CCFM FOREST PEST
WORKING GROUP REPORT
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REVIEW OF CONCEPTUAL ADVANCES IN DISTURBANCE INTERACTIONS

Phase One: Knowledge Synthesis, Knowledge Gaps, and Next Steps

Canadian Council
of Forest
Ministers

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FOREWORD

The following document discusses forest pest disturbance interactions and conceptual modeling advances as informed by two Forest Pest Working Group workshops, grey literature, anecdotal observations, and peer-reviewed articles, including recent systematic, meta-analysis, or selective reviews. While attempts were made to include as much relevant literature as possible, it was impossible to include everything given time constraints, coupled with the recent abundance of pertinent literature. Hence, this document should not be considered an exhaustive review.

CONTEXT

The Forest Pest Working Group (FPWG) under the Canadian Council of Forest Ministers (CCFM) is working towards best practices for analysis, decision-making and action to make forest pest management in Canada more proactive, more coordinated, and ultimately more effective. Its work focuses on developing and implementing a National Forest Pest Strategy, providing an integrated framework for prevention, detection, and response. The aim is to help all the jurisdictions involved work together to maintain healthy forests and a sustainable forest sector. This is achieved through collaborative efforts between provincial, territorial, municipal, and federal governments under the National Forest Pest Strategy with annual work plans based on national interests.

Over the last decade, the FPWG has undertaken various projects to better understand the effects of climate change on forest insects and diseases to inform proactive forest pest management and, ultimately, adaptation. This included a vulnerability assessment of forest health monitoring (FHM) policies and practices, which identified several adaptation options to build adaptive capacity to help reduce FHM vulnerability to climate change. In 2022 the FPWG advanced this theme in terms of adaptation and disturbance interaction impacts in recognition that: 1) forest disturbance agents (e.g., fire, drought, insect outbreaks, and pathogens) are expected to catalyze ecosystem changes in a warming climate, and 2) the cumulative effects of interacting disturbances could have serious consequences on future forests and the socio-economic and ecological values derived from them. The first step, documented here, is a knowledge synthesis of disturbance interactions, associated knowledge gaps and uncertainties, and insight into current forest modeling applications addressing disturbance interactions.

INTRODUCTION

Forest insects and diseases are integral components of Canada's forests; however, climate change is modifying the extent, severity, and frequency of their historical disturbance regimes. Resultant changes may challenge the ability to meet sustainable forest management objectives under future conditions. There exists the potential for amplified, cascading, or cross-scale effects which could exceed ecological thresholds or tipping points, particularly in coniferous forests and the boreal biome (Seidl et al. 2017), including southern boreal (Brecka et al. 2020, Frelich et al. 2021, Chaste et al. 2019, Boulanger et al. 2021); Acadian (Taylor et al. 2017); and the Arctic boreal forest zones (Foster et al. 2022). This could result in more frequent unanticipated behaviour in ecological systems, referred to as ecological surprises (Filbee-Dexter et al. 2017). In fact, a systematic review of global climate sensitivity of six disturbance factors (fire, drought, wind, snow and ice, insects, and pathogens) found that 71% of the recorded interaction effects had an amplifying effect. In contrast, only 16% had a dampening effect (Seidl et al. 2017).

Alterations to natural disturbance regimes due to climate change will challenge the ability to meet sustainable management goals. This is due to the uncertainty around the magnitude and spatial and temporal dynamics of disturbance change and the lack of knowledge about disturbance interactions and ecosystem thresholds. Warming climate could also facilitate the spread and establishment of invasive forest pests that may have otherwise failed to establish. In the context of change and uncertainty, forest managers need information on the magnitude and likelihood of altered disturbance interactions and regimes and the resulting impact(s) on forest conditions in a warming climate to help guide adaptation and inform forest management planning over the long term.

Fundamental to adaptation is the means to assess potential impacts arising from climate-mediated changes in disturbance regimes. While retrospective insights have their place e.g., historical forest pest regimes, they are not representative of future climate-mediated landscapes and therefore have limited application. Conceptual advances in disturbance ecology offer a means to characterize disturbance interactions and help inform adaptation using conceptual models. This field of study has grown in recognition of the potential for rapid, non-linear, and unexpected forest change due to climate change and anthropogenic pressure, including forest fragmentation. Conceptual models are process-driven and capable of integrating disturbance interactions, cause, and effect at varying temporal and spatial scales. A recent review of conceptual advances and empirical approaches to disturbance interaction investigation (Sturtevant and Fortin, 2021) revealed how recent studies have shifted from statistically-based disturbance regimes (i.e., static) to process-based methods where disturbance regimes and ecosystem responses are emergent behaviors (i.e., dynamic).

In the face of increasing uncertainty regarding forest disturbance change, the need to qualify and quantify disturbance interactions and ecosystem thresholds is essential for adaptation. Yet, a lack of knowledge and model integration limits our ability to do so. A first step towards bridging this gap is to characterize the current state of knowledge of disturbance interactions, with an emphasis on forest insects and diseases, and conceptual models to provide a baseline from which to assess and forecast future states. This will help identify uncertainties and knowledge gaps to guide further conversations between forest health and forest management experts around knowledge gaps, uncertainties, and information and research needs. These could be tailored to specific regions of Canada and include interdisciplinary collaboration to advance our understanding of disturbance interactions and application in forest management.

CONCEPTUAL ADVANCES IN DISTURBANCE ECOLOGY – A BRIEF PRIMER

Conceptual advances in the context of disturbance ecology seek to provide a common understanding of disturbance interactions and their processes. This includes terminology and definitions to describe these processes, facilitating a common approach to integrating disturbance interactions into process-based methods. The following section, describing disturbance interactions and processes, borrows from the works by Buma (2015), Kleinman et al. (2019), and Burton et al. (2020), with additional terms and definitions provided in Appendix 1.

Broadly speaking, disturbances affect either forest ecosystem resistance, e.g., the capacity to endure disturbance without changing, or resilience, e.g., the capacity of a forested ecosystem to recover to pre-disturbance conditions, with the new system state referred to as a disturbance or biological legacy. Disturbance legacies that alter resistance by increasing or decreasing the likelihood of the subsequent disturbance, its spatial extent (likelihood at a location), intensity, or severity are known as linked disturbances. Disturbance legacies that alter resilience, e.g., the rate or trajectory of forest recovery from subsequent disturbances, are referred to as compound interactions. Thus, disturbance interactions develop when legacies are functionally connected to a subsequent disturbance event, either in terms of disturbance drivers or recovery mechanisms. Linked and compound disturbances can originate from the same event.

Linked and compound interactions can potentially drive disturbance behaviour beyond historical norms and in unexpected directions due to cascading effects, e.g., a sequence of more than two disturbances, each triggered by the preceding one. When one disturbance enhances the impact of another by decreasing resistance or resilience, the interaction is considered amplifying or synergistic. Alternatively, buffering, dampening or negative interactions describe situations when one disturbance reduces the impact of another by increasing resistance or resilience. Cross-scale interactions refer to processes at one spatial or temporal scale interacting with processes at another scale that often results in nonlinear dynamics with thresholds (Peters et al. 2007). Cumulative effects are the net impact of multiple stressors, disturbances, or degradation. Regardless of the type of interaction, their temporal and spatial characteristics, feedback loops, and ecosystem thresholds are all critical components of disturbance interaction investigation.

