snow can destabilize the snowpack and trigger avalanches (Conway and Benedict 1994).

Most notably, re-freezing of melted snow creates ice barriers between the soil surface and the snowpack, making it difficult for ungulates such as caribou (*Rangifer tarandus*) and musk oxen (*Ovibos moschatus*) to forage for lichen during the winter (Putkonen *et al* 2009, Rennert *et al* 2009). These water and ice layers also facilitate the growth of toxic fungi, which can spoil lichens, further lowering wintertime food sources for ungulates, increasing foraging efforts and negatively impacting fat and protein reserves. In some cases, this can lead to movement of herds outside of their normal ranges, or even starvation and death, as occurred in 2003 on Banks Island,

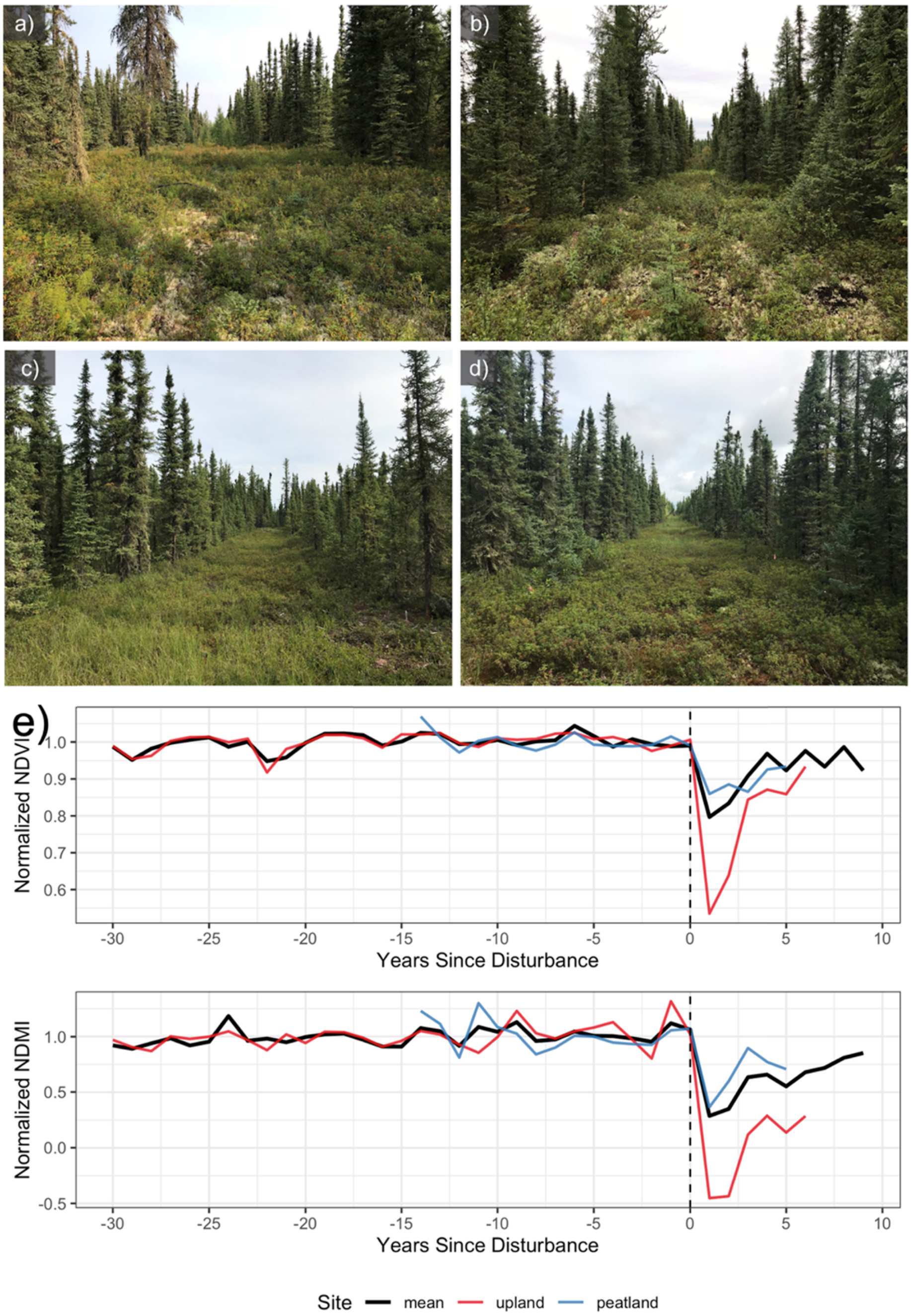

Figure 16. (a), (b) Seismic lines crossing upland boreal forest and (c), (d) peatland sites in northern Alberta, Canada. Note limited tree recovery on seismic lines crossing peatland ecosystems. All lines shown in these photos were cleared between 20 and 40 years ago; (e) case study trajectories for average ($n = 4$) and two individual seismic line locations in Alberta, Canada showing NDVI and NDMI normalized to the pre-disturbance average value.

Canada (Putkonen *et al* 2009), when a severe rain-on-snow event resulted in the death of ~20 000 musk oxen, reducing the island's population by 25%.

Along with direct impacts of rain-on-snow on vegetation freezing and flooding damage (Bjerke *et al* 2015), such severe impacts on ABZ ungulates can have cascading impacts on vegetation, predators, and the human populations that depend on the herds (Sokolov *et al* 2016, Serreze *et al* 2021). A significant decline in ungulates in one region can potentially release that vegetation from grazing and trampling pressure, whereas a movement of ungulates into a new area driven by rain-on-snow may cause significant vegetation damage (Vors and Boyce 2009).

Occurrence of rain-on-snow events depends on several factors, including air temperature, precipitation type, and extent and thickness of the snowpack (McCabe *et al* 2007, Freudiger *et al* 2014). Increases in energy flux to the snow surface, either through increasing temperature or increases in latent heat from rainwater, cause snowmelt as well as subsequent disruption of the insulative effect of the snowpack on the soil through increased liquid water content and increased energy flux to the soil (Rennert *et al* 2009,

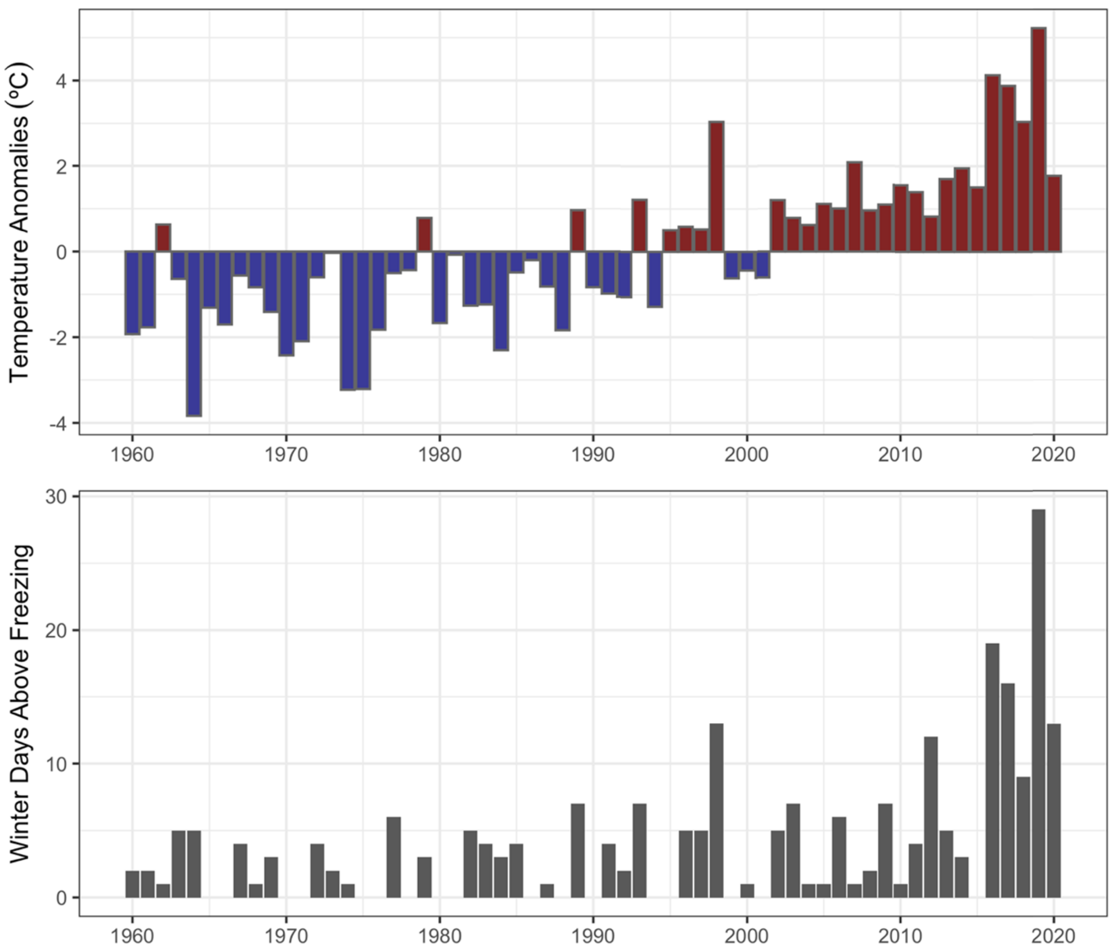

Figure 17. Climate data and temperature anomalies at Utqiagvik, AK (formerly Barrow, AK). Top: mean annual differences from 1960 to 2020 mean. Bottom: number of winter (October–March) days above 0 °C each year from 1960 to 2020. Weather station data are from the NOAA Global Historical Climatology Network.

Kim *et al* 2015, Pan *et al* 2018). While an individual rain-on-snow event is generally short-lived—on the order of days—the subsequent impacts on soil hydrologic and thermal conditions can last months. The frequency of rain-on-snow is predicted to increase in the future in the ABZ due to rising temperatures (Ye *et al* 2008, Jeong and Sishama 2018, Pan *et al* 2018), with potential cascading impacts on hydrology, thermal conditions, ecosystem function, and ecosystem services.

3.5.2. Heat waves and extreme drought

Heat waves and extreme drought can damage ABZ vegetation, lower productivity, and cause vegetation mortality (Hogg *et al* 2008, Allen *et al* 2010, Michaelian *et al* 2011). Heat waves can occur both during the growing season and in winter, with differing impacts on vegetation. Wintertime heat waves occur when temperatures rise above freezing for several days (Phoenix and Lee 2004, Bokhorst *et al* 2011). As a result, snow melts across large regions (Bokhorst *et al* 2008, 2009), initiating spring-like physiological responses in plants such as de-hardening and loss of frost tolerance, increases in photosynthesis, and bud swelling (Crawford 2008, Bokhorst *et al* 2010). Once temperatures return to freezing or below, plants are exposed to extreme cold due to reduction of snow's insulating capacity and buds can be damaged by frost (Bokhorst *et al* 2008, Girardin *et al* 2022). When the warming event is accompanied by little or no soil thaw, plant damage can be worsened by plant transpiration in frozen soil, leading to cavitation and desiccation of leaves, i.e. 'frost drought' (Bokhorst *et al* 2008, Bjerke *et al* 2017, Comeau *et al* 2019). This plant damage can decrease productivity and lead to mortality. For example, an experimental manipulation study of a sub-Arctic heathland found a 50% reduction in gross primary production (GPP) after multiple extreme winter warming events (Bokhorst *et al* 2011). Such extreme warming events are predicted to increase in the future as temperatures rise (Meehl and Tebaldi 2004). In Utqiagvik, Alaska, the number of winter days with maximum temperatures above freezing has steadily increased since 1960, and several record-high days occurred in 2020 (as compared to the previous 20 years) (figure 17). Such temperature anomalies will continue to impact ABZ vegetation, potentially leading to plant damage and decreased productivity if wintertime extremes continue to increase (Richardson *et al* 2018).

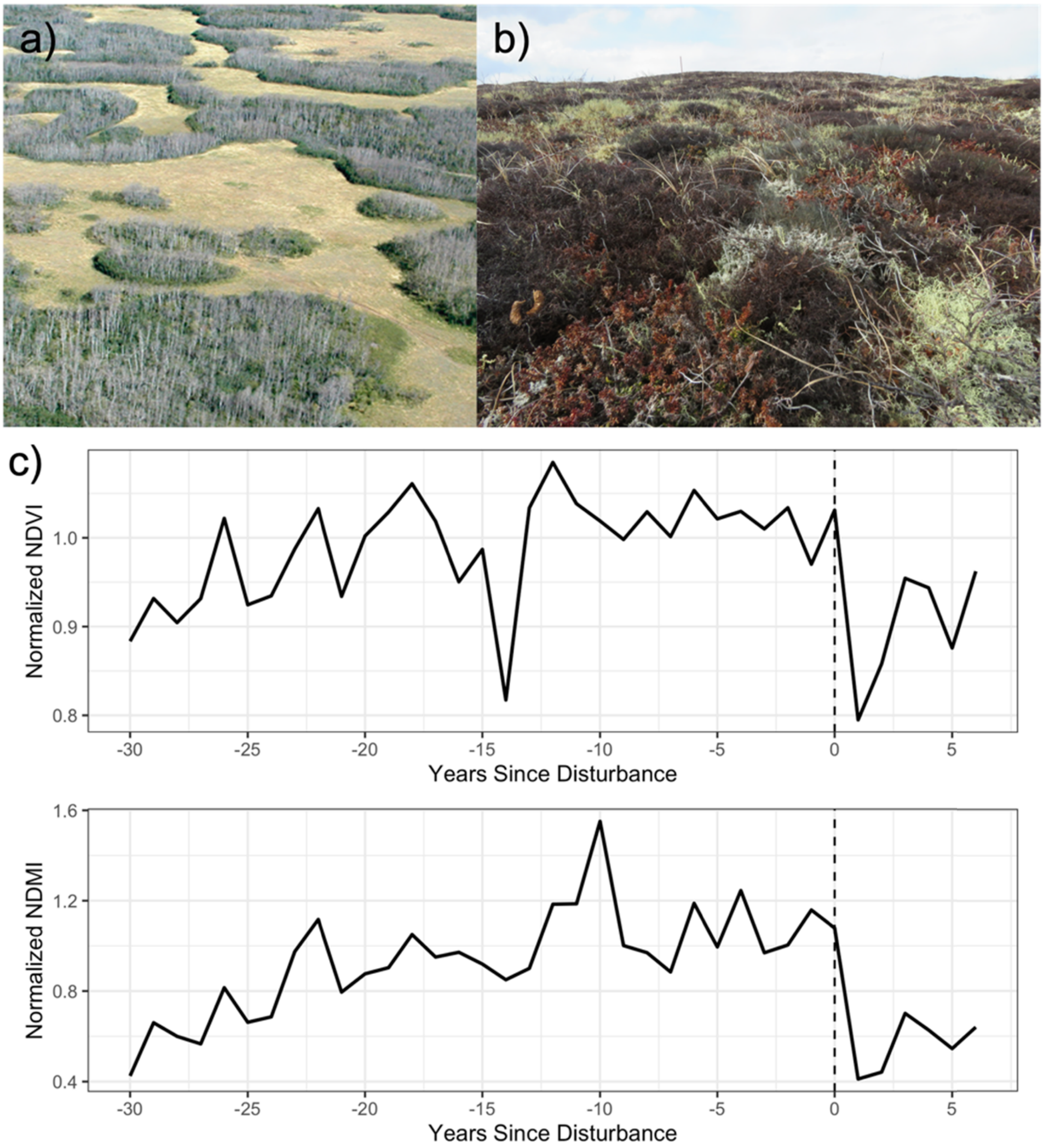

Figure 18. (a) Massive mortality of quaking aspen in Saskatchewan, Canada, from a drought in 2001–2002, photo credit M Michaelian 2004; Michaelian *et al* (2011). John Wiley & Sons. © 2010 Crown in the right of Canada. (b) Browning of tundra vegetation; (c) Landsat-derived NDVI and NDMI over vegetation in response to drought in the Northwest Territories in 2018.

During the growing season, heat waves and severe droughts (either from increased temperatures or decreased precipitation) can lead to water deficits that increase vegetation stress, lower productivity, and can cause widespread mortality under severe conditions (figure 18(a); Hogg *et al* 2008, Allen *et al* 2010, Michaelian *et al* 2011, Peng *et al* 2011, Girardin *et al* 2021, Refsland and Cushman 2021). Such drought stress disrupts plant cell membrane function and can lead to xylem cavitation, with susceptibility to cavitation increasing with canopy height and varying by plant species due to differences in stomatal regulation (Allen *et al* 2010, McDowell and Allen 2015). Species-specific differences in drought response can alter stand structure and species composition if previously dominant species die off and are replaced by more drought-tolerant ones (Anderegg *et al* 2012). Drought can also cause regeneration failure and conversion of forests to woodland or grassland, particularly if compounded by other disturbances like fire (Whitman *et al* 2019, Baltzer *et al* 2021). Such drought and heat wave events can also trigger disease and insect outbreaks within already stressed vegetation (Raffa *et al* 2008, Boyd *et al* 2021, Ruess *et al* 2021). The impact of drought on vegetation greenness and moisture can be seen in a case study in the Northwest Territories for a drought that occurred in 2018 (figure 18(c)). Both NDVI and NDMI drop immediately following the drought, with slow recovery in vegetation moisture and more moderate recovery in NDVI.

Severe droughts and heat wave events are increasing within the North American ABZ, particularly in the southern boreal zone (Michaelian *et al* 2011, Perkins-Kirkpatrick and Lewis 2020, Berner and Goetz 2022). An extreme drought in 2001–2002 in southwestern Canada resulted in a severe aspen mortality event, with 45 Mt of biomass lost, resembling the carbon impacts from a severe wildfire (Michaelian *et al* 2011). Drought and heat wave events impact water quality, nutrient availability, and biogeochemistry (Houle *et al* 2016, Tiwari *et al* 2018) They also have the capacity to feed back to climate change through loss of carbon stocks and subsequent emissions from decomposition (Michaelian *et al* 2011, Ma *et al* 2012), as well as changes to energy and water cycling due to changes in surface roughness, transpiration rates, and latent heat fluxes (Bonan 2008).

3.5.3. Windthrow

Windthrow, or tree blowdown events from high wind, are important disturbance agents within the North American boreal zone that act primarily at the stand-scale (Ruel 2000, Bouchard *et al* 2009). While extreme wind events resulting in stand-replacement are rare in the boreal zone, partial windthrow where some individuals survive is more common, with return intervals ranging from 40 to 450 years in eastern Canada (Ruel 2000, De Grandpré *et al* 2018).

Damage to trees depends on individual tree and stand factors, including tree size, species, canopy position, and previous stem damage, as well as soil depth and moisture, stand density, fragmentation, and angle with respect to wind direction (Peterson 2004). Tree size and species are the most reliable predictor of windthrow survival—some tree species are more 'wind firm' than others, and damage susceptibility increases with increasing tree size (Peterson 2004, Rich *et al* 2007). Because of the differential impact of partial windthrow on tree size and species, these events can cause shifts in the species composition and stand structure of impacted stands (Veblen *et al* 2001, Girard *et al* 2014). Windthrow can also act as a trigger for subsequent bark beetle outbreaks, as beetle populations are able to colonize and grow within downed stems (Wichmann and Ravn 2001).

3.5.4. Limitations, data needs, and unknowns

Some of the main challenges of studying extreme weather events like rain-on-snow, winter warming, and windthrow include the sparsity of weather stations in northern regions, the lack of routinely deployed weather equipment (Putkonen *et al* 2009), and the unpredictable occurrence of events such as severe blowdown (Bouchard *et al* 2009). Detection of rain-on-snow events with satellite measurements is possible using radar, microwave, and multispectral imagery (Serreze *et al* 2000, Bartsch *et al* 2010, Pan *et al* 2018). Accurate detection of windthrow depends on the spatial resolution of remotely sensed measurements compared to the scale of the blowdown (Schwarz *et al* 2003). An enhanced monitoring network of weather conditions and snowpack, such as those present in the SNOTEL network (Schaefer and Paetzold 2001) would help better characterize and identify the occurrence of these events.

