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Natural Disturbance in Central Canada's Forests: Spruce Budworm – Wildfire Interactions in a Changing Climate

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INTRODUCTION

In Canada, 75% of the land classified as forest is in the boreal zone. As such, the boreal forest provides important ecosystem services, e.g., carbon storage, air and water purification, and climate regulation. Boreal forest ecosystem dynamics are significantly impacted by natural disturbance regimes, especially forest fires and insect or disease outbreaks. Historically, these disturbances have helped the forest grow and naturally regenerate by increasing sunlight to the understory, releasing nutrients, and allowing seeds to germinate. Under climate change models, the boreal biome is anticipated to have the largest temperature increase of all forest types and undergo an increase of biotic and abiotic disturbances (Gauthier et al., 2015; Fleming and Candau 1998).

Spruce budworm, *Choristoneura fumiferana* (Clem.), is a defoliating insect that feeds primarily on balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*), but will feed on black spruce (*Picea mariana*) and other conifers during outbreaks. It is one of the most destructive native forest defoliators in North America. Outbreaks occur at irregular intervals averaging 30-40 years, and high levels of defoliation can persist for 10 or more years. Climate change is predicted to affect outbreak frequency (Candau and Fleming 1998; 2011), range of defoliation (Candau and Fleming 2011), and synchrony between the timing of insect emergence in the spring and when the tree is susceptible (Pureswaran et al., 2018). These effects could drastically change natural processes, vigor and species composition within the boreal forest.

In recent years, there have been a number of large (>2km^2) fires that have devastated communities and ecosystems (e.g. Fort McMurray in 2016; California in 2017 and 2018; and, Australia in 2019-2020). In Canada, large fires occur most often in coniferous forests, with the Boreal Shield experiencing the second highest rate of susceptibility and relative area burned, after the Taiga Plains (Gralewicz et al., 2012). Extreme weather patterns and increases in temperature are expected to contribute to a higher frequency of ignitions (Girardin and Mudelsee 2008; Wotton et al., 2010; Lui et al., 2014; Boulanger et al., 2018), more days with ideal conditions for fire to spread (Wang et al., 2015, 2017), a longer fire season (Hanes et al., 2019; Jain et al., 2017), and large fires (Wotton et al., 2017; Wang et al., 2020).

SPRUCE BUDWORM DEFOLIATION

With support from province of Ontario, the Canadian Forest Service's Forest Insect and Disease Survey (FIDS) mapped all areas of large-scale defoliation in Ontario from 1941 until 2008, at which time the province assumed full responsibility for collecting the data. These maps have since been digitized and used for numerous spruce budworm studies. The analysis of these data by Candau et al., (1998) revealed a clear spatiotemporal pattern of frequent defoliation occurring in 3 distinct geographic areas called 'hot spots' separated by two approximately 100 -km wide corridors where defoliation was relatively infrequent. The hot spots and the corridors together form an area called the defoliation belt (Figure 1). The northern limits of the belt are likely due to the lack of preferred host species (i.e., balsam fir and white spruce) and less favourable climate conditions. The southern boundary of the belt occurs where the forest becomes primarily deciduous with only small pockets of spruce budworm hosts.