OBJECTIVES

The overall goal of this FPWG project is to synthesize current advances in conceptual models of forest disturbance interactions and their combined impacts on forest values based on an improved understanding of the underlying ecosystem processes involved and anticipated climate-induced forest change. The first phase, documented here, is a knowledge synthesis of disturbance interactions, associated knowledge gaps and uncertainties, and insight into current forest modeling applications addressing disturbance interactions.

APPROACH

Two virtual knowledge synthesis workshops were held with participants from across Canada representing academia, federal and provincial researchers, and provincial and territorial forest pest management agencies. Affirmative statements were used to help characterize disturbances and identify knowledge gaps and uncertainties. Affirmative statements are a tool used in various National Forest Pest Strategy pest risk analyses. They are intended to encourage discussion and distil evidence to support or refute the statements. In this instance, they also served as a starting point for discussion, given the complexity of interacting disturbances.

Four affirmative statements were developed; three focused on an abiotic trigger, and one on modeling and its current ability to inform adaptation and forest management. The three abiotic statements represent a selection of scenarios being observed across the Canadian landscape as identified by a Task Team which was formed for this project. Scenarios included those concerning drought, severe storms, and warming climate and extreme weather. Severe storms differ from extreme weather in that the latter is defined as an event that ranks above a threshold value near the upper or lower ends of the range of historical measurements. The fourth statement addressed modeling as it applies to disturbance interactions and the ability to inform forest pest management.

Workshop participants engaged in discussion for each affirmative statement and provided supporting or refuting evidence for each, including peer-reviewed works. As some of the workshop discussions involved wildfire and pest interactions that extended beyond those of the affirmative statements, a section is devoted to wildfire in the context of those discussions.

DISTURBANCE INTERACTIONS

The following section summarizes the state of disturbance interaction knowledge and knowledge gaps as informed by the evidence brought forth at the workshops, grey literature, peer-reviewed works and anecdotal observations for disturbance interaction scenarios involving drought, severe storms, and warming climate and extreme weather. As some of the evidence or knowledge gaps originate from work conducted in United States forests, there lies uncertainty about their applicability to Canada's forests. Nonetheless, they serve as a good starting or reference point for further work or discussion.

KNOWLEDGE SYNTHESIS

In addition to pest-specific evidence brought forward at the workshops, recent systematic, meta-analysis, or selective reviews (Table 1) provided for broad summary statements at the forest pest guild level. A compilation of climate-mediated changes to forest pest disturbances was previously completed by the FPWG Climate Change Vulnerability Assessment.

Table 1. Systematic, meta-analysis or selective literature reviews of disturbance interactions research.

REFERENCE	GEOGRAPHIC SCOPE	TOPIC	REVIEW PERIOD
Fettig et al. 2022	North America	Fire and insect interations	2017 - 2022
Canelles et al. 2021	Global	Interactions between insect pests and other disturbances	1990-2019
Kolb et al. 2019	United States	Drought impacts on forest insects and diseases	1987-2014
Pureswaran et al. 2018	North America	Forest insects and climate change	2013-2017
Seidl et al. 2017	Global	Forest disturbances under climate change	1990-2017
Jactel et al. 2012	Global	Drought effects on damage by forest insects and pathogens	Unknown

DROUGHT

In a global review of drought and heat-induced tree mortality, the authors concluded that all forested ecosystems were vulnerable, including those not considered water-limited (Allen et al. 2010). In Canada, drought and wildfire are expected to significantly impact the wood supply and productivity of the southern boreal forest (Brecka et al. 2020). Drought affects both the host and the forest pest, with host response and sensitivity varying by tree species (Aubin et al. 2018) and location (Peng et al. 2011), and forest pest by feeding guild. Community associations, including synchrony of natural enemies, are also affected by drought but have been less studied through a climate change lens.

The severity, frequency, and duration of the drought influence the nature of the response for both host and forest pest. While drought alone can cause tree mortality, it can also act as an abiotic stressor predisposing trees to biotic factors and influencing subsequent disturbances. Chronic or repeated low-intensity drought events may have a bigger influence on tree mortality than an extreme drought event, with higher mortality rates reported for trembling aspen and shade tolerant species following sequential low-intensity droughts in Canada's boreal forests (Sánchez-Pinillos et al. 2021). When looking solely at climate suitability, the cumulative effects of all disturbances are forecast to shift southern boreal biomes to more temperate forests during the 21st century (Frelich et al. 2021).

Jactel et al. (2012), Kolb et al. (2016), Pureswaran et al. (2018), and Canelles et al. (2021) provide the most recent reviews of the effects of drought on forest insects and diseases. Except for Jactel et al. (2012), the authors organize their findings by feeding guild or pathogen group, and hence the following statements are grouped as such.

The following are broad findings at the feeding guild or disturbance level from the above-noted systematic reviews:

- Non-linear drought response for bark beetles in western US forests with moderate drought stress negatively affects bark beetle populations, whereas intense drought stress positively affects populations. This is due to reduced host defense mechanisms from water stress and warmer temperatures resulting in increased survival rates and voltinism.
- In eastern US forests, there was no observed evidence of drought influencing southern pine beetle.
- Effects of drought on the defoliator guild are inconclusive in that both positive, e.g., increased nitrogen levels in foliage improve larval performance and negative impacts, e.g., increased secondary metabolites inhibiting larval performance, have been reported.
- Moderate droughts followed by precipitation result in the greatest performance and impacts of sapsuckers, such as hemlock woolly adelgid.
- Forest pathogen response to drought varies with primary pathogens, e.g., rusts, Phytophthora, and leaf and needle pathogens, potentially decreasing due to lower moisture levels, and secondary pathogens that colonize stressed trees, e.g., root diseases, responding favorably, resulting in increasing levels of host mortality.
- Climate e.g., hotter and drier, plays a key role in aspen decline mortality, with forest insects and herbivores playing a secondary role and having more influence on growth reductions than mortality.
- Drought can have both a short-term increase in wildfire activity and a long-term decrease in wildfire activity; the latter due to increased fuels and the former due to changes in forest

characteristics, including species, structure, and density.

- Drier and warmer weather will increase the incidence of short-interval reburning in northwestern boreal forests and amplify the ecological changes these events cause because wildfire activity and post-fire drought increase synergistically. These interacting disturbances will accelerate climate-driven changes in future boreal forest structure and composition (Whitman et al. 2019).
- Host vulnerability to forest pests following drought is inconclusive; some studies suggest reduced vulnerability due to a less favorable environment, while others suggest increased vulnerability due to damage to roots or crown from biotic factors.

Table 2 summarizes specific evidence and projections of drought-mediated abiotic and biotic disturbance interactions.

Table 2.Evidence and projections of drought-mediated abiotic and biotic disturbances by geographic area (limited to Canada and US), forest type, and interaction.