With respect to extreme drought and heat waves, while the physiological mechanisms underlying plant drought response and vulnerability are well established and emerging remote sensing techniques offer promise (Rogers *et al* 2018), it is still difficult to predict which individuals will die from such drought stress (Trugman *et al* 2021). Critical needs include further understanding of plant physiological and site characteristics that influence drought exposure and susceptibility and better information about how biotic agents interact with drought to cause plant mortality (Trugman *et al* 2021).

3.6. Riverine processes

3.6.1. Background

Despite their relatively small footprint in ABZ landscapes, riparian zones are disproportionately important for ecological disturbance (Scrimgeour *et al* 1994), hydrological processes (Ploum *et al* 2021), biogeochemical cycling (Blackburn *et al* 2017), species diversity (Johansson *et al* 1996, Andersson *et al* 2000, Johnson and Almlöf 2016), and wildlife (Tape *et al* 2016, Cooke and Tauzer 2020). In recent decades, substantial hydrologic changes have been observed on ABZ rivers, including changes to seasonal flow-regimes (Peterson 2002, McClelland *et al* 2006, Smith *et al* 2007, Rawlins *et al* 2010, Holmes *et al* 2021), groundwater relations (Okkonen *et al* 2010), river-ice breakup (Prowse and Beltaos 2002, Beltaos *et al* 2006), biogeochemistry and water quality (Tiwari *et al* 2022), and beaver colonization (Tape *et al* 2018, 2022). In addition, there have been widespread changes observed in permafrost extent both on floodplains and within their catchments (St. Jacques and Sauchyn 2009, Jones and Rinehart 2010, Quinton *et al* 2011, Tananaev and Lotsari 2022). It has been hypothesized that these processes will lead to a reduction in the areal extent of active floodplains in ABZ landscapes due to increased river channelization, smaller peak flows, and reduced riparian disturbance intensity (Ström *et al* 2011, 2012, Nilsson *et al* 2013, Jansson *et al* 2019).

Streams and rivers in the ABZ are strongly influenced by geology and topographic relief as well as hydroclimate, ice cover, and the permafrost regime (Ashmore and Church 2001, Rokaya *et al* 2018), with high variability in river morphology (Nilsson *et al* 2015). Streamflow rates can range from slow-moving tundra streams to large flowing rivers that span Arctic-boreal ecotones (e.g. the Mackenzie and Yukon rivers) (Nilsson *et al* 2015). Riparian ecosystems are especially dynamic because they experience frequent erosion, flooding, and sedimentation (Wiens 2002). Channel migration and flooding can be seen as similar to fire disturbance, both creating short-term destruction to vegetation with the capacity for regeneration following the event (Rood *et al* 2007). Channel migration in particular can 'reset' vegetation succession at any successional stage through floodplain erosion and simultaneous sedimentation and creation of new land for vegetation establishment (Walker and Chapin 1986, Viereck *et al* 1993, Van Cleve *et al* 1996, Helm and Collins 1997, Lininger *et al* 2017).

In addition to channel migration, ice-jam flooding is also an important disturbance in ABZ riparian zones. Ice-jams occur when ice floes in rivers are impeded by stationary ice covers, bridges, islands, or river width constrictions, leading to flooding (Rokaya *et al* 2018). Ice-jam flooding can occur during any river ice freeze-up or breakup period but are most common during the spring breakup period (Beltaos and Prowse 2009, Rokaya *et al* 2018). Ice-jam flooding causes significant economic and structural damage, and can result in loss of human life, made more prevalent by their unpredictable nature (Massie *et al* 2002, Mahabir *et al* 2008, Rokaya *et al* 2018). These floods also disrupt aquatic and riparian habitat through decreased fish habitat, and damage to and even removal of vegetation adjacent to the stream (Lind *et al* 2014, Lindenschmidt *et al* 2016). Ice-jam flooding also exerts a strong influence on the water balance of lakes within river floodplains and deltas, and the floodwaters supply sediment, nutrients, and contaminants. These processes have been investigated in the Slave River and Peace-Athabasca Deltas where floodwaters replenish nearby basins and offset evaporative water loss (e.g. Brock *et al* 2009, Wolfe *et al* 2012) while also increasing concentrations of suspended sediment (and turbidity of the lake water), major nutrients, and contaminants such as polycyclic aromatic compounds and metals (Hall *et al* 2012, Wiklund *et al* 2012, Elmes *et al* 2016, MacDonald *et al* 2016, Kay *et al* 2020). Reductions in the frequency of flooding leave lakes across these landscapes at risk of drying (Wolfe *et al* 2012). Sustainable management of ice-jam flooding thus includes balancing both the detrimental and beneficial aspects of these events on socio-economic and ecological systems (Das *et al* 2018).

Beavers are important ecosystem engineers in the North American ABZ through their dam-building and hydrologic engineering of rivers, streams, sloughs, and lakes. Previously considered only a sub-Arctic species, recent observations show beaver colonization into low arctic tundra regions of Alaska and Canada in recent decades (Tape *et al* 2018, Jones *et al* 2020b, 2022) due to climate-change driven landscape change as well as population recovery from historical over-trapping (Tape *et al* 2018). Beaver dams trap water on the landscape, turning streams and sloughs into connected ponds, widening riparian zones and altering groundwater flow (Westbrook *et al* 2006, Tape *et al* 2022). Jones *et al* (2020b) found that beavers preferentially targeted thermokarst landforms in their dam-building activities within the Baldwin Peninsula, Alaska, accounting for 60% of the increase in surface water in the region between 2002 and 2019. Increases in surface and groundwater due to beaver dams transfers additional heat to the ground and thaws permafrost surrounding and beneath beaver ponds (Tape *et al* 2022). In permafrost-affected regions, beavers have the capacity to initiate and affect lake formation and drainage, ice-wedge degradation, cryogenic landslides, and other thermokarst events (Jones *et al* 2018, 2021). These physical changes to waterways and the surrounding permafrost effectively create warmer patches of mixed aquatic and terrestrial ecosystems that likely act as oases.

3.6.2. Limitations, data needs, and unknowns

Given the role of climate and extreme events on floodplains, spatiotemporal properties of disturbance, succession, and floodplain evolution are likely to be influenced by recent climatic warming at high latitudes, leading to important changes in the structure and function of riparian ecosystems in the ABZ. However, most ecosystem change studies to date have focused on upland and lowland ecosystems, whereas the observational record for riparian zones is comparatively sparse. There is thus substantial uncertainty concerning recent changes and future trajectories on floodplains across gradients of climate, stream order, catchment size, and floodplain morphology. For example, the pace of vegetation succession may increase in a warming climate due to longer, more productive growing seasons and changes in permafrost properties on or near riparian zones, particularly in forest-tundra ecotones (Wilmking and Juday 2005, Kharuk *et al* 2006, Beck *et al* 2011), while altered flow-regimes may influence the frequency and intensity of disturbance regimes. In Alaska, several studies have documented conspicuous, long-term increases in the extent and canopy height of tall shrublands in subarctic and Arctic riparian zones (Tape *et al* 2011, Brodie *et al* 2019, Liljedahl *et al* 2020). Understanding the interactions between biological and physical processes in the context of climate warning is important for assessing long-term impacts of continued warming on ABZ floodplains.

Beaver activity may be an important disturbance within permafrost regions, potentially causing widespread changes to the hydrologic and biotic environment, and initiating permafrost degradation (Tape *et al* 2022). Current research is exploring how these newly constructed oases affect carbon cycling, aquatic and terrestrial biodiversity, fish, and other ecosystem attributes. Further investigation is needed to understand the spatial extent and implications of beaver activity within the North American and circumpolar ABZ (Tape *et al* 2022).

3.7. Mammalian herbivore activity

3.7.1. Background

Mammalian herbivores like moose (*Alces alces*), caribou (*Rangifer tarandus*), and snowshoe and arctic hares (*Lepus americanus, L. arcticus*) impact ABZ ecosystems through coupled herbivore-vegetation feedbacks. For example, selective foraging, trampling, and inputs of excreta, urine, and decomposing carcasses can directly alter plant community composition or indirectly affect ecosystem properties through changes to soil characteristics and nutrient cycling (Olofsson *et al* 2004, Väisänen *et al* 2014, Schmitz *et al* 2018, Leroux *et al* 2020). These species are also a crucial subsistence resource for indigenous communities (Rexstad and Kielland 2006). Caribou in particular occur in high abundance across much of the North American ABZ, numbering in the millions, and are one of the Arctic's most ecologically, culturally, and economically important species (Hummel and Ray 2008, Parlee *et al* 2018, Gagnon *et al* 2020). These large herbivores also make some of the longest terrestrial animal migrations in the world, with some herds traveling over 1000 km from boreal wintering grounds to Arctic tundra breeding grounds (Gurarie *et al* 2019, Joly *et al* 2019). During calving and migratory periods, caribou herds aggregate in dense groups and can alter landscapes as they pass through, impacting vegetation cover and structure, soils, and ecosystem carbon storage (Olofsson and Post 2018).

The distribution and intensity of caribou impacts are driven primarily by grazing and trampling associated with fluctuations in population sizes, which occur on a multi-decadal basis (Gunn 2003, Vors and Boyce 2009, Joly *et al* 2011). These fluctuations are influenced by snow conditions and forage availability (Post and Forchhammer 2002, Gunn 2003, Joly *et al* 2011). A meta-analysis of caribou impacts on vegetation cover across the Eurasian and North American ABZ showed a clear negative effect on lichen (Bernes *et al* 2015). Because lichens are slow to recover from disturbance, this impact is both acute and long-lasting (Suominen and Olofsson 2000, Joly *et al* 2009, Macander *et al* 2020). Reductions in lichens in turn drive density-dependent feedbacks on caribou, causing population declines and influencing population cycles (Manseau *et al* 1996, Gunn 2003). Impacts of caribou trampling and grazing on vegetation can also include transitions to graminoid dominated communities (van der Wal 2006), and constraints on deciduous shrub expansion (Olofsson *et al* 2009, Christie *et al* 2015, Bråthen *et al* 2017) or treeline advance (Munier *et al* 2010, Bryant *et al* 2014). Caribou impacts are most pronounced in arctic environments where population densities are highest. In the boreal zone, low caribou density likely minimizes impacts.

In contrast, herbivores like hares and moose in the boreal forest can shift the age distribution of the foraged species towards younger age classes (Butler 2003, Kielland *et al* 2006). Selective feeding can also shift species composition. For example, moose herbivory can cause a shift from palatable deciduous species towards unpalatable evergreen species (Pastor *et al* 1988, Kielland *et al* 2006). Recent work suggests that moose alter their behavior to favor dense canopy areas during increased summer temperatures, suggesting shifts in areas vulnerable to browsing under warmer conditions (Jennewein *et al* 2020). Whereas moose generally avoid evergreen species like white spruce (*Picea glauca*), snowshoe hares browse heavily on white spruce seedlings, especially during periods of high hare abundance (Rexstad and Kielland 2006, Angell and Kielland 2009, Sharam and Turkington 2009, Hollingsworth *et al* 2010). Snowshoe hare populations in Alaska and Canada exhibit cyclic dynamics, driven by predator population size and herbivore-vegetation feedbacks (Krebs *et al* 2018). During peaks that occur about every ten years, snowshoe hare browsing can alter vegetation composition and plant chemical defenses (Fox and Bryant 1984), suppress the succession of white spruce (Olnes and Kielland 2016), and curb treeline advance (Olnes *et al* 2018).

3.7.2. Limitations, data needs, and unknowns

Most studies of herbivore impacts on vegetation use exclosures to assess what happens when herbivores are removed from a system. However, responses of vegetation to increasing vs. decreasing grazing pressure are not equal (Olofsson 2006). For example, studies that examine the impact of increasing caribou herd size (typically observational) often report stronger impacts than experiments that exclude caribou and examine the impact of decreasing herd size (typically manipulative) (Olofsson 2006). Geographic disparities in research can also influence conclusions. For example, studies of caribou impacts on vegetation primarily come from Fennoscandia (Soininen *et al* 2021). This raises issues of transferability of results because ecological conditions are different. Most caribou in Fennoscandia are managed in domesticated or semi-domesticated herds that often occur at higher densities than wild herds in North America (Bernes *et al* 2015).

Results from remote sensing and modeling studies which attempt to capture the relationship between caribou population density and vegetation productivity have produced mixed results, with some studies reporting significant negative relationships (Rickbeil *et al* 2015, Yu *et al* 2017, Campeau *et al* 2019) and others reporting weak or non-significant relationships (Fauchald *et al* 2017). Recent work by Davidson *et al* (2020a) provides and extensive collection of animal tracking datasets that can be used to analyze climate-driven variation in animal movement and foraging activity. As remote sensing technologies improve, increasing spectral and spatial resolution of satellite imagery might bolster the ability to quantify herbivore impacts across space and time.

4. Temporal and spatial scale of disturbances

Disturbances in the North American ABZ notably occur across a wide range of spatial and temporal scales (table 1). The spatial grain of individual disturbance events ranges from on the order of meters for individual patterned-ground features such as frost circles (Frost *et al* 2013) to 1000s of square kilometers for large boreal 'megafires' (Stephens *et al* 2014). Temporally, ABZ disturbances occur over the course of hours or days, such as windthrow, or over years, such as with drought (Michaelian *et al* 2011). Their return frequency for the same location also varies from a general one-time event, such as with lake drainage (Shur and Jorgenson 2007), to an annual occurrence, such as with cryoturbation (Frost *et al* 2018b). Post-disturbance vegetation recovery times also vary, on the order of years (e.g. rain-on-snow; Bokhorst *et al* 2011), to decades (e.g. wildfire; Amiro *et al* 2010, Kurz *et al* 2013), or not at all (e.g. oil and gas wells; Kang *et al* 2021). Finally, the intensity of the impact on ABZ vegetation varies from productivity changes (e.g. cryoturbation, pathogens; Holsten *et al* 2008, Frost *et al* 2013) to complete vegetation loss (e.g. wildfire; Rogers *et al* 2015).

The temporal and spatial scale of disturbance occurrence and recovery as well as the overall intensity of impact can also vary within disturbance and landscape types. For example, high severity boreal wildfires tend to be stand-replacing large-scale events lasting weeks or months (Sedano and Randerson 2014, Rogers *et al* 2015, Veraverbeke *et al* 2017), in contrast to smoldering fires, which can burn year-round and survive the winter (Scholten *et al* 2021). Spatially, the resolution of individual disturbance events can be quite small but can cover large extents in their overall scale of impact. For example, insect infestations occur at the individual tree scale, but can then spread to whole stands and landscapes (Raffa *et al* 2008). Similarly, though individual seismic lines cover only a few meters in area, their combined extent is vast across the North American ABZ (Jorgensen *et al* 2010).

We compiled these spatiotemporal characteristics across disturbance types (table 1) and analyzed how they vary using a PCA. The results from our PCA analysis (figure 19) indicate the broad spread in the spatiotemporal characteristics associated with ABZ disturbances. The loadings for frequency and intensity and size and occurrence/recovery timeline are opposite one another, indicating negative correlation. In general, high-intensity events occur at a lower frequency than lower severity disturbances which only impact productivity (but not necessarily mortality) (table 1; figure 19). Some of the overarching groups are clustered together in the PCA (e.g. anthropogenic, pests and pathogens, weather), whereas the permafrost-related disturbances span the entire range of the first two principal components.

Understanding spatiotemporal differences is crucial when detecting and studying these disturbances via remote sensing, or when including them in process-based models. Advances in Earth observation sensor resolution have improved the capability to characterize and monitor disturbances and their interactions. However, in the context of detection and monitoring of multi-disturbance landscapes, an integrative approach is necessary to extend knowledge about disturbance (or multi-disturbance) recovery processes across high-latitude landscapes. Integration with remote sensing typically implies validation against pre-and post-disturbance *in situ* data across whole landscapes, and often involves cross-sensor harmonization to extend temporal or spatial ranges. Synthesis of disturbance-related studies toward understanding disturbance processes and their interactions across such a broad and heterogeneous domain requires bridging of temporal and spatial scales across scientific disciplines (i.e. ecology, geology, hydrology, etc) (Cavender-Bares *et al* 2022). The disturbance spatial grain and extent are particularly important, and should match the spatial resolution of the sensor (Senf *et al* 2017b, Duncan *et al* 2020). Sensor pixel size is known to affect the measurement magnitude, location, and geospatial congruence of disturbance hotspots and the characterization of the effects of disturbances on ecosystems (Cavender-Bares *et al* 2022). While some of the mid-resolution sensors like Landsat have long records and are capable of tracking trajectories, they may be limited to tracking only larger-scale disturbances because their pixel size (e.g. 30 m) is large relative to the sub-pixel of disturbances such as cryoturbation (∼1–5 m) or the early stages of insect outbreaks.

Scale is also crucial for the prediction of future disturbance effects, interactions, and feedbacks using process-based modeling. Models that do not consider individual plant species, such as many global climate models, will not fully capture species-specific effects of biotic disturbances, herbivory, and windthrow, or accurately capture successional dynamics following disturbances (Foster *et al* 2019, Shugart *et al* 2020). Ecosystem demographics represented in a modeling framework should interact with vegetation dynamically and be represented at scales that correspond to the frequency and extent of the disturbances that the model framework includes (Seidl *et al* 2011, Albrich *et al* 2020). For example, fine temporal

Table 1. Spatial, temporal, and intensity characteristics of ABZ disturbances.

Disturbance Group	Disturbance	Spatial Grain	Return Interval	Occurrence Timeline	Recovery Timeline	Impact/Intensity
Wildfire	Wildfire	100s of km^2	Decadal to centennial	Weeks to months	Decades to centuries	Some to complete vegetation loss
Insects and pathogens	Bark beetles	Meters to hectares	Decadal to centennial	Months to years	Decades	Some to complete vegetation loss
	Defoliators and leaf miners	Meters to hectares	Annual to decadal	Months to years	Years to decades	Vegetation loss; productivity decline
	Pathogens	Meters to hectares	Annual to decadal	Months to years	Years to decades	Some vegetation mortality; productivity decline
Permafrost	Cryoturbation	Meters	Annual	Months	Years	Stress
	Ice-wedge degradation	Meters	Annual	Years	Years	Partial mortality
	Cryogenic landslides	Meters to hectares	Decadal to centennial	Days to years	Decades	Vegetation loss
	Lake drainage	Meters to hectares	Generally one-time event	Days to years	Years to decades, if at all	Vegetation encroachment
Anthropogenic	Logging	Hectares	Decadal to centennial	Months	Decades to centuries	Vegetation loss
	Oil and gas wells	Meters	One-time event	Years	None	Vegetation loss
	Seismic lines and pipelines	Meters to hectares	One-time event	Weeks to months	Decades	Vegetation loss; vegetation change
Weather-related	Windthrow	Hectares	Decadal to centennial	Days	Decades	Some to complete vegetation loss
	Rain-on-snow	100s of km^2	Annual	Days	Years	Productivity decline; flooding; loss of grazing animals
	Extreme drought and heat waves	100s of km^2	Annual to decadal	Months to years	Years to decades	Vegetation loss; productivity decline
Riverine	Channel migration	Meters to hectares	Annual to decadal	Days to months	Years to decades	Some to complete vegetation loss
	Ice-jam flooding	Hectares	Centennial	Days	Decades	Vegetation loss
	Beaver engineering	Meters to hectares	Decadal	Months	Years to decades	Some to complete vegetation loss
Herbivore activity	Herbivore activity	Hectares to 100s of km^2	Annual to centennial	Months to years	Years to centuries	Vegetation stress; vegetation loss

scales (e.g. daily, table 1) may be required to accurately model the disturbance interactions of a wildfire leading to a cryogenic landslide. It is also crucial to consider gridcell-to-gridcell spread of 'contagious' disturbances like fire or insect infestation, as well as the temporal and spatial scales at which this spread occurs (Johnstone *et al* 2011). Representing the spatial and temporal complexities of multi-disturbance interactions in these systems accurately is an emerging area of high-resolution forest and tundra modeling. As remote sensing and modeling technologies improve, and more accurate and spatially continuous occurrence data are acquired, we will be better able to detect and predict ongoing ABZ disturbances, as well as their future trajectories.