AUTHOR/ TYPE	AREA	FOREST TYPE	INTERACTION	COMMENT
ABIOTIC				
Foster et al. 2022	NWT	Permafrost areas	Fire-permafrost thaw-flooding	Amplified effects - Increased permafrost thawing after significant wildfire years, which follow big drought years. Increased flooding due to permafrost thawing (pers comm. J. Olesinski, November 2022).
Chen et al. 2017	AB	Boreal aspen	Decline	Drought more responsible for decline. Hardwood defoliators (FTC, LAT) both had spatiotemporal variability; future outbreaks could be triggered by earlier springs rather than drought.
Harvey et al. 2021, Smith et al. 2015	Rocky Mountains	Sub-alpine fir	Decline	Cross-scale interactions between site, drought, and decline.

AUTHOR/ TYPE	AREA	FOREST TYPE	INTERACTION	COMMENT
Michaelian et al. 2010	SK and AB	Boreal aspen	Decline	Significant drought mortality (20%) in the study area versus 7% in areas which had no drought.
Woods et al. 2010	BC	All	Decline/dieback	Forecast - Warming climate and drought likely to lead to drought or climate-related decline in several tree species.
Refsland and Cushman 2021	North America	Aspen	Decline	Elevated mortality and reduced growth rates in aspen associated with hotter, drier climate conditions, followed by increased competition and insect herbivory, including FTC and aspen serpentine leafminer. Interactions among spatial and temporal variation in climate and climate and insect herbivory affected tree growth.
Bigler et al. 2017	US Rocky Mountains	High elevation	Mortality	Subalpine-fir and Engelmann spruce were more susceptible to drought-induced mortality than lodgepole pine—trees with poor growth were more likely to die.
Observation	SK	Shelterbelts	Mortality	Mortality/failure in mature white spruce in shelterbelts in the prairie ecozone.
Worrall et al. 2013	North America	Aspen	Frost-pests-decline	Decline-amplified effects from forest tent caterpillar and other secondary pests; frost a factor in decline in some areas.

AUTHOR/ TYPE	AREA	FOREST TYPE	INTERACTION	COMMENT
Boiffin et al. 2013	QC	Black spruce	Fire	Large wildfire years following drought periods led to unfavourable post-fire conditions for black spruce and the probability of regeneration failure and/or shift to jack pine forests.
BIOTIC				
Kolb et al. 2019, Erbilgin et al. 2021	Arizona	Ponderosa pine	Bark beetles	Experimental - Drought alters tree defense mechanisms to bark beetles.
Agne et al. 2018	Pacific North-west (PNW)	Douglas-fir	DFB, DRB	Moisture stress predisposing trees to attack by Douglas-fir beetle and secondary insects that vector DRB.
Maclauchlan and Brooks 2020	BC	High elevation	BBW	Increased incidence causing mortality of sub-alpine fir following drought, often in association with western balsam bark beetle. It can be considered or be treated as either a primary or secondary pest.
Observation	MB, SK, ON	Eastern larch	LBB	Increased incidence of mortality in association with drought.
Preisler et al. 2012	Washington, Oregon	Lodgepole pine	MPB	The effect of drought on tree mortality can vary depending on lag time and outbreak duration.
Hart et al. 2014	Colorado	Spruce	SBB	Drought alters tree defense mechanisms to bark beetles.

AUTHOR/ TYPE	AREA	FOREST TYPE	INTERACTION	COMMENT
Garbutt et al. 2006	Yukon	White spruce	SBB	Outbreak intensified due to drought-stressed trees and warmer summers, which led to one-year cycling.
Observation	SK	Grasslands	WABB	Increased mortality of ash trees in grassland parks.
Howe et al. 2022	BC	Sub-alpine fir	WBBB	Elevational and latitudinal range expansion - Increase in growing season, degree day accumulation, and drought stress.
Howe et al. 2022	BC	High elevation	WBB	Drought stress influences western balsam bark beetle outbreaks.
Koontz et al. 2021	California	Ponderosa pine	WPB	Cross-scale interactions between forest and tree attributes, drought, and mortality rates.
Robbins et al. 2022	California	Ponderosa pine	WPB	30% increase in host mortality compared to increasing temperatures alone due to WPB assiated with drought.
Observation	SK	Cypress Hills	IPS, DSA	Pine engraver beetle attacked trees predisposed by Armillaria and Atropellis stem canker.
Woods et al. 2010	BC	Lodgepole pine	Secondary insects	Extensive mortality of young lodgepole pine plantations due to drought and secondary insects.

AUTHOR/ TYPE	AREA	FOREST TYPE	INTERACTION	COMMENT
Moise et al. 2019	NB	Balsam fir	ESBW	Experimental - Study found that stand density had more influence than drought on spruce budworm performance under outbreak conditions.
Balducci et al. 2021	Eastern boreal	Balsam fir, black spruce	ESBW	Defoliation preceding drought increases tree resistance to drought due to fewer photosynthetic and transpiration surfaces.
Itter et al. 2019	Eastern and western boreal	East – coniferous forests West – mixed wood	East - ESBW West - FTC	Insect defoliation may offset the impacts of water deficit on boreal tree growth by reducing transpirational water demand.
Observation	NWT	Aspen	FTC	Two major FTC outbreaks followed extreme drought years.
Observation	QC	Maple	FTC	Interaction between mortality, defoliation, and drought stress.
Cooke and Roland, 2007	ON	Boreal	FTC	Drought had no discernible impact on tree growth, while FTC did.
Michaelian et al. (in press)	Canada	Aspen	FTC	When drought and defoliation overlap, there is amplification of disturbances.

AUTHOR/ TYPE	AREA	FOREST TYPE	INTERACTION	COMMENT
Volney and Fleming 2000	Ontario	Jackpine	JPBW	Drought 7–4 years before an outbreak was strongly associated with the onset of Jackpine budworm defoliation in Canada. Drought triggers flower production, which influences JPBW outbreaks.
Woods et al. 2010	BC	Douglas-fir	WSBW-DFB	Drought and/or predisposition by western spruce budworm defoliation factors in Douglas-fir beetle outbreaks.
Observation	AB, SK	Jack pine	DM	Mortality of dwarf mistletoe infected jack pine – could increase fire risk.
Kolb et al. 2016	Western US	Host species	DM	Mistletoe-infected trees predisposed to bark beetle and wood borers during drought periods.
Cruickshank and Filipescu 2017	BC	Douglas-fir	DRA	Experimental - Changes to wood properties following DRA infection increase drought tolerance. More frequent droughts may select for trees with higher resistance to DRA.
Hennon et al. 2020	Canada/US	Western white pine	Western white pine pole blight	Drought-site interactions causing decline of western white pine.

DFB=Douglas-fir beetle; BBW = balsam bark weevil; LBB=larch beetle; MPB=mountain pine beetle; SBB=spruce beetle; WABB = western ash bark beetle; WBBB=western balsam bark beetle; WPB=western pine beetle; IPS=pine engraver beetle; ESBW=eastern spruce budworm; FTC=forest tent caterpillar; JPBW=jack pine budworm; LAT=large aspen tortrix; WSBW=western spruce budworm, DM=dwarf mistletoes, DRA=Armillaria root disease, DRB=Blackstain root disease; DSA=Atropellis stem canker.
Observations are from provincial or territorial forest pest managers.

SEVERE STORMS

Severe storms, such as rain, wind, snow and ice, and hail, have the potential to cause significant damage to forested landscapes. Depending upon the severity of the storms, they could also be classified as extreme weather events, discussed in the next section. Severe storm damage can occur at the tree, stand or landscape level with varying spatial patterns depending upon storm intensities. In addition, storm legacies could increase the risk of other disturbances such as primary and secondary beetles, pathogens, and wildfires. Although limited, research on severe storms generally focuses on the storm's legacy and resultant disturbance interactions.

- Severe weather in NWT during the 2021 heat dome was responsible for intense thunderstorms and downbursts, causing wind damage to over 20,000 hectares, with satellite imagery review revealing continuous visible tree damage for more than 60 km and up to 9 km wide.
- Severe storms in the boreal forest are unpredictable spatially and temporally, with relatively minor impacts at a landscape level (Bouchard et al. 2009).
- Increased frequency of windstorms combined with fire will favor succession of deciduous species in the southern boreal forests of Minnesota (Anoszko et al. 2022)
- Cumulative winter storm damage, e.g., downed, and damaged trees, precipitated spruce beetle outbreak in NE BC.
- Hurricane Juan provided for population build-up and expansion of an invasive pest, brown spruce longhorn beetle, into native forests.
- Bark beetles killed the remaining healthy trees following the 2012 winter storm in MB.
- Severe storms often include lightning, which could lead to wildfires.
- Findings from 1998 ice storm studies (Ryall and Smith 2001, Ryall and Smith 2005, Ryall et al. 2006, Deschênes et al. 2019, Lloren et al. 2020):
    - Ice storm damage varied by stand characteristics, including tree species for both conifer and deciduous trees. In red pine plantations, damage was greatest in poorly managed, overstocked stands.
    - In deciduous stands, resilience to ice storms increased the further away damage was to stand edge (QC), while the opposite was true for conifer stands (ON).
    - Trees in the interior of red pine plantations were three to five times more likely to be damaged (ON).
    - The most damaged portions of deciduous stands are less resilient and more likely to shift community composition.
    - There was a landscape context in that the short-term effects of storm damage in deciduous stands were magnified where there was less forest on the surrounding landscape and farther from the forest edge.
    - There were no observed interactions between the degree of ice storm damage and beech scale but suspected interaction with beech bark disease.
    - Pine engraver beetle and white-spotted sawyer beetle preferentially attacked trees damaged by the ice storm and did not colonize healthy trees in Ontario red pine plantations. Populations pulsed in relationship to the availability of stressed and damaged trees.

WARMING CLIMATE AND EXTREME WEATHER

Forest insects are particularly temperature-sensitive and influenced by environmental conditions. As such, most of the responses of forest insects to warming climate are expected to be positive, with shorter generation time, higher fecundity and survival, leading to range expansion and outbreaks (Jactel 2019). Currano et al. (2008) noted that increased CO2 and foliar nitrogen could also lead to increased insect feeding and damage, as evidenced in a previous global warming event (Paleocene-Eocene Thermal Maximum (PETM)), and reduced defence mechanisms in broadleaves due to thinner leaves (Li et al. 2016). Similarly, De Grandpré et al. (2022) found increased host nutritional value from spruce budworm frass and litter deposition and posit that such conditions could lead to self-amplifying defoliator populations and the ability to drive broad-scale outbreaks. Lower parasitism levels could also contribute to more frequent outbreaks (Pureswaran et al. 2018). Warmer weather, however, could lead to phenological mismatching and modifications to forest insect thermal regimes such that seasonality could be disrupted.

Forest pathogen response to warming climate will depend upon moisture levels; hence the ‘warmer and wetter’ or ‘warmer and drier’ approach adopted by the USDA to describe climate-mediated changes to forest diseases. Under a climate change scenario of warmer and drier future conditions, Sturrock et al. (2011) predicted that diseases caused by pathogens directly affected by climate (e.g., Dothistroma needle blight) will have a reduced or unchanged impact on their hosts but an increased impact under a scenario of warmer and wetter conditions. For diseases caused by pathogens indirectly affected by climate (e.g., armillaria root disease) and for decline diseases in general, Sturrock et al. (2011) predicted an increased impact on hosts under a climate-change scenario of warmer and drier future conditions and a reduced or unchanged impact under warmer and wetter future conditions. Overall, forest pathogen damage is expected to increase based on observed and predicted forest pathogen interactions with changes in temperature and precipitation (Teshome et al. 2020).

In a recent review of forest disturbance interactions, Seidl et al. (2017) found that temperature-related variables were the most prominent climatic drivers reported in the forest disturbance literature (42.0%), and the effects on the disturbance regime were highest in the boreal biome. Range expansion of multiple biotic factors in North America have occurred due to temperature-mediated phenological changes to host or forest pest. Better winter survival and development rates, or increased voltinism, have already been observed for eastern spruce budworm, southern pine beetle, mountain pine beetle, hemlock woolly adelgid, and spongy moth (Pureswaran et al. 2018). Examples of failed range expansion include that of eastern hemlock looper in Cote Nord, Québec, which was abruptly halted by two extreme cold waves in one winter (Delisle et al. 2019). Of interest is that the warming pattern, which preceded dispersal, was like that which occurred for the Autumnal moth, Epirrita autumnata, in the birch forests of Fenno-Scandia, where it was successful in expanding its range (Delisle et al. 2019).

Extreme weather events are those breaching normal thresholds and can result from temperature, precipitation, or wind. Such events will have variable effects on forest pests and their hosts, depending on their type, severity, and spatiotemporal characteristics. Extreme temperatures have the potential to cause extensive damage due to phenological disturbances and acute tree stress and include both extreme heat, e.g., heat domes, and extreme cold, e.g., polar vortexes. Acute stress causes a resource pulse, while chronic stress leads to a press or resource degradation. Multiple biotic or abiotic stressors can increase vulnerability to subsequent stressors and thus change the dynamics of an ecosystem (Nolet and Kneeshaw, 2018). In terms of phenological disturbances, extensive areas could be affected since persistent mid-latitude ridges in the jet stream, that lead to long periods of anomalously warm weather, are becoming more common as the Arctic warms and can occur at subcontinental spatial extents (Frelich et al. 2021). Acute stress resulting from one or more extreme events, or co-occurring biotic and abiotic events, could also amplify pest-related tree mortality (De Grandpré et al. 2019).

Table 3 summarizes both evidence and projections of warming climate or extreme weather-mediated abiotic and biotic disturbance interactions.

Table 3. Evidence and projections of abiotic and biotic disturbances resulting from warming climate or extreme weather by geographic area (limited to Canada and US), forest type, and interaction.

AUTHOR/ TYPE	AREA	FOREST/HOST	INTERACTION	COMMENT
Foster et al. 2022	NWT	Arctic boreal	All	Amplified effects of all disturbances with potential for persistent shifts in vegetation composition and increased colonization and spread of non-native and invasive plant species.
ABIOTIC				
Girardin et al. 2022	Canada	All species	Cold season freeze	Changes in cold season freeze frequency a benefit to pine species.
Observation	ON	Jack pine	Extreme cold	Cold snap following bud burst led to dieback and some mortality in jack pine plantations over 1M ha.
Observation	ON	Trembling aspen	Decline	Aspen decline symptoms over 15M ha due to lack of snow.