5. Disturbance interactions

Disturbances within the ABZ can interact with one another, often with positive feedbacks that amplify the impact of subsequent events, such as wildfire and subsequent abrupt permafrost thaw (Gibson *et al* 2018). Other interactions may have a negative or dampening effect on subsequent disturbances, such as cryogenic landslides and subsequent reduction in wildfire potential (figures 20 and 21). Broadly, disturbances may interact by altering the *resistance* of an ecosystem to subsequent disturbances, altering the probability of future disturbances, or by altering an ecosystem's *resilience*, or its ability to recover from a subsequent disturbance and its overall impact

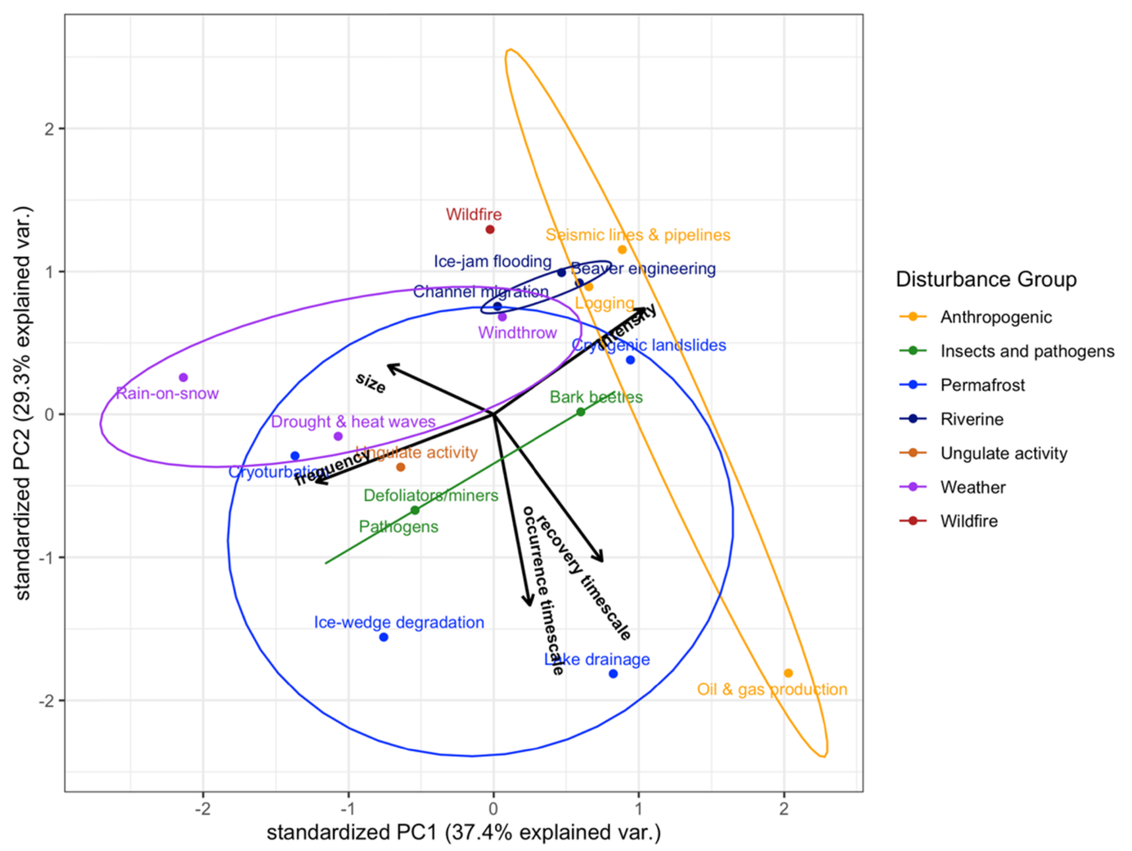

Figure 19. PCA derived from disturbance spatiotemporal characteristics (table 1). Qualitative characteristics were modified to numeric scalar values (table S2).

and severity (Buma 2015). As most of these disturbances are predicted to increase in frequency, severity, and/or extent with climate change (Chen *et al* 2016, Veraverbeke *et al* 2017, Pan *et al* 2018, Pureswaran *et al* 2018, Turetsky *et al* 2020, Berner and Goetz 2022), the opportunity for interactions among these disturbances will likewise increase, leading to potentially nonlinear and cascading impacts on ABZ ecosystems and vegetation (Buma 2015, Seidl *et al* 2017). Typically, studies of disturbances, in the ABZ or otherwise, only focus on a single disturbance type, and thus do not capture the true potential impact of a disturbance that includes its downstream effects on other disturbance regimes (Seidl and Turner 2022). Here, we discuss some of the interactions between ABZ disturbances and present our findings in figures 20 and 21 but note that there are many complex interactions which are still the subject of further study.

Due to the ubiquitous nature of wildfire across the North American ABZ, fire interacts with most other disturbances within these regions (figures 20 and 21). Drought and wildfire are often linked, with low moisture conditions increasing fuel flammability (i.e. decreasing resistance), and post-fire impacts on soil conditions often leading to moisture stress (i.e. decreasing resilience) (Whitman *et al* 2019, Baltzer *et al* 2021). In general, fire probability increases in the initial stages following bark beetle outbreaks as needles dry and thus become more flammable (Jenkins *et al* 2012, 2014). However, once the needles fall, the ground-to-canopy continuity is lost, thus lowering the probability of high severity crown fires. Low severity fires that damage trees but do not kill them can increase susceptibility to insect and pathogen attack and subsequent mortality (Hood and Bentz 2007), however stand-replacing wildfire removes host availability and thus decreases the risk for outbreak (Veblen *et al* 1994). Fire in permafrost areas can lead to thermokarst features, permafrost degradation, and changes to hydrology (Holloway *et al* 2020). Research indicates that tundra fires are becoming more frequent (French *et al* 2015, Hu *et al* 2015) and that post-fire deciduous shrub expansion may, in turn, further facilitate fire (Higuera *et al* 2008, Lantz *et al* 2010a), Bret-Harte *et al* 2013, Gaglioti *et al* 2021). However, herbivory and trampling of expanding deciduous shrubs has the potential to provide a negative feedback effect that lengthens fire return intervals in the Arctic (Olofsson *et al* 2009, Christie *et al* 2015, Bråthen *et al* 2017). Beavers have also been shown to prevent fire spread and provide fire refugia (Fairfax and Whittle 2020).

Aside from fire, windthrow is often a precursor to bark beetle infestation through facilitation of beetle population growth within downed

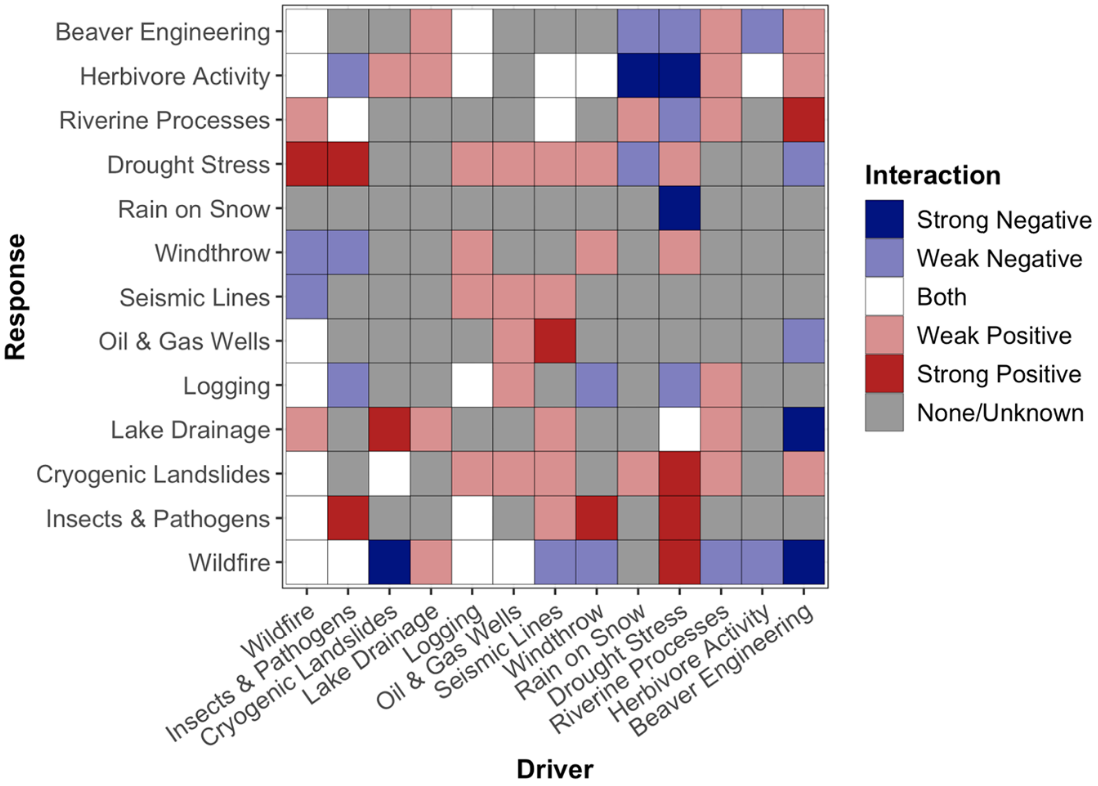

Figure 20. Interactions between disturbances in the North American boreal forest. Driver (*x*-axis) disturbances are the initiating disturbance, whereas response disturbances (*y*-axis) are the potential subsequent disturbances. Negative interactions correspond to a dampening effect of the driver on the response disturbance. Positive interactions correspond to an enhancing effect of the driver on the response disturbance.

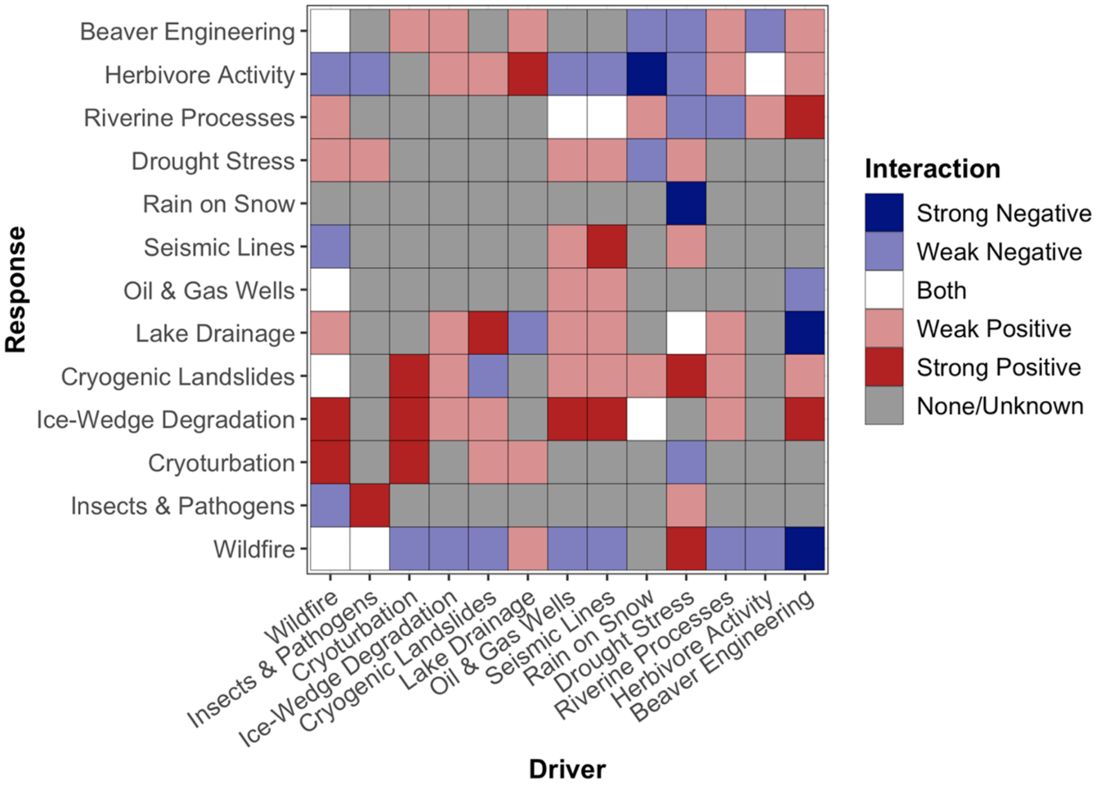

Figure 21. Interactions between disturbances in the North American Arctic tundra. Driver (*x*-axis) disturbances are the initiating disturbance, whereas response disturbances (*y*-axis) are the potential subsequent disturbances. Negative interactions correspond to a dampening effect of the driver on the response disturbance. Positive interactions correspond to an enhancing effect of the driver on the response disturbance.

logs (Christiansen *et al* 1987, Malmstrom and Raffa 2000). Defoliators and bark beetles influence one another, where defoliators can weaken hosts and increase susceptibility to subsequent attacks by bark beetles (Cole *et al* 2022). Likewise, drought and biotic disturbances can enhance one another through decreased vegetation resilience (Malmstrom and Raffa 2000, Boyd *et al* 2021, Ruess *et al* 2021).

Many disturbances are linked with cryoturbation, ice wedge degradation, and cryogenic landslides (figures 20 and 21). For example, a physical disturbance to the landscape, such as a fire or seismic line placement, can reactivate cryoturbation features and local permafrost degradation by removing live vegetation and surface organic material (Frost *et al* 2013). Thaw slumps can also trigger catastrophic drainage of adjacent thermokarst lakes (Marsh *et al* 2009).

Anthropogenic features such as roads, seismic lines, and logging affect the landscape and can result in additional disturbance; roads can lead to additional wildfires by opening access to human ignitions. Across Canada, the majority of human-caused ignitions are within 10 km of communities (Parisien *et al* 2020). These fires then have the potential to destroy human infrastructure. However, roads and infrastructure can also act as fire breaks and prevent fire spread (Narayanaraj and Wimberly 2011, Cochrane *et al* 2012). Some salvage logging can take place after a fire event, but fires can also destroy stands designated for harvest, or previously harvested stands. Insect outbreaks and pathogens have destroyed merchantable timber across Canada (Volney and Fleming 2000, Hennigar *et al* 2007), reducing the area available for harvest. The large network of seismic lines associated with oil and gas exploration has also negatively impacted habitat quality for boreal woodland caribou across Canada, with many populations in decline (Hebblewhite 2017, Nagy-Reis *et al* 2021). This type of habitat fragmentation has been shown to alter animal behavior and reduce mammalian movements globally (Finnegan *et al* 2018, Tucker *et al* 2018).

Many of the disturbances have no or unknown interactions (figures 20 and 21), either because of lack of study (e.g. insect outbreaks and pathogens and subsequent thaw slumps) or because the disturbances are not generally co-located (e.g. cryoturbation and logging). These unknowns present both an opportunity and need for further study as well as the potential for previously geographically separate disturbances to interact as climate change continues to modify their extent and range. Disturbance interactions in particular should be a priority for further field, remote sensing, and modeling studies in the ABZ.

6. Conclusions

Present in all these disturbances is the amplifying effect of climate change, as this region is warming much faster than other areas of the globe (Price *et al* 2013, Smith *et al* 2019, Chylek *et al* 2022). The direction and magnitude of precipitation change is of growing concern, and this shift will feed back to changes in disturbance trajectories—a drier landscape will lead to larger and more severe wildfires, whereas abrupt permafrost thaw may increase in a wetter environment that dampens wildfire risk. Ultimately, disturbances are pivotal in creating local hotspots of change against the backdrop of long-term climate change. These disturbances create the potential for persistent shifts in vegetation composition (e.g. shift towards deciduous dominance post-fire) and biomass and extent (e.g. tall shrub and tree migration at treeline) (Mack *et al* 2021, Maher *et al* 2021, Foster *et al* 2022).

Disturbances also have the capacity to increase colonization and spread of non-native and invasive plant species (Sanderson *et al* 2012, Kent *et al* 2018, Kelly *et al* 2020). Previously, boreal and Arctic ecosystems were seen as too hostile and remote to facilitate invasion of non-native species (Sanderson *et al* 2012), however increasing temperatures and longer growing seasons are facilitating the northward migration of species in response to climate change (Chen *et al* 2011). Many studies have begun to document non-native and invasive plant species within the ABZ (Kent *et al* 2018, Wasowicz *et al* 2020, Leostrin and Pergl 2021), and show increasing establishment of these species following disturbances like fire (e.g. narrowleaf hawksbeard, *Crepis tectorum*, Carlson *et al* 2008) or harvest (e.g. bull thistle, *Cirisum vulgare*, Randall and Rejmánek 1993). Increasing anthropogenic presence and activities such as oil and gas exploration and production will also increase invasion of non-native plants, particularly in the Arctic (Wasowicz *et al* 2020). Through rapid growth, shading, and altered nutrient cycling (especially for N_2-fixing species) invasive plants can reduce growth of native plants, potentially leading to cascading impacts on biogeochemical cycling (Carlson *et al* 2008, Sanderson *et al* 2012). Though non-native and invasive species are gaining more attention in the ABZ, further studies are still needed to determine the potential pace of future colonization as well as how these species will interact with native flora in conjunction with climate change.

Disturbances also interact with human society in fundamental and profound ways. Smoke from large fires in the ABZ can substantially reduce air quality (Trainor *et al* 2009, Johnson *et al* 2021), and fires themselves cause significant destruction of human property and resources (de Groot *et al* 2013, Thomas *et al* 2017). Many disturbances (e.g. insects, pathogens, windthrow, drought) reduce timber resources (Volney and Fleming 2000, Hennigar *et al* 2007, Anderegg *et al* 2012, Boucher *et al* 2018). Permafrost thaw and subsequent ground subsidence is hazardous for travel and can damage critical infrastructure (e.g. roads, airports, homes), with impacts across Alaska

Table 2. Data needs and research opportunities for ABZ disturbances.

Disturbance Group	Disturbance Type	Data Needs and Research Opportunities
Wildfire	Wildfire	• More accurate, comprehensive, and finer scale burned area mapping • More combustion estimates • Post-fire vegetation trajectories and colonization of invasive/non-native species • Influence of forest and fire management • Future fire regime shifts
Insect outbreaks and pathogens	Insect outbreaks and pathogens	• Earlier outbreak detection • Accurate and spatially/temporally consistent datasets • Potential insect range shifts
Permafrost	Cryoturbation	• More accurate and finer-scale mapping
	Ice-wedge degradation	• Data distinguishing between different stages of degradation • Drivers of heterogeneity in degradation • Driver of vegetation succession following degradation
	Cryogenic landslides	• More accurate and finer-scale mapping
	Lake drainage	• More accurate and finer-scale mapping of drainage and associated impacts • Prediction of where and when lake drainage will occur in future
Anthropogenic	Logging	• More accurate and comprehensive records
	Seismic lines	• More accurate and comprehensive records
	Oil & gas well production	• More accurate and comprehensive records • Long-term impacts to vegetation and surrounding landscape
Weather-related	Rain-on-snow	• Enhanced monitoring networks • Cascading impacts on vegetation
	Windthrow	• Enhanced monitoring networks
	Drought and heat waves	• Better prediction of where, when, and which plants will succumb to drought mortality • Drivers of drought exposure and susceptibility
Riverine	Channel migration and ice-jam flooding	• More studies on riparian ecosystems in general • Vegetation succession in riparian ecosystems under climate change
	Beavers	• More beaver studies in general, especially in the Arctic
Mammalian herbivores	Ungulates	• More studies in North America on wild herds • Better data linkages between population size and satellite-derived vegetation response

estimated to exceed $5 billion by 2099 (Daanen *et al* 2012, Melvin *et al* 2017a). Many indigenous communities depend on healthy caribou and other herbivore populations for subsistence, and these animals are central to many indigenous cultures (Rexstad and Kielland 2006, Gagnon *et al* 2020, Lamb *et al* 2022). Understanding how disturbance regimes and their interactions are changing is crucial for adapting human society to climate change in the rapidly warming far north.