AUTHOR/ TYPE	AREA	FOREST/HOST	INTERACTION	COMMENT
Comeau et al., 2019; 2021; Comeau and Daniels, 2022	Haida Gwaii	Yellow cedar	Warmer winters with low precipitation	Freezing damage to roots due to warm winter temperatures and low winter precipitation led to decline; exacerbated by Pacific Decadal Oscillation.
Hennon et al. 2012	Alaska	Yellow cedar	Warmer winters, lower snowpack, and cold springs	More frequent winter warming favored limited cold hardening and lower snowpack that reduced the protection of roots by snow.
Nolet and Kneeshaw (2018)	QC	Maple, beech	Freeze-thaw, drought, forest tent caterpillar	Freeze-thaw event followed by drought and FTC defoliation over a 3-year period negatively affected hard maple recovery with much lesser impact on beech.
Observation	SK	Conifers	High water table and Monochamus	Pine stands on the edge of harvest block stressed by high water table subsequently killed by Monochamus.
Observation	NWT	Trembling aspen	Heat dome – severe storms – windthrow	Extreme temperatures led to severe storms, which resulted in windthrow of 20,000 ha of aspen.
Observation	AB	Boreal	Heat dome	Defoliator populations crashed the year following the heat dome.
Observation	NW ON	Jack pine	Extreme weather	Extreme cold after bud flush caused dieback and some morality to jack pine plantations over 1M ha.
Woods et al. 2010	BC	Engelmann spruce	Severe weather - SBB	Projected - Increased likelihood of SB outbreaks due to windthrow from more frequent severe weather.

AUTHOR/ TYPE	AREA	FOREST/HOST	INTERACTION	COMMENT
Frelich et al. 2021	Canada/ US	Southern boreal	Wildfire	Projected - Warmer climate will increase days with extreme convective windstorms, which will dry fuels leading to increased potential for wildfire ignitions.
BIOTIC				
Chandler et al. 2021	NE US	Eastern hemlock	HWA	Decline in HWA density in 2019 occurred as a result of increased mortality that indirectly resulted from abnormally high rainfall during the summer and autumn of 2018. It is suspected that an increase in native fungal entomopathogens associated with wetter conditions was responsible for mortality.
Hubermann et al. 2022	NWT	Jack pine	MPB	Range expansion – baited tree attacked in 2012 near AB border.
Alberta Forest Health and Adaptation, 2019	AB	Lodgepole pine	MPB	Extreme cold, e.g., polar vortex in February 2019, led to significant overwinter mortality rates of mountain pine beetle, as projected by MacQuarrie et al. 2019.
Aukema et al. 2008	BC	Lodgepole pine	MPB	Warmer winter and summer temperatures explained outbreak probabilities over a 15-year outbreak.
Preisler et al. 2012	WA, OR	Lodgepole pine	MPB	Warmer winter temperatures and drought conditions influenced the size of an outbreak, while precipitation levels the year prior had a positive effect, possibly due to brood size. Two-year cumulative precipitation had a negative effect.

AUTHOR/ TYPE	AREA	FOREST/HOST	INTERACTION	COMMENT
Bleiker 2019	Canada	Pine spp	MPB	Climate facilitated eastern expansion into novel pine forests.
Bentz et al. 2010; 2014;2016	US, BC	Spruce, lodgepole, whitebark pine	SBB and MPB	Range expansion - Improved climate suitability in higher latitudes and elevations.
Observation	BC	Spruce	SBB	Warmer temperatures have led to increased voltinism and influenced the current outbreak in NE BC.
Robbins et al. 2022	CA	Ponderosa pine	WPB	Warmer temperatures led to increased WPB voltinism and increased host mortality associated with drought.
Dooley and Six 2015		Whitebark pine	WPBR-MPB	Trees severely infected with WPBR had lower attack rates, possibly due to lower defences and fewer adults required to attack. However, emergence rates and brood size were greater than on uninfected trees or less severely infected trees.
Maclauchlan et al. 2023	BC	Sub-alpine fir	WBBB	Evidence that WBBB may be able to shorten development time to one year.
Howe et al. 2022	BC	Sub-alpine fir	WBBB	Elevational and latitudinal range expansion - Increase in growing season, degree day accumulation, and drought stress.
Lalande et al. 2020	CO	Sub-alpine fir	DRA-DRB-WBBB -density	Complex of interacting pests, climate and stand density factors in sub-alpine fir decline.

AUTHOR/ TYPE	AREA	FOREST/HOST	INTERACTION	COMMENT
Pureswaran et al. 2015	QC	Balsam fir/spruce	ESBW	Range expansion – defoliation north of historical distribution in Québec.
Hubermann et al. 2022	NWT	Spruce	ESBW	Range expansion into Mackenzie Delta – most northerly record in Canada. More frequent outbreaks.
		Trees and shrubs	Northern tent caterpillar	Range expansion – previous northern extent Norman Wells, 2012 in Taiga Plains in Inuvik.
Ward et al. 2020	BC, AB	Alpine larch	LC	Projected - Range expansion – warming climate could expand the range into higher elevation alpine larch.
Bellemin-Noel et al. 2021; Pureswaran et al. 2018 ;2019 Portalier et al. 2022	Boreal	Black spruce	ESBW	Potential for northern range expansion due to improved synchrony with black spruce phenology and increased severity in mixed balsam fir and black spruce stands in historical range.
Regnière et al. 2012; Portalier et al. 2022	Boreal	Balsam fir	ESBW	Projected contraction at southern limit of range due to higher overwinter mortality rates or host-pest asynchrony.
Zhang et al. 2014	Boreal	Balsam fir/spruce	ESBW	Projected - Warming climate will decrease ESBW-induced tree mortality/outbreak severity. Mortality is linked with wetter years.
Observation	NB	Boreal	ESBW	Warm spring led to populations collapsing.

AUTHOR/ TYPE	AREA	FOREST/HOST	INTERACTION	COMMENT
Tai and Carroll 2022	BC	Douglas-fir	WSBW	Projected - Range expansion and contraction – Optimal synchrony at higher latitudes and elevation due to warming climate and diverging of synchrony at lower latitudes and elevations.
Observation	BC	Western hemlock	WHL	Heat dome caused western hemlock looper population to collapse.
Observation	NWT	Jack pine	DRA	First record in NWT in 2019.
Dudney et al. 2021	Sierra Nevada	Whitebark pine	WPBR	Elevational expansion due to extended growing season; limited by the presence of alternate host. More arid conditions at lower elevations will cause host contraction and maybe range shift.
Pedlar et al. 2020	Eastern Canada	Oaks	Oak wilt	Projected - Models indicate suitable climatic conditions in southern Ontario for pathogen and two insect vectors, with climatically suitability expanding in the next two decades.
Hennon et al. 2020	Canada/ US	Douglas-fir	SNC	Projected - Increased mean winter temperatures driving outbreaks.
Hennon et al. 2021	Canada/ US	Lodgepole pine	Pine stem rusts	Projected - Increased overnight temperatures leading to more frequent infection years.
Observation	SK	Conifers	Needle rusts	Proliferation of needles rusts during extreme wet periods.