These disturbances also have the capacity to feed back to further climate change through direct release of carbon dioxide and other greenhouse gases (Ueyama *et al* 2019), as well as aerosols and black carbon in the case of wildfire. Post-disturbance impacts on soil moisture, decomposition, and vegetation regrowth can feed back to climate through impacts on above- and belowground carbon stores, permafrost dynamics, and energy and water budgets (Randerson *et al* 2006, Bonan 2008, Ward *et al* 2012, Holloway *et al* 2020). Most of the ABZ disturbances discussed here are expected to intensify with a warmer climate (Chen *et al* 2016, Veraverbeke *et al* 2017, Pan *et al* 2018, Pureswaran *et al* 2018, Turetsky *et al* 2020, Berner and Goetz 2022), with a few exceptions: diminished cryoturbation is predicted as permafrost thaws and vegetation increases (Aalto *et al* 2017, 2021), and diminished fluvial disturbance is predicted along with diminished extent of active floodplain surfaces (Jansson *et al* 2019). Though most of these disturbances are natural and integral components of the ABZ system, anthropogenic climate change is pushing their extent, frequency, and severity outside of historical regimes. Continued study and data acquisition is crucial for projecting the future magnitude and direction of these disturbance trajectories and how they may interact (table 2).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Aalto J, Harrison S and Luoto M 2017 Statistical modelling predicts almost complete loss of major periglacial processes in Northern Europe by 2100 *Nat. Commun.* **8** 515

Aalto J, Niittynen P, Riihimäki H and Luoto M 2021 Cryogenic land surface processes shape vegetation biomass patterns in northern European tundra *Commun. Earth Environ.* **2** 222

Albrich K, Rammer W, Turner M G, Ratajczak Z, Braziunas K H, Hansen W D and Seidl R 2020 Simulating forest resilience: a review *Glob. Ecol. Biogeogr.* **29** 2082–96

Allen C D *et al* 2010 A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests *For. Ecol. Manage.* **259** 660–84

Allen D T *et al* 2013 Measurements of methane emissions at natural gas production sites in the United States *Proc. Natl Acad. Sci.* **110** 17768–73

Amiro B D *et al* 2010 Ecosystem carbon dioxide fluxes after disturbance in forests of North America *Biogeosciences* **115** G00K02

Amiro B D, Cantin A, Flannigan M D and de Groot W J 2009 Future emissions from Canadian boreal forest fires *Can. J. For. Res.* **39** 383–95

Anderegg W R L, Kane J M and Anderegg L D L 2012 Consequences of widespread tree mortality triggered by drought and temperature stress *Nat. Clim. Change* **2** 514–8

Anderson R S, Smith S J, Lynch A M and Geils B W 2010 The pollen record of a 20th century spruce beetle (Dendroctonus rufipennis) outbreak in a Colorado subalpine forest, USA *For. Ecol. Manage.* **260** 448–55

Andersson E, Nilsson C and Johansson M E 2000 Plant dispersal in boreal rivers and its relation to the diversity of riparian flora *J. Biogeogr.* **27** 1095–106

Angell A C and Kielland K 2009 Establishment and growth of white spruce on a boreal forest floodplain: interactions between microclimate and mammalian herbivory *For. Ecol. Manage.* **258** 2475–80

Archibald S *et al* 2018 Biological and geophysical feedbacks with fire in the Earth system *Environ. Res. Lett.* **13** 033003

Armstrong J A and Ives W G H 1995 *Forest Insect Pests in Canada* (Ottawa: Natural Resources Canada, Canadian Forest Service)

Ashmore P and Church M 2001 The impact of climate change on rivers and river processes in Canada

Astrup R, Bernier P Y, Genet H, Lutz D A and Bright R M 2018 A sensible climate solution for the boreal forest *Nat. Clim. Change* **8** 11–12

Bachelet D, Lenihan J, Neilson R, Drapek R and Kittel T 2005 Simulating the response of natural ecosystems and their fire regimes to climatic variability in Alaska *Can. J. For. Res.* **35** 2244–57

Balser A W, Jones J B and Gens R 2014 Timing of retrogressive thaw slump initiation in the Noatak Basin, northwest Alaska, USA *J. Geophys. Res.* **119** 1106–20

Baltzer J L *et al* 2021 Increasing fire and the decline of fire adapted black spruce in the boreal forest *Proc. Natl Acad. Sci.* **118** e2024872118

Bandara S, Froese D, Porter T J and Calmels F 2020 Holocene pore-ice δ18O and δ2H records from drained thermokarst lake basins in the Old Crow Flats, Yukon, Canada *Permafr. Periglac. Process.* **31** 497–508

Barnhart T B and Crosby B T 2013 Comparing two methods of surface change detection on an evolving thermokarst using high-temporal-frequency terrestrial laser scanning, Selawik River, Alaska *Remote Sens.* **5** 2813–37

Bartels S F, Chen H Y H, Wulder M A and White J C 2016 Trends in post-disturbance recovery rates of Canada's forests following wildfire and harvest *For. Ecol. Manage.* **361** 194–207

Bartsch A, Kumpula T, Forbes B C and Stammler F 2010 Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding *Ecol. Appl.* **20** 2346–58

Bartsch A, Pointner G, Ingeman-Nielsen T and Lu W 2020 Towards circumpolar mapping of arctic settlements and infrastructure based on Sentinel-1 and Sentinel-2 *Remote Sens.* **12** 2368

Beck P S A, Juday G P, Alix C, Barber V A, Winslow S E, Sousa E E, Heiser P, Herriges J D and Goetz S J 2011 Changes in forest productivity across Alaska consistent with biome shift *Ecol. Lett.* **14** 373–9

Beermann F, Teltewskoi A, Fiencke C, Pfeiffer E-M and Kutzbach L 2015 Stoichiometric analysis of nutrient availability within soils of polygonal tundra *Biogeochemistry* **122** 211–27

Beltaos S, Prowse T D and Carter T 2006 Ice regime of the lower Peace River and ice-jam flooding of the Peace-Athabasca Delta *Hydrol. Process.* **20** 4009–29

Beltaos S and Prowse T 2009 River-ice hydrology in a shrinking cryosphere *Hydrol. Process.* **23** 122–44

Bentz B J, Régnière J, Fettig C J, Hansen E M, Hayes J L, Hicke J A, Kelsey R G, Negrón J F and Seybold S J 2010 Climate change and bark beetles of the Western United States and Canada: direct and indirect effects *BioScience* **60** 602–13

Bergeron Y, Leduc A, Harvey B D and Gauthier S 2002 A natural fire regime: a guide for sustainable management of the Canadian boreal forest *Silva Fenn.* **36** 81–95

Berner L T *et al* 2020 Summer warming explains widespread but not uniform greening in the arctic tundra biome *Nat. Commun.* **11** 4621

Berner L T, Assmann J J, Massey R, Normand S and Goetz S J 2021 lsatTS—an R package for deriving vegetation greenness time series using Landsat satellite data (available at: https://github.com/logan-berner/lsatTS)

Berner L T, Assmann J J, Normand S and Goetz S J lsatTS- an R package for deriving vegetation greenness time series using Landsat satellite data *Ecography* accepted

Berner L T and Goetz S J 2022 Satellite observations document trends consistent with a boreal forest biome shift *Glob. Change Biol.* **28** 3275–92

Bernes C, Bråthen K A, Forbes B C, Speed J D M and Moen J 2015 What are the impacts of reindeer/caribou (Rangifer tarandus L.) on arctic and alpine vegetation? A systematic review *Environ. Evid.* **4** 26

Bhatt U S *et al* 2010 circumpolar arctic tundra vegetation change is linked to Sea Ice decline *Earth Interact.* **14** 1–20

Billings W D and Peterson K M 1980 Vegetational change and Ice-wedge polygons through the thaw-lake cycle in Arctic Alaska *Arct. Alp. Res.* **12** 413

Biskaborn B K *et al* 2019 Permafrost is warming at a global scale *Nat. Commun.* **10** 264

Bjerke J W, Karlsen S R, Hogda K A, Malnes E, Jepsen J U, Lovibond S, Vikhamar-Schuler D and Tommervik H 2014 Record-low primary productivity and high plant damage in the Nordic Arctic Region in 2012 caused by multiple weather events and pest outbreaks *Environ. Res. Lett.* **9** 084006

Bjerke J W, Tømmervik H, Zielke M and Jørgensen M 2015 Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in a grassland of sub-Arctic Norway *Environ. Res. Lett.* **10** 095007

Bjerke J W, Treharne R, Vikhamar-Schuler D, Karlsen S R, Ravolainen V, Bokhorst S, Phoenix G K, Bochenek Z and Tommervik H 2017 Understanding the drivers of extensive plant damage in boreal and Arctic ecosystems: insights from field surveys in the aftermath of damage *Sci. Total Environ.* **599–600** 1965–76

Blackburn M, Ledesma J L J, Näsholm T, Laudon H and Sponseller R A 2017 Evaluating hillslope and riparian contributions to dissolved nitrogen (N) export from a boreal forest catchment *J. Geophys. Res. Biogeosci.* **122** 324–39

Bockheim J G, Hinkel K M, Eisner W R and Dai X Y 2004 Carbon pools and accumulation rates in an age-series of soils in drained thaw-lake basins *Soil Sci. Soc. Am. J.* **68** 697–704

Bockheim J G and Tarnocai C 1998 Recognition of cryoturbation for classifying permafrost-affected soils *Geoderma* **81** 281–93

Bockheim J G, Walker D A, Everett L R, Nelson F E and Shiklomanov N I 1998 Soils and cryoturbation in moist nonacidic and Acidic Tundra in the Kuparuk River Basin, Arctic Alaska, U.S.A *Arct. Alp. Res.* **30** 166

Bokhorst S, Bjerke J W, Bowles F P, Melillo J M, Callaghan T V and Phoenix G K 2008 Impacts of extreme winter warming in the sub-Arctic: growing season responses of dwarf-shrub heathland *Glob. Change Biol.* **14** 2603–12

Bokhorst S, Bjerke J W, Davey M, Taulavuori K, Taulavuori E, Laine K, Callaghan T V and Phoenix G K 2010 Impacts of extreme winter warming events on plant physiology in a sub-Arctic heath community *Physiol. Plant.* **140** 128–40

Bokhorst S, Bjerke J W, Street J E, Callaghan T V and Phoenix G K 2011 Impacts of multiple extreme winter warming events on sub-Arctic heathland: phenology, reproduction, growth, and CO_2 flux responses *Glob. Change Biol.* **17** 2817–30

Bokhorst S, Bjerke J W, Tommervik H, Callaghan T V and Phoenix G K 2009 Winter warming events damage sub-Arctic vegetation: consistent evidence from an experimental manipulation and a natural event *J. Ecol.* **97** 1408–15

Bonan G B 2008 Forests and climate change: forcings, feedbacks, and the climate benefits of forests *Science* **320** 1444–9

Bond-Lamberty B, Peckham S D, Ahl D E and Gower S T 2007 Fire as the dominant driver of central Canadian boreal forest carbon balance *Nature* **450** 89–92

Bone R M and Mahnic R J 1984 Norman wells: the oil center of the Northwest Territories *Arctic* **37** 53–60

Bose A K, Harvey B D and Brais S 2015 Does partial harvesting promote old-growth attributes of boreal mixedwood trembling aspen (Populus tremuloides Michx.) stands? *For. Ecol. Manage.* **353** 173–86

Bouchard M, Pothier D and Ruel J-C 2009 Stand-replacing windthrow in the boreal forests of eastern Quebec *Can. J. For. Res.* **39** 481–7

Boucher D, Boulanger Y, Aubin I, Bernier P Y, Beaudoin A, Guindon L and Gauthier S 2018 Current and projected cumulative impacts of fire, drought, and insects on timber volumes across Canada *Ecol. Appl.* **28** 1245–59

Boucher Y, Arseneault D, Sirois L and Blais L 2009 Logging pattern and landscape changes over the last century at the boreal and deciduous forest transition in Eastern Canada *Landsc. Ecol.* **24** 171–84

Boulanger Y and Arsenault D 2004 Spruce budworm outbreaks in eastern Quebec over the last 450 years *Can. J. For. Res.* **34** 1035–43

Boyd M A, Berner L T, Foster A C, Goetz S J, Rogers B M, Walker X J and Mack M C 2021 Historic declines in growth portend trembling aspen death during a contemporary leaf miner outbreak in Alaska *Ecosphere* **12** e03569

Bråthen K A, Ravolainen V T, Stien A, Tveraa T and Ims R A 2017 Rangifer management controls a climate-sensitive tundra state transition *Ecol. Appl.* **27** 2416–27

Bret-Harte M S, Mack M C, Shaver G R, Huebner C, Johnston M, Mojica C A, Pizano C and Reiskind J A 2013 The response of Arctic vegetation and soils following an unusually severe tundra fire *Phil. Trans. R. Soc.* B **368** 20120490

Brewer M C, Carter L D, Glenn R and Murray D F 1993 Sudden drainage of a thaw lake on the Alaskan Arctic Coastal Plain *China Society of Glaciology and Geocryology 6th Int. Conf. on Permafrost* (*Beijing*)

Brock B E, Yi Y, Clogg-Wright K P, Edwards T W D and Wolfe B B 2009 Multi-year landscape-scale assessment of lakewater balances in the Slave River Delta, NWT, using water isotope tracers *J. Hydrol.* **379** 81–91

Brodie J F, Roland C A, Stehn S E and Smirnova E 2019 Variability in the expansion of trees and shrubs in boreal Alaska *Ecology* **100** e02660

Bryant J P, Joly K, Chapin F S, DeAngelis D L and Kielland K 2014 Can antibrowsing defense regulate the spread of woody vegetation in arctic tundra? *Ecography* **37** 204–11

Buma B 2015 Disturbance interactions: characterization, prediction, and the potential for cascading effects *Ecosphere* **6** 70

Burn C R and Lewkowicz A G 1990 Canadian landform examples—17 retrogressive thaw slumps *Can. Geogr.* **34** 273–6

Burnham A, Han J, Clark C E, Wang M, Dunn J B and Palou-Rivera I 2012 Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum *Environ. Sci. Technol.* **46** 619–27

Burton P J, Messier C, Weetman G F, Prepas E E, Adamowicz W L and Tittler R 2003 The current state of boreal forestry and the drive for change *Towards Sustainable Management of the Boreal Forest* (Ottawa: NRC Research Press) ed P J Burton, C Messier, D W Smith and W L Adamowicz pp 1–40

Bush E and Lemmen D S 2019 Canada's changing climate report (Ottawa, ON: Government of Canada)

Butler L G 2003 The role of mammalian herbivores in primary succession on the Tanana river floodplain, interior Alaska *MS Thesis* University of Alaska Fairbanks, Fairbanks, AK

Butt N, Beyer H L, Bennett J R, Biggs D, Maggini R, Mills M, Renwick A R, Seabrook L M and Possingham H P 2013 Biodiversity risks from fossil fuel extraction *Science* **342** 425–6

Calef M P, Varvak A, McGuire A D, Chapin F S III and Reinhold K B 2015 Recent changes in annual burned area in interior Alaska: the impact of fire management *Earth Interact.* **19** 1–17

Campbell E M and Antos J A 2015 Advance regeneration and trajectories of stand development following the mountain pine beetle outbreak in boreal forests of British Columbia *Can. J. For. Res.* **45** 1327–37

Campbell E M, Antos J A and vanAkker L 2019 Resilience of southern Yukon boreal forests to spruce beetle outbreaks *For. Ecol. Manage.* **433** 52–63

Campbell E M, MacLean D A and Bergeron Y 2008 The severity of budworm-caused growth reductions in balsam fir/spruce stands varies with the hardwood content of surrounding forest landscapes *For. Sci.* **54** 195–205

Campeau A B, Rickbeil G J M, Coops N C and Côté S D 2019 Long-term changes in the primary productivity of migratory caribou (Rangifer tarandus) calving grounds and summer pasture on the Quebec-Labrador Peninsula (Northeastern Canada): the mixed influences of climate change and caribou herbivory *Polar Biol.* **42** 1005–23

Caners R and Lieffers V J 2014 Divergent pathways of successional recovery for *in-situ* oil sands exploration drilling pads on wooded moderate-rich fens in Alberta, Canada *Res. Ecol.* **22** 657–67

Carlson M L *et al* 2008 *Invsasiveness Ranking System for Non-Native Plants of Alaska* (Anchorage, AK: US Department of Agriculture, Forest Service)

Carpino O A, Berg A A, Quinton W L and Adams J R 2018 Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada *Environ. Res. Lett.* **13** 084018

Cavender-Bares J *et al* 2022 Integrating remote sensing with ecology and evolution to advance biodiversity conservation *Nat. Ecol. Evol.* **6** 506–19

Cessna J, Alonzo M G, Foster A C and Cook B D 2021 Mapping boreal forest spruce beetle health status at the individual crown scale using fused spectral and structural data *Forests* **12** 1145

Chapman T B, Veblen T T and Schoennagel T 2012 Spatiotemporal patterns of mountain pine beetle activity in the southern Rocky Mountains *Ecology* **93** 2175–85

Chen D, Fu C, Hall J V, Hoy E E and Loboda T V 2021a Spatio-temporal patterns of optimal Landsat data for burn severity index calculations: implications for high northern latitudes wildfire research *Remote Sens. Environ.* **258** 112393

Chen D, Shevade V, Baer A and Loboda T V 2021b Missing burns in the high Northern latitudes: the case for regionally focused burned area products *Remote Sens.* **13** 4145

Chen H Y H, Luo Y, Reich P B, Searle E B and Biswas S R 2016 Climate change-associated trends in net biomass change are age dependent in western boreal forests of Canada *Ecol. Lett.* **19** 1150–8

Chen I, Hill J, Ohlemüler R, Roy D and Thomas C 2011 Rapid range shifts of species associated with high levels of climate warming *Science* **333** 1024–6

Chen M, Rowland J C, Wilson C J, Altmann G L and Brumby S P 2014 Temporal and spatial pattern of thermokarst lake area changes at Yukon Flats, Alaska *Hydrol. Process.* **28** 837–52

Chen Y, Romps D M, Seeley J T, Veraverbeke S, Riley W J, Mekonnen Z A and Randerson J T 2021c Future increases in Arctic lightning and fire risk for permafrost carbon *Nat. Clim. Change* **11** 404–10

Chomphosy W H, Varriano S, Lefler L H, Nallur V, McClung M R and Moran M D 2021 Ecosystem services benefits from the restoration of non-producing US oil and gas lands *Nat. Sustain.* **4** 547–54

Chowdhury S, Chao D K, Shipman T C and Wulder M A 2017 Utilization of Landsat data to quantify land-use and land-cover changes related to oil and gas activities in West-Central Alberta from 2005 to 2013 *Null* **54** 700–20

Christiansen E, Waring R H and Berryman A A 1987 Resistance of conifers to bark beetle attack: searching for general relationships *For. Ecol. Manage.* **22** 89–106

Christie K S, Bryant J P, Gough L, Ravolainen V T, Ruess R W and Tape K D 2015 The role of vertebrate herbivores in regulating shrub expansion in the arctic: a synthesis *BioScience* **65** 1123–33

Chylek P, Folland C, Klett J D, Wang M, Hengartner N, Lesins G and Dubey M K 2022 Annual mean arctic amplification 1970–2020: observed and simulated by CMIP6 climate models *Geophys. Res. Lett.* **49** e2022GL099371

Cochrane M A, Moran C J, Wimberly M C, Baer A D, Finney M A, Beckendorf K L, Eidenshink J and Zhu Z 2012 Estimation of wildfire size and risk changes due to fuels treatments *Int. J. Wildland Fire* **21** 357–67

Cole H M, Andrus R A, Butkiewicz C, Rodman K C, Santiago O, Tutland N J, Waupochick A and Hart S J 2022 Outbreaks of Douglas-fir beetle follow Western Spruce Budworm defoliation in the Southern Rocky Mountains, USA *Forests* **13** 371

Comeau V M, Daniels L D, Knochenmus G, Chavardès R D and Zeglen S 2019 Tree-rings reveal accelerated yellow-cedar decline with changes to winter climate after 1980 *Forests* **10** 1085

Conway H and Benedict R 1994 Infiltration of water into snow *Water Resour. Res.* **30** 641–9

Cook B, Corp L, Nelson R, Middleton E, Morton D, McCorkel J, Masek J, Ranson K, Ly V and Montesano P 2013 NASA Goddard's LiDAR, hyperspectral and thermal (G-LiHT) airborne imager *Remote Sens.* **5** 4045–66

Cooke H A and Tauzer L M 2020 Unique songbird communities in mature riparian spruce forest compared with upland forest in southern Yukon *Can. J. For. Res.* **50** 473–86

Coops N C, Johnson M, Wulder M A and White J C 2006 Assessment of QuickBird high spatial resolution imagery to detect red attack damage due to mountain pine beetle infestation *Remote Sens. Environ.* **103** 67–80

Crawford R M M 2008 Cold climate plants in a warmer world *Plant Ecol. Divers* **1** 285–97

Cray H A and Pollard W H 2019 Use of stabilized thaw slumps by Arctic birds and mammals: evidence from Herschel Island, Yukon *Can. Field Nat.* **132** 279–84

Cyr D, Gauthier S, Bergeron Y and Carcaillet C 2009 Forest management is driving the eastern North American boreal forest outside its natural range of variability *Front. Ecol. Environ.* **7** 519–24

Daanen R P, Grosse G, Darrow M M, Hamilton T D and Jones B M 2012 Rapid movement of frozen debris-lobes: implications for permafrost degradation and slope instability in the south-central Brooks Range, Alaska *Nat. Hazards Earth Syst. Sci.* **12** 1521–37

Daanen R P, Misra D and Epstein H 2007 active-layer hydrology in nonsorted circle ecosystems of the Arctic Tundra *Vadose Zone J.* **6** 694–704

Dabros A, Pyper M and Castilla G 2018 Seismic lines in the boreal and arctic ecosystems of North America: environmental impacts, challenges, and opportunities *Environ. Rev.* **26** 16

Darrow M M, Gyswyt N L, Simpson J M, Daanen R P and Hubbard T D 2016 Frozen debris lobe morphology and movement: an overview \hack\newline of eight dynamic features, southern Brooks Range, Alaska *Cryosphere* **10** 977–93

Darrow M M, Simpson J M, Daanen R P and Hubbard T 2015 Characterizing a frozen debris lobe, Dalton Highway, Alaska *Cold Regions Engineering 2015: developing and Maintaining Resilient Infrastructure*

Das A, Reed M and Lindenschmidt K-E 2018 Sustainable ice-jam flood management for socio-economic and socio-ecological systems *Water* **10** 135

Davidson S C *et al* 2020a Ecological insights from three decades of animal movement tracking across a changing Arctic *Science* **370** 712–5

Davidson S J, Goud E M, Franklin C, Nielsen S E and Strack M 2020b Seismic line disturbance alters soil physical and chemical properties across boreal forest and peatland soils *Front. Earth Sci.* **8** 2296–6463

Davidson S J, Goud E M, Malhotra A, Estey C O and Korsah P 2021 Linear disturbances shift boreal peatland plant communities toward earlier peak greenness *J. Geophys. Res.* **126** e2021JG006403

De Grandpré L, Waldron K, Bouchard M, Gauthier S, Beaudet M, Ruel J-C, Hébert C and Kneeshaw D D 2018 Incorporating insect and wind disturbance in a natural disturbance-based management framework for the boreal forest *Forests* **9** 471

de Groot W J, Cantin A, Flannigan M D, Soja A J, Gowman L M and Newbery A 2013 A comparison of Canadian and Russian boreal forest fire regimes *For. Ecol. Manage.* **294** 23–34

de la Giroday H M C, Carroll A L and Aukema B H 2012 Breach of the northern Rocky Mountain geoclimatic barrier: initiation of range expansion by the mountain pine beetle: range expansion by the mountain pine beetle *J. Biogeogr.* **39** 1112–23

Deane P J, Wilkinson S L, Moore P A and Waddington J M 2020 Seismic lines in treed boreal peatlands as analogs for wildfire modification treatments *Fire* **3** 21

DeRose R J, Bentz B J, Long J N and Shaw J D 2013 Effect of increasing temperatures on the distribution of spruce beetle in Engelmann spruce forests of the Interior West, USA *For. Ecol. Manage.* **308** 198–206

DeRose R J and Long J N 2012 Factors influencing the spatial and temporal dynamics of engelmann spruce mortality during a spruce beetle outbreak on the Markagunt Plateau, Utah *For. Sci.* **58** 1–14

DeRose R J, Long J N and Ramsey R D 2011 Combining dendrochronological data and the disturbance index to assess Engelmann spruce mortality caused by a spruce beetle outbreak in southern Utah, USA *Remote Sens. Environ.* **115** 2342–9

Dieleman C M, Rogers B M, Potter S, Veraverbeke S, Johnstone J F, Laflamme J, Solvik K, Walker X J, Mack M C and Turetsky M R 2020 Wildfire combustion and carbon stocks in the southern Canadian boreal forest: implications for a warming world *Glob. Change Biol.* **26** 6062–79

Duncan B N *et al* 2020 Space-based observations for understanding changes in the Arctic-Boreal Zone *Rev. Geophys.* **58** e2019RG000652

Eidenshink J, Schwind B, Brewer K, Zhu Z-L, Quayle B and Howard S 2007 A project for monitoring trends in burn severity *Fire Ecol.* **3** 3–21

Elmes M C, Wiklund J A, Van Opstal S R, Wolfe B B and Hall R I 2016 Characterizing baseline concentrations, proportions, and processes controlling deposition of river-transported bitumen-associated polycyclic aromatic compounds at a floodplain lake (Slave River Delta, Northwest Territories, Canada) *Environ. Monit. Assess.* **188** 282

EMR 2006 *Best Management Practices—Oil and Gas; Seismic Exploration* (Whitehourse, YT: Yukon Government, Energy, Mines, and Resources, Oil and Gas Management Branch)

Ermokhina K and Myalo E 2012 Phytoindicators of landslide disturbances in the central Yamal *Proc. 10th Int. Conf. on Permafrost* vol 2 pp 531–6

Fairfax E and Whittle A 2020 Smokey the Beaver: beaver-dammed riparian corridors stay green during wildfire throughout the western United States *Ecol. Appl.* **30** e02225

Farquharson L M, Romanovsky V E, Cable W L, Walker D A, Kokelj S V and Nicolsky D 2019 Climate change drives widespread and rapid thermokarst development in very cold permafrost in the canadian high arctic *Geophys. Res. Lett.* **46** 6681–9

Fauchald P, Park T, Tømmervik H, Myneni R and Hausner V H 2017 Arctic greening from warming promotes declines in caribou populations *Sci. Adv.* **3** e1601365

Filicetti A T, Cody M and Nielsen S E 2019 Caribou conservation: restoring trees on seismic lines *Remote Sens.* **10** 185

Finnegan L, Pigeon K E, Cranston J, Hebblewhite M, Musiani M, Neufeld L, Schmiegelow F, Duval J, Stenhouse G B and Festa-Bianchet M 2018 Natural regeneration on seismic lines influence movement behaviour of wolves and grizzly bears *PLoS One* **13** e0195480

Foster A C, Armstrong A H, Shuman J K, Shugart H H, Rogers B M, Mack M C, Goetz S J and Ranson K J 2019 Importance of tree- and species-level interactions with wildfire, climate, and soils in interior Alaska: implications for forest change under a warming climate *Ecol. Modell.* **409** 108765

Foster A C, Shuman J K, Rogers B M, Walker X J, Mack M C, Bourgeau-Chavez L L, Veraverbeke S and Goetz S J 2022 Bottom-up drivers of future fire regimes in western boreal North America *Environ. Res. Lett.* **17** 025006

Foster A C, Walter J A, Shugart H H, Sibold J and Negron J 2017 Spectral evidence of early-stage spruce beetle infestation in Engelmann spruce *For. Ecol. Manage.* **384** 347–57

Fox J F and Bryant J P 1984 Instability of the snowshoe hare and woody plant interaction *Oecologia* **63** 128–35

French N H F, Jenkins L K, Loboda T V, Flannigan M, Jandt R, Bourgeau-Chavez L L and Whitley M 2015 Fire in arctic tundra of Alaska: past fire activity, future fire potential, and significance for land management and ecology *Int. J. Wildland Fire* **24** 1045–61

Freudiger D, Kohn I, Stahl K and Weiler M 2014 Large-scale analysis of changing frequencies of rain-on-snow events with flood-generation potential *Hydrol. Earth Syst. Sci.* **18** 2695–709

Frey K E and McClelland J W 2009 Impacts of permafrost degradation on arctic river biogeochemistry *Hydrol. Process.* **23** 169–82

Frost G V, Epstein H E and Walker D A 2014 Regional and landscape-scale variability of Landsat-observed vegetation dynamics in northwest Siberian tundra *Environ. Res. Lett.* **9** 025004

Frost G V, Epstein H E, Walker D A, Matyshak G and Ermokhina K 2013 Patterned-ground facilitates shrub expansion in Low Arctic tundra *Environ. Res. Lett.* **8** 015035

Frost G V, Epstein H E, Walker D A, Matyshak G and Ermokhina K 2018b Seasonal and long-term changes to active-layer temperatures after tall shrubland expansion and succession in Arctic Tundra *Ecosystems* **21** 507–20

Frost G V, Loehman R A, Saperstein L B, Macander M J, Nelson P R, Paradis D P and Natali S M 2020 Multi-decadal patterns of vegetation succession after tundra fire on the Yukon-Kuskokwim Delta, Alaska *Environ. Res. Lett.* **15** 025003

Frost G, Christopherson T, Jorgenson M, Liljedahl A, Macander M, Walker D and Wells A 2018a Regional patterns and asynchronous onset of ice-wedge degradation since the Mid-20th century in Arctic Alaska *Remote Sens.* **10** 1312

Fuchs M, Lenz J, Jock S, Nitze I, Jones B M, Strauss J, Günther F and Grosse G 2019 Organic carbon and nitrogen stocks along a thermokarst lake sequence in Arctic Alaska *J. Geophys. Res. Biogeosci.* **124** 1230–47

Gaglioti B V, Berner L T, Jones B M, Orndahl K M, Williams A P, Andreu-Hayles L, D'Arrigo R D, Goetz S J and Mann D H 2021 Tussocks enduring or shrubs greening: alternate responses to changing fire regimes in the Noatak River Valley, Alaska *J. Geophys. Res.* **126** e2020JG006009

Gagnon C A, Hamel S, Russell D E, Powell T, Andre J, Svoboda M Y and Berteaux D 2020 Merging indigenous and scientific knowledge links climate with the growth of a large migratory caribou population *J. Appl. Ecol.* **57** 1644–55

Gao B 1996 NDWI-A normalized difference water index for remote sensing of vegetation liquid water from space *Remote Sens. Environ.* **58** 257–66

Gauthier S, Bernier P, Kuuluvainen T, Shvidenko A Z and Schepaschenko D G 2015 Boreal forest health and global change *Science* **349** 819–22

Gauthier S, Vaillancourt M-A, Leduc A, De Grandpré L, Kneeshaw D, Morin H, Drapeau P and Bergeron Y 2009 *Ecosystem Management in the Boreal Forest* (Quebec: Presses de l'Université du Québec)

Gibson C M, Chasmer L E, Thompson D K, Quinton W L, Flannigan M D and Olefeldt D 2018 Wildfire as a major driver of recent permafrost thaw in boreal peatlands *Nat. Commun.* **9** 3041

Girard F, De Grandpré L and Ruel J-C 2014 Partial windthrow as a driving process of forest dynamics in old-growth boreal forests *Can. J. For. Res.* **44** 1165–76

Girardin M P, Guo X J, Metsaranta J, Gervais D, Campbell E, Arsenault A, Isaac-Renton M, Harvey J E, Bhatti J and Hogg E H 2021 A national tree-ring data repository for Canadian forests (CFS-TRenD): structure, synthesis, and applications *Environ. Rev.* **29** 225–41

Girardin M P, Xiao Jing G, David G, Juha M, Campbell Elizabeth M, André A, Miriam I-R and Hogg Edward H 2022 Cold-season freeze frequency is a pervasive driver of subcontinental forest growth *Proc. Natl Acad. Sci.* **119** e2117464119

Goetz S J *et al* 2012 Observations and assessment of forest carbon dynamics following disturbance in North America *J. Geophys. Res.* **117** G02022

Goetz S J, Bunn A G, Fiske G J and Houghton R A 2005 Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance *Proc. Natl Acad. Sci. USA* **102** 13521–5

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 Google Earth engine: planetary-scale geospatial analysis for everyone *Remote Sens. Environ.* **202** 18–27

Goulden M L and Bales R C 2019 California forest die-off linked to multi-year deep soil drying in 2012–2015 drought *Nat. Geosci.* **12** 632–7

Gray L K, Russell J H, Yanchuk A D and Hawkins B J 2013 Predicting the risk of cedar leaf blight (Didymascella thujina) in British Columbia under future climate change *Agric. For. Meteorol.* **180** 152–63

Grosse G *et al* 2011 Vulnerability of high-latitude soil organic carbon in North America to disturbance *Geophys. Res. Lett.* **116** G00K06

Gruber S 2012 Derivation and analysis of a high-resolution estimate of global permafrost zonation *Cryosphere* **6** 221–33

Gunn A 2003 Voles, lemmings and caribou—population cycles revisited? *Ran* **23** 105

Günther F, Overduin P P, Sandakov A V, Grosse G and Grigoriev M N 2013 Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region *Biogeosciences* **10** 4297–318

Gurarie E *et al* 2019 Tactical departures and strategic arrivals: divergent effects of climate and weather on caribou spring migrations *Ecosphere* **10** e02971

Haggstrom D A and Kelleyhouse D G 1996 Silviculture and wildlife relationships in the boreal forest of interior Alaska *For. Chron.* **72** 59–62

Hall J P and Moody B H 1994 *Forest Depletions Caused by Insects and Diseases in Canada 1982–1987* (Ottawa: National Resources of Canada)

Hall R I, Wolfe B B, Wiklund J A, Edwards J W D, Farwell A J and Dixon D G 2012 Has Alberta oil sands development altered delivery of polycyclic aromatic compounds to the Peace-Athabasca Delta? *PLoS One* **7** e46089

Hall R J, Castilla G, White J C, Cooke B J and Skakun R S 2016 Remote sensing of forest pest damage: a review and lessons learned from a Canadian perspective *Can. Entomol.* **148** S296–356

Hall R J, Skakun R S, Metsaranta J M, Landry R, Fraser R H, Raymond D, Gartrell M, Decker V and Little J 2020 Generating annual estimates of forest fire disturbance in Canada: the National Burned Area composite *Int. J. Wildland Fire* **29** 878–91

Hanes C C, Wang X, Jain P, Parisien M-A, Little J M and Flannigan M D 2019 Fire-regime changes in Canada over the last half century *Can. J. For. Res.* **49** 256–69

Hansen E M, Bentz B J, Powell J A, Gray D R and Vandygriff J C 2011 Prepupal diapause and instar IV developmental rates of the spruce beetle, Dendroctonus rufipennis (Coleoptera: curculionidae, Scolytinae) *J. Insect Physiol.* **57** 1347–57

Harden J W, Trumbore S E, Stocks B J, Hirsch A, O'Neill K P and Kasischke S 2000 The role of fire in the boreal carbon budget *Glob. Change Biol.* **6** 174–8

Harms T K, Abbott B W and Jones J B 2014 Thermo-erosion gullies increase nitrogen available for hydrologic export *Biogeochemistry* **117** 299–311

Hart S J, Veblen T T, Mietkiewicz N and Kulakowski D 2015 Negative feedbacks on bark beetle outbreaks: widespread and severe spruce beetle infestation restricts subsequent infestation *PLoS One* **10** e0127975

He J, Loboda T V, Chen D and French N H F 2022 Cloud-to-ground lightning and near-surface fire weather control wildfire occurrence in Arctic Tundra *Geophys. Res. Lett.* **49** e2021GL096814

Hebblewhite M 2017 Billion dollar boreal woodland caribou and the biodiversity impacts of the global oil and gas industry *Biol. Conserv.* **206** 102–11

Helm D J and Collins W B 1997 Vegetation succession and disturbance on a boreal forest floodplain, Susitna River, Alaska *Can. Field-Nat.* **111** 553–66

Hennigar C R, MacLean D A, Porter K B and Quiring D T 2007 Optimized harvest planning under alternative foliage-protection scenarios to reduce volume losses to spruce budworm *Can. J. For. Res.* **37** 1755–69

Herndon E, Kinsman-Costello L, Di Domenico N, Duroe K, Barczok M, Smith C and Wullschleger S D 2020 Iron and iron-bound phosphate accumulate in surface soils of ice-wedge polygons in arctic tundra *Environ. Sci. Process. Impacts* **22** 1475–90

Higuera P E, Brubaker L B, Anderson P M, Brown T A, Kennedy A T and Hu F S 2008 Frequent fires in Ancient Shrub Tundra: implications of Paleorecords for Arctic environmental change *PLoS One* **3** e0001744

Hinkel K M, Eisner W R, Bockheim J G, Nelson F E, Peterson K M and Dai X 2003 Spatial extent, age, and carbon stocks in drained thaw lake basins on the barrow Peninsula, Alaska *Arct. Antarct. Alp. Res.* **35** 291–300

Hinkel K M, Jones B M, Eisner W R, Cuomo C J, Beck R A and Frohn R 2007 Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska *J. Geophys. Res.* **112** F02S16

Hogg E H, Brandt J P and Michallian M 2008 Impacts of a regional drought on the productivity, dieback, and biomass of western Canadian aspen forests *Can. J. For. Res.* **38** 610–22

Hollingsworth T N, Lloyd A H, Nossov D R, Ruess R W, Charlton B A and Kielland K 2010 Twenty-five years of vegetation change along a putative successional chronosequence on the Tanana River, Alaska *Can. J. For. Res.* **40** 1273–87

Holloway J E, Lewkowicz A G, Douglas T A, Li X, Turetsky M R, Baltzer J L and Jin H 2020 Impact of wildfire on permafrost landscapes: a review of recent advances and future prospects *Permafr. Periglac. Process.* **31** 371–82

Holmes R M, Shiklomanov A I, Suslova A, Tretiakov M, McClelland J W, Scott L, Spencer R G M and Tank S E 2021 River discharge [in “State of the Climate in 2020”] *Bull. Am. Meteorol. Soc.* **102** S290–3

Holsten E H, Hennon P E and Werner R A 1985 *Insects and Diseases of Alaska Forests* (Anchorage, AK: USDA Forest Service, Forest Pest Management and State and Private Forestry)

Holsten E, Hennon P, Trummer L, Kruse J, Schultz M and Lundquist J 2008 *Insects and Diseases of Alaskan Forests* (Anchorage, AK: USDA Forest Service Alaska Region Forest Health Protection)

Hood S and Bentz B 2007 Predicting postfire Douglas-fir beetle attacks and tree mortality in the northern Rocky Mountains *Can. J. For. Res.* **37** 1058–69

Hope E S, McKenney D W, Pedlar J H, Stocks B J and Gauthier S 2016 Wildfire suppression costs for Canada under a changing climate *PLoS One* **11** e0157425

Houle D, Lajoie G and Duchesne L 2016 Major losses of nutrients following a severe drought in a boreal forest *Nat. Plants* **2** 16187

Hu F S, Higuera P E, Duffy P, Chipman M L, Rocha A V, Young A M, Kelly R and Dietze M C 2015 Arctic tundra fires: natural variability and responses to climate change *Front. Ecol. Environ.* **13** 369–77

Hummel M and Ray J C 2008 *Caribou and the North: A Shared Future* (Toronto: Dundurn)

Jactel H, Brockerhoff E and Duelli P 2005 A test of the biodiversity-stability theory: meta-analysis of tree species diversity effects on insect pest infestations, and re-examination of responsible factors *Forest Diversity and Function: Temperate and Boreal Systems* ed M Scherer-Lorenzen, C Körner and E-D Schulze (Berlin: Springer) pp 235–62

Jansson R, Ström L and Nilsson C 2019 Smaller future floods imply less habitat for riparian plants along a boreal river *Ecol. Appl.* **29** e01977

Jenkins M J, Page W G, Hebertson E G and Alexander M E 2012 Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management *For. Ecol. Manage.* **275** 23–34

Jenkins M J, Runyon J B, Fettig C J, Page W G and Bentz B J 2014 Interactions among the mountain pine beetle, fires, and fuels *For. Sci.* **60** 489–501

Jennewein J S *et al* 2020 Behavioral modifications by a large-northern herbivore to mitigate warming conditions *Mov. Ecol.* **8** 39