HWA=hemlock woolly adelgid; DFB=Douglas-fir beetle; MPB=mountain pine beetle; SBB=spruce beetle; WBBB=western balsam bark beetle;; ESBW=eastern spruce budworm; LC=larch casebearer; WHL=western hemlock looper; WSBW=western spruce budworm, DRA=Armillaria root disease, DRB=Blackstain root disease; WPBR=White pine blister rust. Observations are from provincial or territorial forest pest managers.

WILDFIRE

A recent review of wildfire and disturbance interactions suggests that forest disturbances do not increase probability of wildfire (as fire weather conditions are often a major overriding driver) but can affect ignition potential and fire behavior (Kane et al. 2017). Wildfire as a disturbance was not explicitly identified as a knowledge priority by the Task Team because work is currently being undertaken in other Working Groups of Canadian Council of Forest Ministers. As such, the following does not summarize all wildfire-forest pest interactions, only those brought forward in the workshop as they apply to bark beetles, eastern spruce budworm (ESBW) and western spruce budworm (WSBW).

- Current evidence suggests that bark beetle outbreaks have minimal effect on fire probability and severity but can exacerbate fire behavior, particularly during the ‘red’ needle phase. This is partly because extreme weather and topography can override bark beetle effects. Modeling fire behavior is challenged by the heterogeneous nature of bark beetle mortality on the landscape (Fettig et al. 2022, Wayman and Safford, 2021).
- The direct effects of wildfire on bark beetles, including prescribed fires, vary by levels of tree injury and local bark beetle populations. In the short-term, there is a pulse of activity as bark beetles attack injured trees (Fettig et al., 2022).
- ESBW alters surface and ladder fuels, fuel connectivity and ignition potential.
    - Two separate 300-year landscape simulation models found the following:
    - ESBW reduces long-term wildfire risk by acting as a natural thinning agent that periodically removes ladder fuels in mixed forests in Minnesota (Sturtevant et al. 2012);
    - ESBW defoliation had no effect on fire size while logging increased fire size through conversion to early seral flammable conifer hosts (James et al. 2011); and
    - Wildfire ignition risk is influenced by season and timeline of eastern spruce budworm outbreaks; spring season and lagged defoliation (8-10 years) increased risk, whereas summer and current defoliation decreased risk (James et al. 2017, Stocks, 1987).
- In an ESBW vegetation simulation, Sato et al. (2022 under review) reported a pulse of increased fuel and fire size that depletes after an outbreak, such that the ESBW-driven enhancement is minor over longer timescales.
- Fire mitigation practices have been found to increase the impacts of defoliators due to an increase in shade intolerant host tree species (Fettig et al. 2022).
- WSBW outbreaks in the Pacific Northwest were found to decrease fire risk with no influence on burn severity (Meigs et al. 2016).

KNOWLEDGE GAPS

Workshop discussions did not include research needs; hence, the following section summarizes knowledge gaps identified in peer-reviewed articles for each of the abiotic stressors, drought, severe storms, and warming climate and extreme weather.

DROUGHT

Based on the evidence provided in Table 2, most empirical or experimental studies address the linked interactions between drought and a biotic disturbance, primarily bark beetles, with very few studies on compound, cross-scale, or cascading interactions. Forest diseases are not well represented, with only a few studies on white pine blister rust, western white pine pole blight, dwarf mistletoes, and Armillaria and Blackstain root disease. Most studies on forest diseases were forecasting in nature. Some empirical studies noted the amplification of drought-related mortality, including trembling aspen defoliated by forest tent caterpillar or serpentine leafminer and fire-permafrost thaw-flooding complex in permafrost areas.

Several broad themes emerged when reviewing drought-related knowledge gaps or research needs identified in the literature. At a host level, these include physiological thresholds and their effect on trees, tree mortality mechanisms and regional mortality patterns. At a pest-level, these include the response of forest pests to drought-induced water stress on trees, and at a system-level top-down regulation of forest pests by parasitoid, predator, or antagonist species, feedback mechanisms and impacts, and the effects on forest pest regimes and concurrent climate or disturbance drivers. Specific research needs included the following:

- Yellow cedar decline - Further research is required on fine-scale drivers of decline (Comeau and Daniels 2022).
- Aspen decline – Need to quantify the relative importance of multiple factors in driving the dynamics of tree populations and assess whether interactions among multiple drivers play an important role in predicting forest dynamics (Refsland and Cushman 2021).

Hemlock woolly adelgid research identified for Unites States includes examining the direct effects of drought on hemlock survival during active adelgid infestations (Kolb et al. 2016)—uncertainty as to whether this is a concern for Canadian forests.

- Bark beetles - Future research identified for the United States include: (1) the role of temperature in drought-induced outbreaks of bark beetles; (2) the identification of bark beetle species that are capable of self-perpetuating outbreaks after drought subsides; (3) the level of drought-associated tree mortality that would occur without bark beetle infestation; (4) the effectiveness of manipulating forest composition and structure to reduce drought stress and bark beetle infestations; (5) the level of drought intensity in pine forests of the eastern U.S. that would shift the role of drought in southern pine beetle outbreaks from a negative to a positive driver; (6) integration of mechanistically-based models of bark beetle response to drought and temperature into models that predict climate impacts on forest vegetation (Kolb et al. 2016).
- Fungal pathogens – Need for empirical data and predictive tools on how changes in drought frequency and intensity will alter fungal pathogens (Kolb et al. 2016).
- Dwarf mistletoes - Research that compares the impacts of intense drought between mistletoes and their host trees (Kolb et al. 2016).
- Armillaria root disease - Research on how biotic disease resistance or tolerance to Armillaria root disease is related to drought tolerance or timber product quality (Cruikshank and Filipescu, 2017).
- General - Cross-scale effects of drought at stand-to-landscape scales (Clark et al. 2016).

SEVERE STORMS

There has been minimal work on severe storms, with a few studies concerning the 1998 ice storm in eastern Canada. Severe storm legacies, however, have the potential to trigger other disturbances, particularly forest pests which attack stressed or downed trees or increase the risk of wildfire. Of interest, the empirical studies on ice and snow damage were one of the few, including forest intactness, edge effect or fragmentation as a variable influencing forest damage.

Vogt (2020) identified the following knowledge gaps as they apply to weather-related disturbances in the southern United States.

- What are the cascading effects of compounded disturbances (based on their severity levels) on the abiotic and biotic components in the ecosystem?
- How do populations and communities of woodboring insects and other late insect colonizers of trees change over time?
- Does the level of disturbance result in different rates of residual tree mortality and associated different responses by insects and fungal pathogens?
- Would we expect enhanced activity of invasive non-native species in weather-disturbed areas? What forest biomes are most at risk of invasion by non-native species following severe storms?
- Do the timing and type of post-weather disturbance management activities affect biotic communities and regeneration dynamics?

WARMING CLIMATE AND EXTREME WEATHER

Studies on biotic interactions with warming climate and extreme weather (Table 3) had similarities to those of drought studies (Table 2); most dealt with linked binary interactions, where the emphasis was on bark beetles, and very few studies on forest diseases. Range expansion was noted for most bark beetle species, both in latitude and elevation, because of warming climate and changes in development rates. Only two studies examined the cascading effects of multiple forest pests, both in high elevation ecosystems.

Overall knowledge gaps are like those identified for drought, a better understanding of disturbance interactions and their feedbacks and direct and indirect effects of warming climate and extreme weather on pests, hosts, and natural enemies. The following are knowledge gaps identified in some of the empirical studies referenced in Table 3.