Jeong D I and Sishama L 2018 Rain-on-snow events over North America based on two Canadian regional climate models *Clim. Dyn.* **50** 303–16

Jin H, Jönsson A M, Bolmgren K, Langvall O and Eklundh L 2017 Disentangling remotely-sensed plant phenology and snow seasonality at northern Europe using MODIS and the plant phenology index *Remote Sens. Environ.* **198** 203–12

Johansson M E, Nilsson C and Nilsson E 1996 Do rivers function as corridors for plant dispersal? *J. Veget. Sci.* **7** 593–8

Johnson M S, Strawbridge K, Knowland K E, Keller C and Travis M 2021 Long-range transport of Siberian biomass burning emissions to North America during FIREX-AQ *Atmos. Environ.* **252** 118241

Johnson R K and Almlöf K 2016 Adapting boreal streams to climate change: effects of riparian vegetation on water temperature and biological assemblages *Freshw. Sci.* **35** 984–97

Johnstone J F, Chapin F S III, Hollingsworth T N, Mack M, CRomanovsky V and Turetsky M 2010 Fire, climate change, and forest resilience in interior Alaska *Can. J. For. Res.* **40** 1302–12

Johnstone J F, Rupp T S, Olson M and Verbyla D 2011 Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests *Landsc. Ecol.* **26** 487–500

Joly K *et al* 2019 Longest terrestrial migrations and movements around the world *Sci. Rep.* **9** 15333

Joly K, Jandt R R and Klein D R 2009 Decrease of lichens in Arctic ecosystems: the role of wildfire, caribou, reindeer, competition and climate in north-western Alaska *Polar Res.* **10** 433–42

Joly K, Klein D R, Verbyla D L, Rupp T S and Chapin F S 2011 Linkages between large-scale climate patterns and the dynamics of Arctic caribou populations *Ecography* **34** 345–52

Jones B M *et al* 2020a Identifying historical and future potential lake drainage events on the western Arctic coastal plain of Alaska *Permafr. Periglac. Process.* **31** 110–27

Jones B M *et al* 2022 Lake and drained lake basin systems in lowland permafrost regions *Nat. Rev. Earth Environ.* **3** 85–98

Jones B M and Arp C D 2015 Observing a catastrophic thermokarst lake drainage in Northern Alaska *Permafr. Periglac. Process.* **26** 119–28

Jones B M, Breen A L, Gaglioti B V, Mann D H, Rocha A V, Grosse G, Arp C D, Kunz M L and Walker D A 2013 Identification of unrecognized tundra fire events on the north slope of Alaska *J. Geophys. Res.* **118** 1334–44

Jones B M, Grosse G, Arp C D, Jones M C, Walter Anthony K M and Romanovsky V E 2011 Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska *J. Geophys. Res.* **116** G00M03

Jones B M, Grosse G, Arp C D, Miller E, Liu L, Hayes D J and Larsen C F 2015 Recent Arctic tundra fire initiates widespread thermokarst development *Sci. Rep.* **5** 15865

Jones B M, Tape K D, Clark J A, Bondurant A C, Ward Jones M K, Gaglioti B V, Elder C D, Witharana C and Miller C E 2021 Multi-dimensional remote sensing analysis documents beaver-induced permafrost degradation, Seward Peninsula, Alaska *Remote Sens.* **13** 4863

Jones B M, Tape K D, Clark J A, Nitze I, Grosse G and Disbrow J 2020b Increase in beaver dams controls surface water and thermokarst dynamics in an Arctic tundra region, Baldwin Peninsula, northwestern Alaska *Environ. Res. Lett.* **15** 075005

Jones B M, Tape K D, Nitze I, Grosse G, Arp C D and Zimmerman C E 2018 Spying on tundra beavers with time series remote sensing data *5th European Conf. on Permafrost* (*Chamonix Mont-Blanc, France*)

Jones J B and Rinehart A J 2010 The long-term response of stream flow to climatic warming in headwater streams of interior Alaska *Can. J. For. Res.* **40** 1210–8

Jones M C, Grosse G, Jones B M and Anthony K W 2012 Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska *JGR Biogeosci.* **117** G00M07

Jorgensen J C, Ver Hoef J M and Jorgenson M T 2010 Long-term recovery patterns of arctic tundra after winter seismic exploration *Ecol. Appl.* **20** 205–21

Jorgenson M T, Brown D R N, Hiemstra C A, Genet H, Marcot B G, Murphy R J and Douglas T A 2022 Drivers of historical and projected changes in diverse boreal ecosystems: fires, thermokarst, riverine dynamics, and humans *Environ. Res. Lett.* **17** 45016

Jorgenson M T, Kanevskiy M, Shur Y, Moskalenko N, Brown D R N, Wickland K, Striegl R and Koch J 2015 Role of ground ice dynamics and ecological feedbacks in recent ice wedge degradation and stabilization *J. Geophys. Res. Earth Surf.* **120** 2280–97

Jorgenson M T *et al* Rapid transformation of tundra ecosystems from ice-wedge degradation *Glob. Planet. Change* accepted

Jorgenson M T, Shur Y L and Pullman E R 2006 Abrupt increase in permafrost degradation in Arctic Alaska *Geophys. Res. Lett.* **33** L02503

Ju J and Masek J G 2016 The vegetation greenness trend in Canada and US Alaska from 1984–2012 Landsat dat *Remote Sens. Environ.* **176** 1–16

Kade A, Walker D A and Raynolds M K 2005 Plant communities and soils in cryoturbated tundra along a bioclimate gradient in the Low Arctic, Alaska *Phytocoenologia* **35** 761–820

Kanevskiy M, Shur Y, Jorgenson T, Brown D R N, Moskalenko N, Brown J, Walker D A, Raynolds M K and Buchhorn M 2017 Degradation and stabilization of ice wedges: implications for assessing risk of thermokarst in northern Alaska *Geomorphology* **297** 20–42

Kang M, Brandt A R, Zheng Z, Boutot J, Yung C, Peltz A S and Jackson R B 2021 Orphaned oil and gas well stimulus—maximizing economic and environmental benefits *Elementa* **9** 00161

Kang M, Mauzerall D L, Ma D Z and Celia M A 2019 Reducing methane emissions from abandoned oil and gas wells: strategies and costs *Energy Policy* **132** 594–601

Kang M, Shanna C, Celia Michael A, Mauzerall Denise L, Markus B, Miller Alana R, Yuheng C, Conrad Mark E, Darrah Thomas H and Jackson Robert B 2016 Identification and characterization of high methane-emitting abandoned oil and gas wells *Proc. Natl Acad. Sci.* **113** 13636–41

Karlsson J M, Lyon S W and Destouni G 2012 Thermokarst lake, hydrological flow and water balance indicators of permafrost change in Western Siberia *J. Hydrol.* **464–465** 459–66

Kasischke E S *et al* 2010 Alaska's changing fire regime—implications for vulnerability of its boreal forests *Can. J. For. Res.* **40** 1313–24

Kasischke E S, Williams D and Barry D 2002 Analysis of the patterns of large fires in the boreal forest region of Alaska *Int. J. Wildland Fire* **11** 131–44

Kautz M, Meddens A, Hall R J and Arneth A 2016 Biotic disturbances in Northern Hemisphere forests—a synthesis of recent data, uncertainties and implications for forest monitoring and modelling *Glob. Ecol. Biogeogr.* **26** 533–52

Kay M L *et al* 2020 Evaluating temporal patterns of metals concentrations in floodplain lakes of the Athabasca Delta (Canada) relative to pre-industrial baselines *Sci. Total Environ.* **704** 135309

Kelly L T *et al* 2020 Fire and biodiversity in the Anthropocene *Science* **370** eabb0355

Kent A, Drezner T D and Bello R 2018 Climate warming and the arrival of potentially invasive species into boreal forest and tundra in the Hudson Bay Lowlands, Canada *Polar Biol.* **41** 2007–22

Kent G 2017 Fort McMurray fires will have economic impact on Alberta, think tank says *Edmonton J.* (available at: https://edmontonjournal.com/news/local-news/fort-mcmurray-fires-will-have-economic-impact-on-alberta-think-tank-says)

Kharuk V I, Ranson K J, Im S T and Naurzbaev M M 2006 Forest-tundra larch forests and climatic trends *Russ. J. Ecol.* **37** 291–8

Kielland K, Bryant J P and Ruess R W 2006 Mammalian herbivory, ecosystem engineering, and ecological cascades in Alaskan boreal forests *Alaska's Changing Boreal Forest* (New York: Oxford University Press) p 354

Kim Y, Kimball J S, Robinson D A and Derksen C 2015 New satellite climate data records indicate strong coupling between recent frozen season changes and snow cover over high northern latitudes *Environ. Res. Lett.* **10** 084004

King G E and King D E 2013 Environmental risk arising from well-construction failure—differences between barrier and well failure, and estimates of failure frequency across common well types, locations, and well age *SPE Prod. Oper.* **28** 323–44

King M, Altdorff D, Li P, Galagedara L, Holden J and Unc A 2018 Northward shift of the agricultural climate zone under 21st-century global climate change *Sci. Rep.* **8** 7904

Koch J C, Jorgenson M T, Wickland K P, Kanevskiy M and Striegl R 2018 Ice wedge degradation and stabilization impact water budgets and nutrient cycling in arctic trough ponds *J. Geophys. Res. Biogeosci.* **123** 2604–16

Kokelj S V, Lantz T C, Wolfe S A, Kanigan J C, Morse P D, Coutts R, Molina-Giraldo N and Burn C R 2014 Distribution and activity of ice wedges across the forest-tundra transition, western Arctic Canada: ice wedges across tree line *J. Geophys. Res. Earth Surf.* **119** 2032–47

Kokelj S V, Tunnicliffe J, Lacelle D, Lantz T C, Chin K S and Fraser R 2015 Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada *Glob. Planet. Change* **129** 56–68

Krause S C and Raffa K F 1996 Differential growth and recovery rates from defoliation in deciduous and evergreen conifers *Trees Struct. Funct.* **10** 308–16

Krebs C J, Boonstra R and Boutin S 2018 Using experimentation to understand the 10-year snowshoe hare cycle in the boreal forest of North America *J. Anim. Ecol.* **87** 87–100

Kurz W A, Dymond C C, Stinson G, Rampley G J, Neilson E T, Carroll A L, Ebata T and Safranyik L 2008 Mountain pine beetle and forest carbon feedback to climate change *Nature* **452** 987–90

Kurz W A, Shaw C H, Boisvenue C, Stinson G, Metsaranta J, Leckie D, Dyk A, Smyth C and Neilson E T 2013 Carbon in Canada's boreal forest—a synthesis *Environ. Rev.* **21** 260–92

Lacelle D, Brooker A, Fraser R H and Kokelj S V 2015 Distribution and growth of thaw slumps in the Richardson Mountains–Peel Plateau region, northwestern Canada *Geomorphology* **235** 40–51

Lachenbruch A H 1962 Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost *Mechanics of Thermal Contraction Cracks and Ice-Wedge Polygons in Permafrost* vol 70, ed A H Lachenbruch (Geological Society of America)

Lafrenière M J, Louiseize N L and Lamoureux S F 2017 Active layer slope disturbances affect seasonality and composition of dissolved nitrogen export from High Arctic headwater catchments *Arctic Sci.* **3** 429–50

Lamb C T *et al* 2022 Indigenous-led conservation: pathways to recovery for the nearly extirpated Klinse-Za mountain caribou *Ecol. Appl.* **32** e2581

Lantuit H and Pollard W H 2008 Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada *Geomorphology* **95** 84–102

Lantz T C 2017 Vegetation succession and environmental conditions following catastrophic lake drainage in Old Crow Flats, Yukon *Arctic* **70** 177–89

Lantz T C, Gergel S E and Henry G H R 2010a Response of green alder (Alnus viridis subsp. fruticosa) patch dynamics and plant community composition to fire and regional temperature in north-western Canada *J. Biogeogr.* **37** 1597–610

Lantz T C, Gergel S E and Kokelj S V 2010b Spatial heterogeneity in the shrub tundra ecotone in the Mackenzie Delta Region, Northwest Territories: implications for arctic environmental change *Ecosystems* **13** 194–204

Lantz T C and Kokelj S V 2008 Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada *Geophys. Res. Lett.* **35** L06502

Lantz T C and Turner K W 2015 Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon *J. Geophys. Res.* **120** 513–24

Lara M J, Nitze I, Grosse G, Martin P and McGuire A D 2018 Reduced arctic tundra productivity linked with landform and climate change interactions *Sci. Rep.* **8** 2345

Lee P and Boutin S 2006 Persistence and developmental transition of wide seismic lines in the western Boreal Plains of Canada *J. Environ. Manage.* **78** 240–50

Leibman M O 1995 Cryogenic landslides on the Yamal Peninsula, Russia: preliminary observations *Permafr. Periglac. Process.* **6** 259–64

Leostrin A and Pergl J 2021 Alien flora in a boreal region of European Russia: an example of Kostroma oblast *Biol. Invasions* **23** 3337–50

Leroux S J, Wiersma Y F and Vander Wal E 2020 Herbivore impacts on carbon cycling in boreal forests *Trends Ecol. Evol.* **35** 1001–10

Lewkowicz A G and Way R G 2019 Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment *Nat. Commun.* **10** 1329

Lewkowicz A and Harris C 2005 Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada *Permafr. Periglac. Process.* **16** 115–30

Li Y, Liu H, Zhu X, Yue Y, Xue X and Shi L 2021 How permafrost degradation threatens boreal forest growth on its southern margin? *Sci. Total Environ.* **762** 143154

Liljedahl A K *et al* 2016 Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology *Nat. Geosci.* **9** 312–8

Liljedahl A K, Timling I, Frost G V and Daanen R P 2020 Arctic riparian shrub expansion indicates a shift from streams gaining water to those that lose flow *Commun. Earth Environ.* **1** 50

Lind L, Nilsson C, Polvi L E and Weber C 2014 The role of ice dynamics in shaping vegetation in flowing waters *Biol. Rev.* **89** 791–804

Lindenschmidt K-E, Das A, Rokaya P and Chu T 2016 Ice-jam flood risk assessment and mapping *Hydrol. Process.* **30** 3754–69

Lininger K B, Wohl E, Sutfin N A and Rose J R 2017 Floodplain downed wood volumes: a comparison across three biomes *Earth Surf. Process. Landf.* **42** 1248–61

Liu S *et al* 2011 Simulating the impacts of disturbances on forest carbon cycling in North America: processes, data, models, and challenges *J. Geophys. Res.* **116** G00K08

Ma Z, Peng C, Zhu Q, Chen H, Yu G, Li W, Zhou X, Wang W and Zhang W 2012 Regional drought-induced reduction in biomass carbon sink of Canada's boreal forests *Proc. Natl Acad. Sci.* **109** 2423–7

Macander M J *et al* 2020 Lichen cover mapping for caribou ranges in interior Alaska and Yukon *Environ. Res. Lett.* **15** 055001

MacDonald L A, Wiklund J A, Elmes M C, Wolfe B B and Hall R I 2016 Paleolimnological assessment of riverine and atmospheric pathways and sources of metal deposition at a floodplain lake (Slave River Delta, Northwest Territories, Canada) *Sci. Total Environ.* **544** 811–23

Macdonald S E and Fenniak T E 2007 Understory plant communities of boreal mixedwood forests in western Canada: natural patterns and response to variable-retention harvesting *For. Ecol. Manage.* **242** 34–48

Mack M C, Walker X J, Johnstone J F, Alexander H D, Melvin A M, Jean M and Miller S N 2021 Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees *Science* **372** 280–3

Mackay J R 1981 An experiment in lake drainage, Richards Island, Northwest Territories: a progress report Current research, part A. Geological Survey of Candaa, Paper 81–1A pp 63–68

Mackay J R 1988 Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie Geological Survey of Canada, Paper 88–1D pp 83–90

Mackay J R and Burn C R 2002 The first 20 years (1978–1979–1998–1999) of ice-wedge growth at the Illisarvik experimental drained lake site, western Arctic coast, Canada *Can. J. Earth Sci.* **39** 95–111

Madani N *et al* 2021 The impacts of climate and wildfire on ecosystem gross primary productivity in Alaska *J. Geophys. Res.* **126** e2020JG006078

Mahabir C, Robichaud C, Hicks F and Fayek A R 2008 Regression and fuzzy logic based ice jam flood forecasting *Cold Region Atmospheric and Hydrologic Studies the Mackenzie GEWEX Experience: Volume 2: Hydrologic Processes* ed M Woo (Berlin: Springer) pp 307–25

Maher C T, Dial R J, Pastick N J, Hewitt R E, Jorgenson M T and Sullivan P F 2021 The climate envelope of Alaska's northern treelines: implications for controlling factors and future treeline advance *Ecography* **44** 1–13

Malmstrom C M and Raffa K F 2000 Biotic disturbance agents in the boreal forest: considerations for vegetation change models *Glob. Change Biol.* **6** 35–48

Manseau M, Huot J and Crete M 1996 Effects of summer grazing by caribou on composition and productivity of vegetation: community and landscape level *J. Ecol.* **84** 503–13

Marsh P and Neumann N N 2001 Processes controlling the rapid drainage of two ice-rich permafrost-dammed lakes in NW Canada *Hydrol. Process.* **15** 3433–46

Marsh P, Russell M, Pohl S, Haywood H and Onclin C 2009 Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000 *Hydrol. Process.* **23** 145–58

Masek J G, Vermote E F, Saleous N E, Wolfe R, Hall F G, Huemmrich K F, Feng Gao J K and Lim T-K 2006 A Landsat surface reflectance dataset for North America, 1990–2000 *IEEE Geosci. Remote Sens. Lett.* **3** 68–72

Masrur A, Petrov A N and DeGroote J 2018 Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001–2015 *Environ. Res. Lett.* **13** 014019

Massie D D, White K D and Daly S F 2002 Application of neural networks to predict ice jam occurrence *Cold Reg. Sci. Technol.* **35** 115–22

McCabe G, Clark M and Hay L 2007 Rain-on-snow events in the western United States *Bull. Am. Meteorol. Soc.* **88** 319–28

McCarty J L *et al* 2021 Reviews and syntheses: arctic fire regimes and emissions in the 21st century *Biogeosciences* **18** 5053–83

McClelland J W, Déry S J, Peterson B J, Holmes R M and Wood E F 2006 A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century *Geophys. Res. Lett.* **33** L06715

McDaniel C N and Borton D N 2002 Increased human energy use causes biological diversity loss and undermines prospects for sustainability *BioScience* **52** 929–36

McDowell N G and Allen C D 2015 Darcy's law predicts widespread forest mortality under climate warming *Nat. Clim. Change* **5** 669–72

McKenzie D, Peterson D L and Littell J J 2009 Global warming and stress complexes in forests of Western North America *Developments in Environmental Science* vol 8 (Amsterdam: Elsevier) ch 15, pp 319–37 (available at: http://linkinghub.elsevier.com/retrieve/pii/S1474817708000156)

Meddens A J H and Hicke J A 2014 Spatial and temporal patterns of Landsat-based detection of tree mortality caused by mountain pine beetle outbreak in Colorado, USA *For. Ecol. Manage.* **322** 78–88

Meehl G A and Tebaldi C 2004 More intense, more frequent, and longer lasting heat waves in the 21st century *Science* **305** 994–7

Meilby H, Strange N and Thorsen B J 2001 Optimal spatial harvest planning under risk of windthrow *For. Ecol. Manage.* **149** 15–31

Mekonnen Z A, Riley W, Randerson J, Grant R F and Rogers B M 2019 Expansion of high-latitude deciduous forests driven by interactions between climate warming and fire *Nat. Plants* **5** 952–8

Melvin A M *et al* 2017a Climate change damages to Alaska public infrastructure and the economics of proactive adaptation *Proc. Natl Acad. Sci.* **114** E122–31

Melvin A M, Murray J, Boehlert B, Martinich J A, Rennels L and Rupp T S 2017b Estimating wildfire response costs in Alaska's changing climate *Clim. Change* **141** 783–95

Michaelian M, Hogg E H, Hall R J and Arsenault E 2011 Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest *Glob. Change Biol.* **17** 2084–94