- Arctic boreal zone – Better understanding of insect range shifts, cascading effects of rain on snow, drivers of drought exposure and susceptibility (Foster et al. 2022).
- Forest diseases - Identifying how host infection surfaces (i.e., roots, leaves, stem tissue) respond to warming and water deficit across aridity gradients (Dudney et al. 2021).
- Forest diseases – Research is needed to determine specific temperature and precipitation influences and physiological limits of the host and pathogen (Hennon et al. 2021).
- Western balsam bark beetle - Future work should identify specific supercooling points, the relationship between temperature and development rate, and how relatively high within-stand variability in age and size class of subalpine fir affects the irruptive dynamics (Howe et al. 2022).
- Eastern spruce budworm - Long-term studies over several generations to determine whether the peak emergence dates of overwintering larvae might shift in adaptation to the budburst phenology of black spruce (Pureswaran et al. 2018;2019).

- General - Characterization of resistance mechanisms in genetic survivors of disturbances (Six et al. 2018).
- General - Characterizing thresholds for systems beyond which changes are irreversible will be an important component of forest management in a changing climate (Bentz et al. 2010).
- General – Better understand the effects of elevated atmospheric CO2 on insects and diseases (Agne et al. 2018).
- General - There is an urgent need for ensemble-based simulations to reduce predictions' uncertainties and provide a solid basis for guiding forest management strategies (Chaste et al. 2019).

DISTURBANCE IMPACTS

Workshop discussion on disturbance impacts determined that a good first step was assessing the relevancy of existing impacts identified for other major pests in recent pest risk analyses. As such, impacts or benefits are not described in this report but are found in existing pest risk assessments (mountain pine beetle) or pest risk analyses (emerald ash borer, brown spruce long horn beetle) (https://www.ccfm.org/knowledge-centre/). A pest risk analysis for eastern spruce budworm by Natural Resources Canada, Canadian Forest Service, is forthcoming. The limitation of this approach is the lack of forest pathogen impact information.

CONCEPTUAL ADVANCES AND DISTURBANCE INTERACTIONS MODELING

The ability to inform adaptation relies upon empirical or experimental evidence combined with advanced model frameworks capable of simulating complex disturbance interactions across multiple scales. The following section briefly summarizes the theory and practice of disturbance interactions modeling as well as some of the challenges and prospects of such endeavours.

THEORY AND PRACTICE

Traditionally abiotic and biotic disturbances have been described at the landscape level in terms of their severity, extent, and frequency. However, different processes operating at different scales can work synergistically to amplify disturbances across scales (Sturtevant and Fortin, 2021). Cross-scale interactions alter the pattern-process relationships across scales such that fine-scale processes can influence a broad spatial extent or a long time period, or broad-scale drivers can interact with fine-scale processes to determine system dynamics (Peters et al. 2007).

Thus, conceptual advances in disturbance interactions investigation acknowledge that disturbance regimes result from processes across temporal and spatial scales, resulting in nonlinear cross-scale dynamics, inherent uncertainty, and are influenced by anthropogenic disturbances. The ideal conceptual model in disturbance interactions investigation includes:
1) disentangling disturbance interaction mechanisms and processes,
2) deterministic and stochastic elements of anthropogenic disturbance, and
3) uncertainty due to climate change across multiple scales (Sturtevant and Fortin, 2021).

Disturbance interactions are informed by empirical or experimental studies, which seek to better understand forest ecosystem dynamics that emerge from the interactions of multiple disturbances, as well as biophysical and demographic drivers within forested landscapes (Sturtevant and Fortin, 2021). Many conceptual frameworks or models that address disturbance interactions exist (Anderegg et al. 2015, Cooke and Carroll 2017, Harmon and Bell 2020, Hennon et al. 2020, Lewis and Lindgren 2000, Micheletti et al. 2021, Raffa et al. 2008, Wang et al. 2012), and range from those examining one forest pest to those studying forest pest systems.

CHALLENGES AND PROSPECTS

Workshop discussions acknowledged the complexities of disturbance interactions, including the potential for non-linear dynamics, stochastic events, synergistic effects, and reciprocal feedbacks. However, it was also recognized that existing models lack the ability to inform forest management decisions as they apply to disturbance interactions and their impacts. A recent review by Sturtevant and Fortin (2021) found that, although the emerging trend is towards more explicit modeling of disturbance processes and their emergent effects on system dynamics and landscape structure, statistically-based static models of disturbance regimes, e.g., those that focus on system response rather than feedback to the system, are still commonly applied. Disturbance interaction modeling is therefore limited by a lack of empirical study that includes non-linear threshold behavior, cross-scaled interactions, and a means to reduce the uncertainty.

To address this knowledge gap, Sturtevant and Fortin (2021) suggest that 1) empirical disturbance interaction studies should define the nature and form of interactions explicitly, and 2) models capture the direction and magnitude of interaction processes, including those that transcend spatiotemporal scales. Raffa et al. (2008) suggested that factors to consider in a cross-scale analysis of forest pests include: plant resistance and tolerance to the guild’s form of feeding; the plant herbivore response profile to environmental stress; the levels and manners in which natural enemies and symbionts exert feedback; and the effects of weather on both plant suitability and insect phenology.

Experimentation, conceptual advances, and empirical approaches are means to address areas of uncertainty, particularly as it applies to thresholds. In this manner, ecosystem response can be captured via controlled studies that focus on disturbance interaction mechanisms, which can then serve as a basis for model parameter estimation. Identifying sources of uncertainty as either being within or external to models (Srivastava et al. 2021) or using consensus models could also help reduce uncertainty (Boulanger et al. 2022). Srivastava et al. (2021) introduced the concept of ‘wildcards’ to address uncertainty. Wildcards are defined as biological or bioclimatic processes with a high degree of uncertainty and a large impact on our ability to address the biotic consequences of climate change. In essence, these are like ecological surprises but extend to any biological level, ranging from an organism to an ecosystem, encompassing events and processes and explicitly invoking the dual conditions of high uncertainty and high impact on the outcome.

While the workshop touched on several models, SpaDES[1], SELES[1], and LANDIS[1], much of the discussion revolved around PERFICT[2] following the presentation by Dr. Eliot McIntire on the topic. PERFICT, a re-imagined foundation for predictive

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[1] SpaDES: Spatial Discrete Event Simulation; SELES: Spatially Explicit Landscape Event Simulator, LANDIS: Forest Landscape Disturbance and Succession Model. [2] PERFICT based on seven principles applied to ecological modeling: make frequent Predictions, Evaluate models, make models Reusable, Freely accessible and Interoperable, built within Continuous workflows that are routinely Tested (PERFICT).

ecology, was identified as a tool with the potential to address some of the noted challenges. PERFICT is based on the premise that ecology needs a framework that enables the transferability of each component of the modelling workflow and makes cross-study evaluations rapid and commonplace, and nimble enough to adapt to the real-time engagement needs of stakeholders (McIntire et al. 2022). PERFICT represents seven principles that facilitate cross-study model comparison, hypothesis testing, and ensemble modelling while promoting utility, flexibility, adaptability, and scientific longevity (McIntire et al. 2022).