Miner K R, Turetsky M R, Malina E, Bartsch A, Tamminen J, McGuire A D, Fix A, Sweeney C, Elder C D and Miller C E 2022 Permafrost carbon emissions in a changing Arctic *Nat. Rev. Earth Environ.* **3** 55–67

Morimoto M and Juday G P 2018 Developing adaptive approaches to forest harvest management in boreal Alaska under rapid climate change *J. For.* **116** 437–50

Morissette J L, Cobb T P, Brigham R M and James P C 2002 The response of boreal forest songbird communities to fire and post-fire harvesting *Can. J. For. Res.* **32** 2169–83

Mu C C *et al* 2017 Thaw depth determines dissolved organic carbon concentration and biodegradability on the northern qinghai-tibetan plateau: thaw depth determines dissolved C export *Geophys. Res. Lett.* **44** 9389–99

Munier A, Hermanutz L, Jacobs J D and Lewis K 2010 The interacting effects of temperature, ground disturbance, and herbivory on seedling establishment: implications for treeline advance with climate warming *Plant Ecol.* **210** 19–30

Myers-Smith I H *et al* 2020 Complexity revealed in the greening of the Arctic *Nat. Clim. Change* **10** 106–17

Nagy-Reis M *et al* 2021 Habitat loss accelerates for the endangered woodland caribou in western Canada *Conserv. Sci. Pract.* **3** e437

Nallur V, McClung M R and Moran M D 2020 Potential for reclamation of abandoned gas wells to restore ecosystem services in the Fayatteville shale of Arkansas *Environ. Manage.* **66** 180–90

Narayanaraj G and Wimberly M C 2011 Influences of forest roads on the spatial pattern of wildfire boundaries *Int. J. Wildland Fire* **20** 792–803

National Forestry Database 2020 Table 5.1 Net merchantable volume of roundwood harvested by ownership, category and species group (available at: http://nfdp.ccfm.org/en/data/harvest.php)

Nelson J L, Zavaleta E S and Chapin F S 2008 Boreal fire effects on subsistence resources in Alaska and adjacent Canada *Ecosystems* **11** 156–71

Nguyen-Xuan T, Bergeron Y, Simard D, Fyles J W and Pare D 2000 The importance of forest floor disturbance in the early regeneration patterns of the boreal forest of western and central Quebec: a wildfire versus logging comparison *Can. J. For. Res.* **30** 1353–64

Nilsson C, Jansson R, Kuglerová L, Lind L and Ström L 2013 Boreal riparian vegetation under climate change *Ecosystems* **16** 401–10

Nilsson C, Polvi L E and Lind L 2015 Extreme events in streams and rivers in arctic and subarctic regions in an uncertain future *Freshw. Biol.* **60** 2535–46

Nitze I, Cooley S W, Duguay C R, Jones B M and Grosse G 2020 The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska: fast-forward into the future *Cryosphere* **14** 4279–97

Norby R J, Sloan V L, Iversen C M and Childs J 2019 Controls on fine-scale spatial and temporal variability of plant-available inorganic nitrogen in a polygonal Tundra Landscape *Ecosystems* **22** 528–43

Northrup J M and Wittemyer G 2013 Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation *Ecol. Lett.* **16** 112–25

NRC 2018 Mountain pine beetle: the threat of mountain pine beetle to Canada's boreal forest *Fire, Insects, and Disturbances* (available at: www.nrcan.gc.ca/forests/fire-insects-disturbances/top-insects/13381)

Okkonen J, Jyrkama M and Kløve B 2010 A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland) *Hydrogeol. J.* **12** 429–39

Olnes J and Kielland K 2016 Stage-dependent effects of browsing by snowshoe hares on successional dynamics in a boreal forest ecosystem *Ecosphere* **7** e01475

Olnes J, Kielland K, Genet H, Juday G and Ruess R W 2018 Functional responses of white spruce to snowshoe hare herbivory at the treeline *PLoS One* **13** e0198453

Olofsson J 2006 Short- and long-term effects of changes in reindeer grazing pressure on tundra heath vegetation *J. Ecol.* **94** 431–40

Olofsson J, Oksanen L, Callaghan T, Hulme P E, Oksanen T and Suominen O 2009 Herbivores inhibit climate-driven shrub expansion on the tundra: herbivores inhibit shrub expansion *Glob. Change Biol.* **15** 2681–93

Olofsson J and Post E 2018 Effects of large herbivores on tundra vegetation in a changing climate, and implications for rewilding *Phil. Trans. R. Soc.* B **373** 20170437

Olofsson J, Stark S and Oksanen L 2004 Reindeer influence on ecosystem processes in the tundra *Oikos* **105** 386–96

Olthof I, Fraser R H and Schmitt C 2015 Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk Coastal Plain, Northwest Territories, Canada since 1985 *Remote Sens. Environ.* **168** 194–204

Osko T and MacFarlane A 2001 *Natural Reforestation on Seismic Lines and Wellsites in Comparison to Natural Burns or Logged Sites* (Boyle, AB: Alberta-Pacifc Forest Industries)

Ovenden L 1986 Vegetation colonizing the bed of a recently drained thermokarst lake (Illisarvik), Northwest Territories *Can. J. Bot.* **64** 2688–92

Pan C G, Kirchner P B, Kimball J S, Kim Y and Du J 2018 Rain-on-snow events in Alaska, their frequency and distribution from satellite observations *Environ. Res. Lett.* **13** 075004

Parisien M-A, Barber Q E, Hirsch K G, Stockdale C A, Erni S, Wang X, Arseneault D and Parks S A 2020 Fire deficit increases wildfire risk for many communities in the Canadian boreal forest *Nat. Commun.* **11** 2121

Parks S A, Miller C, Holsinger L M, Baggett L S and Bird B L 2015 Wildland fire limits subsequent fire occurrence *Int. J. Wildland Fire* **25** 182–90

Parlee B L, John S and Natcher David C 2018 Undermining subsistence: barren-ground caribou in a "tragedy of open access" *Sci. Adv.* **4** e1701611

Pasher J, Seed E and Duffe J 2013 Development of boreal ecosystem anthropogenic disturbance layers for Canada based on 2008–2010 Landsat imagery *Can. J. Remote Sens.* **18** 42–58

Pastick N J, Jorgensen M T, Goetz S J, Jones B M, Wylie B K, Minsley B J, Genet H, Knight J F, Swanson D K and Jorgenson J C 2019 Spatiotemporal remote sensing of ecosystem change and causation across Alaska *Glob. Change Biol.* **25** 1171–89

Pastor J R, Naiman B, Dewey B and McInnes P 1988 Moose, microbes, and the boreal forest *Bioscience* **38** 770–7

Peng C, Ma Z, Lei X, Zhu Q, Chen H, Wang W, Liu S, Li W, Fang X and Zhou X 2011 A drought-induced pervasive increase in tree mortality across Canada's boreal forests *Nat. Clim. Change* **1** 467–71

Perkins-Kirkpatrick S E and Lewis S C 2020 Increasing trends in regional heatwaves *Nat. Commun.* **11** 3357

Peterson B J 2002 Increasing river discharge to the Arctic Ocean *Science* **298** 2171–3

Peterson C J 2004 Within-stand variation in windthrow in southern boreal forests of Minnesota: is it predictable? *Can. J. For. Res.* **34** 365–75

Peterson R A and Krantz W B 2003 A mechanism for differential frost heave and its implications for patterned-ground formation *J. Glaciol.* **49** 69–80

Phillips C A, Rogers B M, Elder M, Cooperdock S, Moubarak M, Randerson J T and Frumhoff P C 2022 Escalating carbon emissions from North American boreal forest wildfires and the climate mitigation potential of fire management *Sci. Adv.* **8** eabl7161

Phoenix G K and Lee J A 2004 Predicting impacts of Arctic climate change: past lessons and future challenges *Ecol. Res.* **19** 65–74

Pickell P D, Andison D W, Coops N C, Gergel S E and Marshall P L 2015 The spatial patterns of anthropogenic disturbance in the western Canadian boreal forest following oil and gas development *Can. J. For. Res.* **45** 732–43

Pickell P D, Hermosilla T, Coops N C, Masek J G, Franks S and Huang C 2014 Monitoring anthropogenic disturbance trends in an industrialized boreal forest with Landsat time series *Remote Sens. Lett.* **5** 783–92

Pickett S T A and White P S 1985 *The Ecology of Natural Disturbance and Patch Dynamics* (San Diego, CA: Academic)

Ploum S W, Leach J A, Laudon H and Kuglerová L 2021 Groundwater, soil, and vegetation interactions at Discrete Riparian Inflow Points (DRIPs) and implications for boreal streams *Front. Water* **3** 669007

Polishchuk Y M, Bryksina N A and Polishchuk V Y 2015 Remote analysis of changes in the number of small thermokarst lakes and their distribution with respect to their sizes in the cryolithozone of Western Siberia, 2015 *Izv. Atmos. Ocean. Phys.* **51** 999–1006

Post E and Forchhammer M C 2002 Synchronization of animal population dynamics by large-scale climate *Nature* **420** 168–71

Potapov P V *et al* 2008 Mapping the world's intact forest landscapes by remote sensing *Ecol. Soc.* **13** 51

Potter C 2020a Changes in growing season phenology following wildfires in Alaska *Remote Sens. Earth Syst. Sci.* **3** 95–109

Potter S *et al* 2020b Climate change decreases the cooling effect from postfire albedo in boreal North America *Glob. Change Biol.* **26** 1592–607

Powers R P, Hermosilla T, Coops N C and Chen G 2015 Remote sensing and object-based techniques for mapping fine-scale industrial disturbances *Int. J. Appl. Earth Observ. Geoinf.* **34** 51–57

Price D T *et al* 2013 Anticipating the consequences of climate change for Canada's boreal forest ecosystems *Environ. Rev.* **21** 322–65

Prowse T D and Beltaos S 2002 Climatic control of river-ice hydrology: a review *Hydrol. Process.* **16** 805–22

Pureswaran D S, Roques A and Battisti A 2018 Forest insects and climate change *For. Entomol.* **4** 35–50

Putkonen J, Grenfell T C, Rennert K, Bitz C, Jacobson P and Russell D 2009 Rain on snow: little understdood killer in the north *EOS Trans. Am. Geophys. Union* **90** 221–8

Quinton W L, Hayashi M and Chasmer L E 2011 Permafrost-thaw-induced land-cover change in the Canadian subarctic: implications for water resources *Hydrol. Process.* **25** 152–8

R Core Team 2021 R: a language and environment for statistical computing (available at: www.R-project.org/)

Racine C H, Dennis J G and Patterson W A III 1985 Tundra fire regimes in the Noatak River Watershed, Alaska: 1956–83 *Arctic* **38** 194–200

Raffa K F, Aukema B H, Bentz B J, Carroll A L, Hicke J A, Turner M G and Romme W H 2008 Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of Bark Beetle Eruptions *BioScience* **58** 501

Randall J M and Rejmánek M 1993 Interference of bull thistle (Cirsium vulgare) with growth of ponderosa pine (Pinus ponderosa) seedlings in a forest plantation *Can. J. For. Res.* **23** 1507–13

Randerson J T *et al* 2006 The impact of boreal forest fire on climate warming *Science* **314** 1130–2

Rantanen M, Karpechko A Y L A, Nordling K, Hyvärinen O, Ruosteenoja K, Vihma T and Laaksonen A 2022 The Arctic has warmed nearly four times faster than the globe since 1979 *Commun. Earth Environ.* **3** 168

Rawlins M A *et al* 2010 Analysis of the Arctic system for freshwater cycle intensification: observations and expectations *J. Clim.* **23** 5715–37

Raynolds M K, Walker D A, Ambrosius K J, Brown J, Everett K R, Kanevskiy M, Kofinas G P, Romanovsky V E, Shur Y and Webber P J 2014 Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska *Glob. Change Biol.* **20** 1211–24

Refsland T K and Cushman J H 2021 Continent-wide synthesis of the long-term population dynamics of quaking aspen in the face of accelerating human impacts *Oecologia* **197** 25–42

Rennert K J, Roe G, Putkonen J and Bitz C M 2009 Soil thermal and ecological impacts of rain on snow events in the circumpolar Arctic *J. Clim.* **22** 2302–15

Rexstad E and Kielland K 2006 Mammalian herbivore population dynamics in the Alaskan boreal forest *Alaska's Changing Boreal Forest* ed F S Chapin III, M W Oswood, K Van Cleve, L A Vierececk and D L Verbyla (New York: Oxford University Press) p 354

Rich R L, Frelich L E and Reich P B 2007 Wind-throw mortality in the southern boreal forest: effects of species, diameter and stand age *J. Ecol.* **95** 1261–73

Richardson A D *et al* 2018 Ecosystem warming extends vegetation activity but heightens vulnerability to cold temperatures *Nature* **560** 368–71

Rickbeil G J M, Coops N C and Adamczewski J 2015 The grazing impacts of four barren ground caribou herds (Rangifer tarandus groenlandicus) on their summer ranges: an application of archived remotely sensed vegetation productivity data *Remote Sens. Environ.* **164** 314–23

Rocha A V, Loranty M M, Higuera P E, Mack M C, Hu F S, Jones B M, Breen A L, Rastetter E B, Goetz S J and Shaver G R 2012 The footprint of Alaskan tundra fires during the past half-century: implications for surface properties and radiative forcing *Environ. Res. Lett.* **7** 044039

Rogers B M, Balch J K, Goetz S J, Lehmann C E R and Turetsky M 2020 Focus on changing fire regimes: interactions with climate, ecosystems, and society *Environ. Res. Lett.* **15** 030201

Rogers B M, Randerson J T and Bonan G B 2013 High-latitude cooling associated with landscape changes from North American boreal forest fires *Biogeosciences* **10** 699–718

Rogers B M, Soja A J, Goulden M L and Randerson J T 2015 Influence of tree species on continental differences in boreal fires and climate feedbacks *Nat. Geosci.* **8** 228–34

Rogers B M, Solvik K, Hogg E H, Ju J, Masek J G, Michaelian M, Berner L T and Goetz S J 2018 Detecting early warning signals of tree mortality in boreal North America using multiscale satellite data *Glob. Change Biol.* **24** 2284–304

Rokaya P, Budhathoki S and Lindenschmidt K-E 2018 Ice-jam flood research: a scoping review *Nat. Hazards* **94** 1439–57

Rood B S, Goater L A, Mahoney J M, Pearce C M and Smith D G 2007 Floods, fire, and ice: disturbance ecology of riparian cottonwoods *Can. J. Bot.* **85** 1019–32

Rouse J, Haas R, Schell J and Deering D 1974 Monitoring vegetation systems in the Great Plains with ERTS *NASA Spec. Publ.* **351** 309–17

Rowland J C *et al* 2010 Arctic landscapes in transition: responses to thawing permafrost *Eos Trans. Am. Geophys. Union* **91** 229–30

Roy-Léveillée P and Burn C R 2010 Permafrost conditions near shorelines of oriented lakes in Old Crow Flats, Yukon Territory *Conf. Proc. GEO* pp 1509–16

Ruel J-C 2000 Factors influencing windthrow in balsam fir forests: from landscape studies to individual tree studies *For. Ecol. Manage.* **135** 169–78

Ruess R W, Winton L M and Adams G C 2021 Widespread mortality of trembling aspen (Populus tremuloides) throughout interior Alaskan boreal forests resulting from a novel canker disease *PLoS One* **16** e0250078

Sanderson L A, McLaughlin J A and Antunes P M 2012 The last great forest: a review of the status of invasive species in the North American boreal forest *Forestry* **85** 329–240

Schaefer G L and Paetzold R F 2001 SNOTEL: (SNOwpack TELelmetry) and SCAN (soil climate analysis network) *Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives* ed G Kenneth and M V K Sivakumar (Nebraska, GN: Lincoln, USA High Plains Climate Center and World Meteorological Organization) p 248

Schieck J, Stuart-Smith K and Norton M 2000 Bird communities are affected by amount and dispersion of vegetation retained in mixedwood boreal forest harvest areas *For. Ecol. Manage.* **126** 239–54

Schmidt M, Davidson S J and Strack M 2022 CO_2 uptake decreased and CH_4 emissions increased in first two years of peatland seismic line restoration *Wetl. Ecol. Manage.* **30** 313–29

Schmitz O J, Wilmers C C, Leroux S J, Doughty C E, Atwood T B, Galetti M, Davies A B and Goetz S J 2018 Animals and the zoogeochemistry of the carbon cycle *Science* **362** eaar3213

Schneider R R 2002 *Alternative Futures: Alberta's Boreal Forest at the Crossroads* (Edmonton, AB: Federation of Alberta Naturalists)

Scholten R C, Jandt R, Miller E A, Rogers B M and Veraverbeke S 2021 Overwintering fires in boreal forests *Nature* **593** 399–404

Schuur E A G *et al* 2015 Climate change and the permafrost carbon feedback *Nature* **520** 171–9

Schwarz M, Steinmeier C, Holecz F, Stebler O and Wagner H 2003 Detection of windthrow in mountainous regions with different remote sensing data and classification methods *Scand. J. For. Res.* **18** 525–36

Scrimgeour G J, Prowse T D, Culp J M and Chambers P A 1994 Ecological effects of river ice break-up: a review and perspective *Freshw. Biol.* **32** 261–75

Sedano F and Randerson J T 2014 Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems *Biogeosciences* **11** 3739–55

Seidl R *et al* 2011 Modelling natural disturbances in forest ecosystems: a review *Ecol. Modell.* **222** 903–24

Seidl R *et al* 2017 Forest disturbances under climate change *Nat. Clim. Change* **7** 395–402

Seidl R, Müller J, Hothorn T, Bässler C, Heurich M and Kautz M 2016 Small beetle, large-scale drivers: how regional and landscape factors affect outbreaks of the European spruce bark beetle *J. Appl. Ecol.* **53** 530–40

Seidl R and Turner M G 2022 Post-disturbance reorganization of forest ecosystems in a changing world *Proc. Natl Acad. Sci.* **119** e2202190119

Senf C, Campbell E M, Pflugmacher D, Wulder M A and Hostert P 2017a A multi-scale analysis of western spruce budworm outbreak dynamics *Landsc. Ecol.* **32** 501–14

Senf C, Seidl R and Hostert P 2017b Remote sensing of forest insect disturbances: current state and future directions *Int. J. Appl. Earth Observ. Geoinf.* **60** 49–60

Senf C, Wulder M A, Campbell E M and Hostert P 2016 Using landsat to assess the relationship between spatiotemporal patterns of western spruce budworm outbreaks and regional-scale weather variability *Can. J. Remote Sens.* **42** 706–18

Serreze M C, Gustafson J, Barrett A P, Druckenmiller M L, Fox S, Voveris J, Stroeve J, Sheffield B, Forbes B C and Rasmus S 2021 Arctic rain on snow events: bridging observations to understand environmental and livelihood impacts *Environ. Res. Lett.* **16** 105009

Serreze M C, Walsh J E, Chapin F S III, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel W C, Morison J, Zhang T and Barry R G 2000 Observational evidence of recent change in the northern high-latitude environment *Clim. Change* **46** 159–207

Sharam G J and Turkington R 2009 Growth, camphor concentration, and Nitrogen response of white spruce (Picea glauca) leaves to browsing and fertilization *Ecoscience* **16** 258–64

Shaw C H, Rodrigue S, Voicu M F, Latifovic R, Pouliot D, Hayne S, Fellows M and Kurz W A 2021 Cumulative effects of natural and anthropogenic disturbances on the forest carbon balance in the oil sands region of Alberta, Canada; a pilot study (1985–2012) *Carbon Balance Manage.* **16** 3

Sherriff R L, Berg E E and Miller A E 2011 Climate variability and spruce beetle (Dendroctonus rufipennis) outbreaks in south-central and southwest Alaska *Ecology* **92** 1459–70

Shugart H H, Foster A C, Wang B, Druckenbrod D, Ma J, Lerdau M, Saathi S, Yang X and Yan X 2020 Gap models across micro- to mega-scales of time and space: examples of Tansley's ecosystem concept *For. Ecosyst.* **7** 14

Shur Y L and Jorgenson M T 2007 Patterns of permafrost formation and degradation in relation to climate and ecosystems *Permafr. Periglac. Process* **18** 7–19

Simard D G, Fyles J W, Pare D and Nguyen T 2001 Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest *Can. J. Soil Sci.* **81** 229–37

Simpson J M, Darrow M M, Huang S L, Daanen R and Hubbard T D 2016 Investigating movement and characteristics of a frozen debris lobe, south-central Brooks Range, Alaska *Environ. Eng. Geosci.* **22** 259–77

Singh P, Kumar N and Arora M 2000 Degree-day factors for snow and ice for Dokriani Glacier, Garhwal Himalayas *J. Hydrol.* **234** 1–11

Smith D M *et al* 2019 The polar amplification model intercomparison project (PAMIP) contribution to CMIP6: investigating the causes and consequences of polar amplification *Geosci. Model Dev.* **12** 1139–64

Smith L C, Pavelsky T M, MacDonald G M, Shiklomanov A I and Lammers R B 2007 Rising minimum daily flows in northern Eurasian rivers: a growing influence of groundwater in the high-latitude hydrologic cycle *J. Geophys. Res.* **112** G04S47

Smith S L, O'Neill H B, Isaksen K, Noetzli J and Romanovsky V E 2022 The changing thermal state of permafrost *Nat. Rev. Earth Environ.* **3** 10–23

Soininen E M *et al* 2021 Location of studies and evidence of effects of herbivory on Arctic vegetation: *a systematic map Environmental Evidence* **10** 25

Soja A J, Tchebakova N M, French N H F, Flannigan M D, Shugart H H, Stocks B J, Sukhinin A I, Parfenova E I, Chapin F S and Stackhouse P W 2007 Climate-induced boreal forest change: predictions versus current observations *Glob. Planet. Change* **56** 274–96

Sokolov A A, Sokolova N A, Ims R A, Brucker L and Ehrich D 2016 Emergent rainy winter warm spells may promote boreal predator expansion into the arctic *Arctic* **69** 121–9

Song X, Wang G, Hu Z, Ran F and Chen X 2018 Boreal forest soil CO_2 and CH_4 fluxes following fire and their responses to experimental warming and drying *Sci. Total Environ.* **644** 862–72

St Jacques J-M and Sauchyn D J 2009 Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada *Geophys. Res. Lett.* **36** L01401

Stephens S L *et al* 2014 Temperate and boreal forest mega-fires: characteristics and challenges *Front. Ecol. Environ.* **12** 115–22

Stocks B J *et al* 2002 Large forest fires in Canada, 1959–1997 *J. Geophys. Res.* **108** 8149

Stocks B J and Kaufmann J B 1997 Biomass consumption and behavior of woodland fires in boreal, temperate, and tropical ecosystems: parameters necessary to interpret historical fire regimes and future fire scenarios *Sediment Records of Biomass Burning and Global Change* NATO ASI Series 51 ed J S Clark, H Cachier, J G Goldammer and B Stocks (Berlin: Springer)

Strack M, Hayne S, Lovitt J, McDermid G J, Rahman M M, Saraswati S and Xu B 2019 Petroleum exploration increases methane emissions from northern peatlands *Nat. Commun.* **10** 2804

Ström L, Jansson R and Nilsson C 2012 Projected changes in plant species richness and extent of riparian vegetation belts as a result of climate-driven hydrological change along the Vindel River in Sweden *Freshw. Biol.* **57** 49–60

Ström L, Jansson R, Nilsson C, Johansson M E and Xiong S 2011 Hydrologic effects on riparian vegetation in a boreal river: an experiment testing climate change predictions *Glob. Change Biol.* **17** 254–67

Sulla-Menashe D, Friedl M A and Woodcock C E 2016 Sources of bias and variability in long-term Landsat time series over Canadian boreal forests *Remote Sens. Environ.* **177** 206–19

Sulla-Menashe D, Woodcock C E and Friedl M A 2018 Canadian boreal forest greening and browning trends: an analysis of biogeographic patterns and the relative roles of disturbance versus climate drivers *Environ. Res. Lett.* **13** 014007

Suominen O and Olofsson J 2000 Impacts of semi-domesticated reindeer on structure of tundra and forest communities in Fennoscandia: a review *Ann. Zool. Fenn.* **37** 233–49

Sutton J T, Hermanutz L and Jacobs J D 2006 Are frost boils important for the recruitment of arctic-alpine plants? *Arct. Antarct. Alp. Res.* **38** 273–5

Swanson D K 2016 *Stability of Ice-wedges in Kobuk Valley National Park and the Noatak National Preserve, 1951–2009* (Fort Collins, CO: US Department of the Interior)

Swanson D K 2019 Thermokarst and precipitation drive changes in the area of lakes and ponds in the National Parks of northwestern Alaska, 1984–2018 *null* **51** 265–79

Swanson D K 2021 Permafrost thaw-related slope failures in Alaska's Arctic National Parks, 1980–2019 *Permafr. Periglac. Process.* **32** 392–406

Swanson D K and Nolan M 2018 Growth of retrogressive thaw slumps in the Noatak Valley, Alaska, 2010–2016, measured by airborne photogrammetry *Remote Sens.* **10** 983

Tananaev N and Lotsari E 2022 Defrosting northern catchments: fluvial effects of permafrost degradation *Earth-Sci. Rev.* **228** 103996

Tank S E, Vonk J E, Walvoord M A, McClelland J W, Laurion I and Abbott B W 2020 Landscape matters: predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach *Permafr. Periglac. Process.* **31** 358–70

Tape K D, Christie K, Carroll G and O'Donnell J A 2016 Novel wildlife in the Arctic: the influence of changing riparian ecosystems and shrub habitat expansion on snowshoe hares *Glob. Change Biol.* **22** 208–19

Tape K D, Clark J A, Jones B M, Kantner S, Gaglioti B V, Grosse G and Nitze I 2022 Expanding beaver pond distribution in Arctic Alaska, 1949–2019 *Sci. Rep.* **12** 7123

Tape K D, Jones B M, Arp C D, Nitze I and Grosse G 2018 Tundra be dammed: beaver colonization of the Arctic *Glob. Change Biol.* **24** 4478–88

Tape K D, Verbyla D and Welker J M 2011 Twentieth century erosion in Arctic Alaska foothills: the influence of shrubs, runoff, and permafrost *J. Geophys. Res.* **116** G04024

Thomas D, Butry D, Gilbert S, Webb D and Fung J 2017 The costs and losses of wildfires: a literature review (National Institute of Stardards and Technology, US Department of Commerce)

Tiwari T, Sponseller R A and Laudon H 2018 Extreme climate effects on dissolved organic carbon concentrations during snowmelt *J. Geophys. Res.* **123** 1277–88

Tiwari T, Sponseller R A and Laudon H 2022 The emerging role of drought as a regulator of dissolved organic carbon in boreal landscapes *Nat. Commun.* **13** 5125

Tondu J M, Turner K W, Wiklund J A, Wolfe B B, Hall R I and McDonaled I 2017 Limnological evolution of Zelma Lake, a recently drained thermokarst lake in Old Crow Flats (Yukon, Canada) *Arctic Sci.* **3** 220–36

Trainor S F *et al* 2009 Vulnerability and adaptation to climate-related fire impacts in rural and urban interior Alaska *Polar Res.* **28** 100–18

Treharne R, Rogers B M, Gasser T, MacDonald E and Natali S 2022 Identifying barriers to estimating carbon release from interacting feedbacks in a warming Arctic *Front. Clim.* **3** 2624–9553

Trugman A T, Anderegg L D L, Anderegg W R L, Das A J and Stephenson N L 2021 Why is tree drought mortality so hard to predict? *Trends Ecol. Evol.* **36** 520–32

Tucker C J 1979 Red and photographic infrared linear combinations for monitoring vegetation *Remote Sens. Environ.* **8** 127–50

Tucker M A *et al* 2018 Moving in the Anthropocene: global reductions in terrestrial mammalian movements *Science* **359** 466–9

Tukey J W 1977 *Exploratory data analysis* (Reading, MA: Addison-Wesley Pub. Co.)

Turetsky M R *et al* 2020 Carbon release through abrupt permafrost thaw *Nat. Geosci.* **13** 138–43

Turetsky M R, Kane E S, Harden J W, Ottmar R D, Manies K L, Hoy E and Kasischke E S 2011 Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands *Nat. Geosci.* **4** 27–31

Turner K W, Pearce M D and Hughes D 2021 Detailed characterization and monitoring of a retrogressive thaw slump from remotely piloted aircraft systems and identifying associated influence on carbon and nitrogen export *Remote Sens.* **13** 171

Turner K W, Wolfe B B and McDonald I 2022 Monitoring 13 years of drastic catchment change and the hydroecological responses of a drained thermokarst lake *Arctic Sci.* 2368–7460

Ueyama M, Iwata H, Nagano H, Tahara N, Iwama C and Harazono Y 2019 Carbon dioxide balance in early-successional forests after forest fires in interior Alaska *Agric. For. Meteorol.* **275** 196–207

US EPA 2015 Ecoregions of North America *Data and Tools* (available at: www.epa.gov/eco-research/ecoregions-north-america)

USFS 2004 Horizontal drilling using high volume hydraulic fracturing (available at: www.fs.usda.gov/detail/wayne/landmanagement/?cid=stelprdb5387922)

USGS 2021 Landsat Collection 2 (version. 1.1) (U.S. Geological Survey Fact Sheet) (Accessed 15 January 2021)

Vachula R S, Liang J, Sae-Lim J and Xie H 2022 Ignition frequency and climate controlled Alaskan tundra fires during the Common Era *Quat. Sci. Rev.* **280** 107418

Väisänen M, Ylänne H, Kaarlejärvi E, Sjögersten S, Olofsson J, Crout N and Stark S 2014 Consequences of warming on tundra carbon balance determined by reindeer grazing history *Nat. Clim. Change* **4** 384–8

Van Cleve K, Viereck L A and Dyrness C T 1996 State factor control of soils and forest succession along the Tanana River in Interior Alaska, U.S.A *Arct. Alp. Res.* **28** 388 van der Wal R 2006 Do herbivores cause habitat degradation or vegetation state transition? Evidence from the tundra *Oikos* **114** 177–86

van Rensen C K, Nielsen S E, White B, Vinge T and Lieffers V J 2015 Natural regeneration of forest vegetation on legacy seismic lines in boreal habitats in Alberta's oil sands region *Biol. Conserv.* **184** 127–35

Vanderwel M C, Mills S C and Malcolm J R 2009 Effects of partial harvesting on vertebrate species associated with late-successional forests in Ontario's boreal region *For. Chron.* **85** 91–104

Veblen T T, Hadley K S, Nel E M, Kitzberger T, Reid M and Villalba R 1994 Disturbance regime and disturbance interactions in a rocky mountain subalpine forest *J. Ecol.* **82** 125

Veblen T T, Kulakowski D, Eisenhart K S and Baker W L 2001 Subalpine forest damage from a severe windstorm in northern Colorado *Can. J. For. Res.* **31** 2089–97

Veblen T T, Kulakowski D and Reid M S 1991 Disturbance and stand development of a Colorado subalpine forest *J. Biogeogr.* **18** 707–16

Venier L A *et al* 2014 Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests *Environ. Rev.* **22** 457–90

Veraverbeke S, Rogers B M, Goulden M L, Jandt R R, Miller C E, Wiggins E B and Randerson J T 2017 Lightning as a major driver of recent large fire years in North American boreal forests *Nat. Clim. Change* **7** 529–34

Verbesselt J and Herold M 2012 Near real-time disturbance detection using satellite image time series *Remote Sens. Environ.* **123** 98–108

Verbesselt J, Hyndman R, Newnham G and Culvenor D 2010 Detecting trend and seasonal changes in satellite image time series *Remote Sens. Environ.* **114** 106–15

Verbyla D 2011 Browning boreal forests of western North America *Environ. Res. Lett.* **6** 041003

Verdonen M, Berner L T, Forbes B C and Kumpula T 2020 Periglacial vegetation dynamics in Arctic Russia: decadal analysis of tundra regeneration on landslides with time series satellite imagery *Environ. Res. Lett.* **15** 105020

Viereck L A, Dyrness C T and Foote M J 1993 An overview of the vegetation and soils of the floodplain ecosystems of the Tanana River, interior Alaska *Can. J. For. Res.* **23** 889–98

Virkkala A-M *et al* 2022 The ABCflux database: arctic–boreal \chemCO$_2$ flux observations and ancillary information aggregated to monthly time steps across terrestrial ecosystems *Earth Syst. Sci. Data* **14** 179–208

Virkkala A-M, Virtanen T, Lehtonen A, Rinne J and Luoto M 2018 The current state of CO$_2$ flux chamber studies in the Arctic tundra: a review *Prog. Phys. Geogr. Earth Environ.* **42** 162–84

Volney W J A and Fleming R A 2000 Climate change and impacts of boreal forest insects *Agric. Ecosyst. Environ.* **82** 283–94

Vors L S and Boyce M S 2009 Global declines of caribou and reindeer: caribou reindeer decline *Glob. Change Biol.* **15** 2626–33

Walker D A, Kuss P, Epstein H E, Kade A N, Vonlanthen C M, Raynolds M K and Daniëls F J A 2011 Vegetation of zonal patterned-ground ecosystems along the North America Arctic bioclimate gradient: north America Arctic patterned-ground vegetation *Appl. Veget. Sci.* **14** 440–63

Walker L R and Chapin F S 1986 Physiological controls over seedling growth in primary succession on an Alaskan floodplain *Ecology* **67** 1508–23

Walker X J *et al* 2020a ABoVE: synthesis of burned and unburned forest site data, AK and Canada, 1983–2016 (https://doi.org/10.3334/ORNLDAAC/1744)

Walker X J *et al* 2020b Fuel availability not fire weather controls boreal wildfire severity and carbon emissions *Nat. Clim. Change* **10** 1130–6

Walker X J, Rogers B M, Baltzer J L, Cumming S G, Day N J, Goetz S J, Johnstone J F, Schuur E A G, Turetsky M R and Mack M C 2018 Cross-scale controls on carbon emissions from boreal forest megafires *Glob. Change Biol.* **24** 4251–65

Wang J A, Baccini A, Farina M, Randerson J T and Friedl M A 2021 Disturbance suppresses the aboveground carbon sink in North American boreal forests *Nat. Clim. Change* **11** 435–41

Wang J A and Friedl M A 2019 The role of land cover change in Arctic-Boreal greening and browning trends *Environ. Res. Lett.* **14** 125007

Wang X, Studens K, Parisien M-A, Taylor S W, Candau J-N, Boulanger Y and Flannigan M D 2020 Projected changes in fire size from daily spread potential in Canada over the 21st century *Environ. Res. Lett.* **15** 104048

Ward D S, Kloster S, Mahowald N M, Rogers B M, Randerson J T and Hess P G 2012 The changing radiative forcing of fires: global model estimates for past, present, and future *Chem. Phys.* **12** 10857–86

Warrack J, Kang M and von Sperber C 2021 Groundwater phosphorus concentrations: global trends and links with agricultural and oil and gas activities *Environ. Res. Lett.* **17** 014014

Wasowicz P *et al* 2020 Non-native vascular flora of the Arctic: taxonomic richness, distribution and pathways *Ambio* **49** 693–703

Westbrook C J, Cooper D J and Baker B W 2006 Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area *Water Resour. Res.* **42** W06404

White J C, Wulder M A, Hermosilla T, Coops N C and Hobart G W 2017 A nationwide annual characterization of 25years of forest disturbance and recovery for Canada using Landsat time series *Remote Sens. Environ.* **194** 303–21

Whitman E, Parisien M-A, Thompson D K and Flannigan M D 2019 Short-interval wildfire and drought overwhelm boreal forest resilience *Sci. Rep.* **9** 18796

Whitman E, Parks S A, Holsinger L M and Parisien M-A 2022 Climate-induced fire regime amplification in Alberta, Canada *Environ. Res. Lett.* **17** 055003

Wichmann L and Ravn H P 2001 The spread of Ips typographus (L.)(Coleoptera, Scolytidae) attacks following heavy windthrow in Denmark, analysed using GIS *For. Ecol. Manage.* **148** 31–39

Wiens J A 2002 Riverine landscapes: taking landscape ecology into the water *Freshw. Biol.* **47** 501–15

Wiklund J A, Hall R I and Wolfe B B 2012 Timescales of hydrolimnological change in floodplain lakes of the Peace-Athabasca Delta, northern Alberta, Canada *Ecohydrology* **5** 351–67

Wilkinson S L, Furukawa A K, Wotton B M and Waddington J M 2021 Mapping smouldering fire potential in boreal peatlands and assessing interactions with the wildland-human interface in Alberta, Canada *Int. J. Wildland Fire* **30** 552–63

Williams J P, Regehr A and Kang M 2021 Methane emissions from abandoned oil and gas wells in Canada and the United States *Enviorn. Sci. Technol.* **55** 563–70

Williams T J, Quinton W L and Baltzer J L 2013 Linear disturbances on discontinuous permafrost: implications for thaw-induced changes to land cover and drainage patterns *Environ. Res. Lett.* **8** 025006

Wilmking M and Juday G P 2005 Longitudinal variation of radial growth at Alaska's northern treeline—recent changes and possible scenarios for the 21st century *Glob. Planet. Change* **47** 282–300

Witharana C *et al* 2021 An object-based approach for mapping tundra ice-wedge polygon troughs from very high spatial resolution optical satellite imagery *Remote Sens.* **13** 558

Witharana C, Bhuiyan M A E, Liljedahl A K, Kanevskiy M, Epstein H E, Jones B M, Daanen R, Griffin C G, Kent K and Ward Jones M K 2020 Understanding the synergies of deep learning and data fusion of multispectral and panchromatic high resolution commercial satellite imagery for automated ice-wedge polygon detection *ISPRS J. Photogramm. Remote Sens.* **170** 174–91

Wolfe B B, Hall R I, Edwards T W D and Johnston J W 2012 Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: paleolimnological investigations of the Peace–Athabasca Delta *Environ. Rev.* **20** 191–210

Wolfe B B and Turner K W 2008 Near-record precipitation causes rapid drainage of Zelma Lake, Old Crow Flats, Northern Yukon Territory *Meridian* 7–12

Wolter J, Lantuit H, Fritz M, Macias-Fauria M, Myers-Smith I and Herzschuh U 2016 Vegetation composition and shrub extent on the Yukon coast, Canada, are strongly linked to ice-wedge polygon degradation *Polar Res.* **35** 27489

Wu L, He F and Spence J R 2020 Recovery of a boreal ground-beetle (Coleoptera: carabidae) fauna 15 years after variable retention harvest *J. Appl. Ecol.* **57** 1717–29

Wulder M A *et al* 2019 Current status of Landsat program, science, and applications *Remote Sens. Environ.* **225** 127–47

Wulder M A, White J C, Bentz B, Alvarez M F and Coops N C 2006 Estimating the probability of mountain pine beetle red-attack damage *Remote Sens. Environ.* **101** 150–66

Xu W, Scholten R C, Hessilt T D, Liu Y and Veraverbeke S 2022 Overwintering fires rising in eastern Siberia *Environ. Res. Lett.* **17** 045005

Ye H, Yang D and Robinson D 2008 Winter rain on snow and its association with air temperature in northern Eurasia *Hydrol. Process.* **22** 2728–36

Yoshikawa K and Hinzman L D 2003 Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near council, Alaska *Permafr. Periglac. Process* **14** 151–60

Yu Q, Epstein H, Engstrom R and Walker D 2017 Circumpolar arctic tundra biomass and productivity dynamics in response to projected climate change and herbivory *Glob. Change Biol.* **23** 3895–907

Zeppenfeld T, Svoboda M, DeRose R J, Heurich M, Müller J, Čížková P, Starý M, Bače R and Donato D C 2015 Response of mountain Picea abies forests to stand-replacing bark beetle outbreaks: neighbourhood effects lead to self-replacement *J. Appl. Ecol.* **52** 1402–11

Zhang Y, Woodcock C E, Chen S, Wang J A, Sulla-Menashe D, Zuo Z, Olofsson P and Wang Y 2022 Mapping causal agents of disturbance in boreal and arctic ecosystems of North America using time series of Landsat data *Remote Sens. Environ.* **272** 112935

Zwieback S, Kokelj S V, Günther F, Boike J, Grosse G and Hajnsek I 2018 Sub-seasonal thaw slump mass wasting is not consistently energy limited at the landscape scale *Cryosphere* **12** 549–64