At the core of the PERFICT approach are modules distinctive to a process but generic to other systems or questions. For example, one module could be based on information from one peer-reviewed paper, while another could be based on a different study. To determine which dataset is relevant or important, datasets are processed through a validation chain. The nimbleness of reusable and interoperable modules allows science to respond rapidly to changing policy demands (McIntire et al. 2022). The benefits are many, including examining uncertainty by comparing outputs of various models and potentially identifying opportunities for consensus models, which may further reduce uncertainty (Boulanger et al. 2022).

DISCUSSION

The results of this knowledge synthesis are promising in terms of conceptual advances in disturbance interaction modeling and the existence of a platform, e.g., PERFICT, which will facilitate easier model evaluation, comparison, and improvement. This will not only help in reducing uncertainty but will also allow science to respond quickly and adapt to changing policy demands. However, critical knowledge gaps exist, including physiological effects of climate change on trees and pests, particularly forest pathogens and minor pests, and spatiotemporal disturbance interaction dynamics, which have the potential to cause non-linear changes to ecosystem structure and function. This calls for in depth, holistic research on key biological models, where empirical data on species interactions under various climatic conditions would feed process-based models (Jactel et al. 2019). Additional research needs also exist with regard to the effects of forest fragmentation on forest disturbances and the levels of intactness required to ensure resiliency, as evidenced by the lack of evidence in this regard. New technologies and platforms, such as data obtained using satellites or Laser imaging, Detection, and Ranging (LiDAR) technology, represent significant opportunities to better parameterize spatially explicit simulation models (Canelles et al. 2021).

In the absence of system-specific adaptation measures, management could be informed by existing projections and applied to a portion of the land base. This may have particularly relevancy to the southern boreal forests, which are forecasted to shift from conifer-dominated to more temperate hardwood-dominated forests (Chaste et al. 2019, Frelich et al. 2021). Regarding mountain pine beetle adaptation Sambaraju et al. (2019) suggest that forest managers use projections of extreme weather conditions (e.g., prolonged droughts) as guides to make reforestation decisions or plant warm-adapted trees in new environments via assisted migration. Regardless of adaptation measures informed by modeling, genetic survivors of disturbance will be one of our best informants on climate change adaptation from which we should seek to better understand their success.

Extreme events and climate variability could affect ecosystems to a greater degree than mean trends in climate. Gradual species response to directional climate warming is likely to be overshadowed by abrupt transitions triggered by weather-disturbance interactions (Boiffin et al. 2013). Multiple stressors or compound disturbances, e.g., extreme events followed by biotic disturbances or vice versus, will influence ecosystem dynamics such that resiliency will be challenged, potentially resulting in accelerated climate misadaptation (Nolet and Kneeshaw, 2018). Ecological surprises will likely have the greatest impact and represent those events which are the most challenging for adaptation as they are indeed surprises, breaching unforeseen thresholds. Even today, known major pests are behaving outside predicted or known patterns. Ecological surprises may include secondary pests or those currently considered innocuous. Thus, researchers and forest managers may benefit from acknowledging that the long-term effect of current forest dynamics and management policies will extend long into the future. On the local scale, managers should pay particular attention to current forest pests and those that may have future impacts (Canelles et al. 2021). Now more than ever, collaborative efforts amongst all forest management aspects, e.g., forest health, forest research, growth and yield, and wildfire management, are necessary to ensure that adaptation measures encompass the complexities of disturbance interactions anticipated in the future.

SUMMARY

Disturbance interactions have the potential to cause large, nonlinear, or unexpected changes in ecosystem structure and function. Finding generality across these complex events is an important first step in predicting their occurrence and understanding their significance (Buma, 2015). Given the knowledge gaps and time scale required to fill those gaps, multiple approaches to addressing these gaps are necessary. The first could involve developing a collaborative and coordinated research response which would review, prioritize, and address knowledge gaps identified in this report. The second could include assessing the portability of other well-studied systems and applying them to similar taxa or feeding guilds. Platforms such as PERFICT could facilitate the timely completion of the latter. Sturtevant and Fortin (2021) concluded that conceptual understanding, empirical study, and simulation modeling should continually reinforce one another if we are to unravel the complexities of disturbance interactions in time and space. Clarity in concepts (knowledge), an empirical foundation (data and analysis), and model designs (synthesis and software) will ultimately enhance understanding of complex systems, but the choice of which processes to model explicitly and which processes to aggregate remains the fundamental challenge of our time.

PROPOSED NEXT STEPS FOR 2023/2024

The 2022 knowledge synthesis workshops provided a snapshot of the state of forest disturbance interaction knowledge and modeling tools available to assess and forecast these interactions. The FPWG proposes a follow-up exercise in 2023-24 that involves exchanges between forest health and forest management experts around knowledge gaps, uncertainties, and information needs which could be tailored for specific regions of Canada. The overall objective would be to support regional dialogues that facilitate exchanges between scientific experts and practitioners about the implications of disturbance interactions on future forest resilience and management planning and steps to prioritize and address key knowledge gaps and uncertainties.

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APPENDIX - GLOSSARY OF DISTURBANCE INTERACTIONS

From: Burton, P. J., Jentsch, A., & Walker, L. R. (2020). The ecology of disturbance interactions. Bioscience, 70(10), 854-870. https://doi.org/10.1093/biosci/biaa088, unless otherwise noted.

Biological Legacy	Biotic characteristic (biomass, structure, or function) or imprint of an ecosystem that remains after a disturbance
Cascade	A sequence of more than two disturbances, each triggered by the preceding one; can be a single pathway (chain) or a set of interacting pathways (network)
Chain	See Cascade
Compound Disturbances	Multiple disturbance events that occur without sufficient time for ecosystem recovery between them
Cumulative Effects	The net impact of multiple stressors, disturbances, or degradation, which may be additive or synergistic
Disturbance Event	Relatively abrupt change in resource availability or ecological structure or function, often associated with the conversion of live to dead biomass
Disturbance Agent	Type of disturbance, such as volcanic eruption, landslide, flood, fire, herbivory, or cultivation
Disturbance Regime	The combination of disturbance agents and disturbance attributes that characterize a particular landscape or region
Ecosystem Recovery	Process of returning to a predisturbance or alternative condition regarding biomass, structure, function or species composition; see Succession
Extreme Events	Severe and statistically infrequent disturbances, leaving sparse biological legacies; see Biological Legacy
Interaction	The alteration of one disturbance (e.g., probability, extent, or severity) by a previous or co-occurring disturbance
Lag	Temporal delay between two sequential events, or between a trigger and a response
Link	When one disturbance is a causal factor in the occurrence or attributes of a subsequent disturbance
Loop	A sequence of linked disturbances that returns an ecosystem to a previous condition
Network	See Cascade
Reference Conditions or Reference Dynamics	Attributes of an ecosystem prior to a disturbance or a change in disturbance regime
Resilience	Capacity to recover to pre-disturbance conditions (Kleinman et al. 2019)
Resistance	Capacity to endure disturbance without changing (Kleinman et al. 2019)
Succession	Change in species composition over time, generally triggered by a disturbance; see Ecosystem Recovery
Threshold	Level of stress or disturbance intensity that results in an abrupt or qualitative system change, such as mortality or disturbance propagation

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