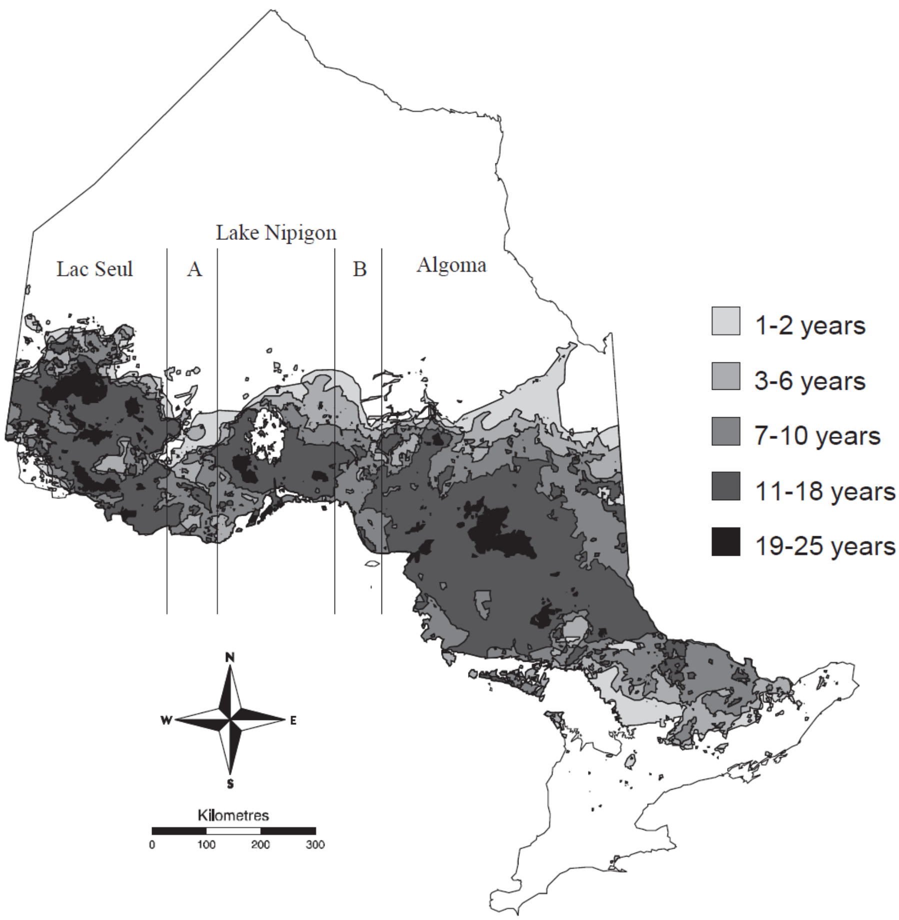

Figure 1. Map of spruce budworm defoliation in Ontario depicting the defoliation belt of three hotspots separated by two 100km wide corridors. The key shows the number of years of defoliation recorded for each area from 1941 to 1996 (Candau et al., 1998).

Refining their initial analysis, Candau and Fleming (2005) identified important bioclimatic conditions that affect the spatial distribution of spruce budworm defoliation, including maximum and minimum winter temperatures, presence of balsam fir and white spruce, and minimum spring temperature. Low defoliation frequencies at the northern edge of the defoliation belt correspond to low winter temperatures, which may cause mortality of second instar larvae during periods of extremely low winter temperatures (Candau and Fleming 2005). Low defoliation frequencies also tend to occur when the maximum May temperature is high (> 17.9°C). High defoliation frequency patterns were observed where average springs are cool (< -2.7°C) and summers or June are dry (e.g. <86mm of precipitation in the summer). The synchronicity of budburst with larval emergence is important for spruce budworm to be able to feed: if budburst or larval emergence occurs too early or too late, the larvae will not have an adequate food source or conditions for an outbreak. Phenologically, budburst tends to advance with increasing temperatures for balsam fir and black spruce, while larval emergence tends to occur once average air temperatures reach 10°C (Pureswaran et al., 2019).

WILDFIRE

Wildfire in Canada is tracked through a national database[1] that compiles wildfire data from provinces, territories, fire protection agencies, and parks. These data show that over the past 40 years large fires (>2 km^2) occur more often between 100 and 300 km from populated places and transportation networks, and less often under 100 km from population and infrastructure due to increased fire suppression efforts (Gralewicz et al., 2012). The wildfire database also shows that over time, fire regimes have shifted: there has been an increase in lightning-caused fires and a decrease in human-caused fires, fire seasons have become longer, and large fires have been getting larger (Hanes et al., 2019). These regime shifts may be due to a changing climate, biotic and abiotic factors, a combination thereof, or improvements in detection and reporting, tracking, and diagnosing the cause of fires.

SPRUCE BUDWORM – WILDFIRE INTERACTIONS

Potential interactions between spruce budworm and wildfire have long been inferred from the observation of frequent large fires occurring shortly after a period of several years of severe defoliation. The process involved the accumulation of what has been referred to as "ladder fuel", i.e., broken dead tree crowns and other dead tree components after several years of severe defoliation. This particular type of fuel dramatically increases the connectivity between the forest floor and the canopy, thus allowing surface fires to reach the canopy easier and quicker. Spruce budworm defoliation and wildfire occurrence in central Canada are linked. Fleming et al., 2002 found that, within the defoliation belt (Figure 1), areas with a moderate frequency of defoliation (9-11 years) were most likely to burn, whereas areas with high and low frequencies of defoliation rarely had fires. This is likely because areas with high frequency defoliation may not have enough fuel to burn, and low frequency defoliation may not support large fires due to a lack of ladder fuels. It takes at least 20 years for an area to recover from a large fire and regenerate to the species composition necessary to support a population of spruce budworm. Within the defoliated areas, fires occurred disproportionately more often 3–9 years after a spruce budworm outbreak. Recent work has shown

[1] The Canadian National Fire Database can be access at https://cwfis.cfs.nrcan.gc.ca/ha/nfdb

that the spruce budworm – fire interaction period (SFIP) varies from east to west (Figure 2; Candau et al., 2018). Forest composition and climate are suspected to affect the SFIP through surface and ladder fuel decomposition rates, along with other important variables like hardwood content, climate moisture, prevalence of host species (balsam fir, white spruce and black spruce), length of defoliation period, and prevalence of primary host species (balsam fir and white spruce). There was little evidence of spruce budworm – fire interaction resulting in large fires in the southeastern (high hardwood content and rarity of defoliation), northeastern (little to no history of defoliation), western and southwestern (very dry) reaches of the belt. These variables define the boundaries of likely interactions between fire and spruce budworm defoliation.

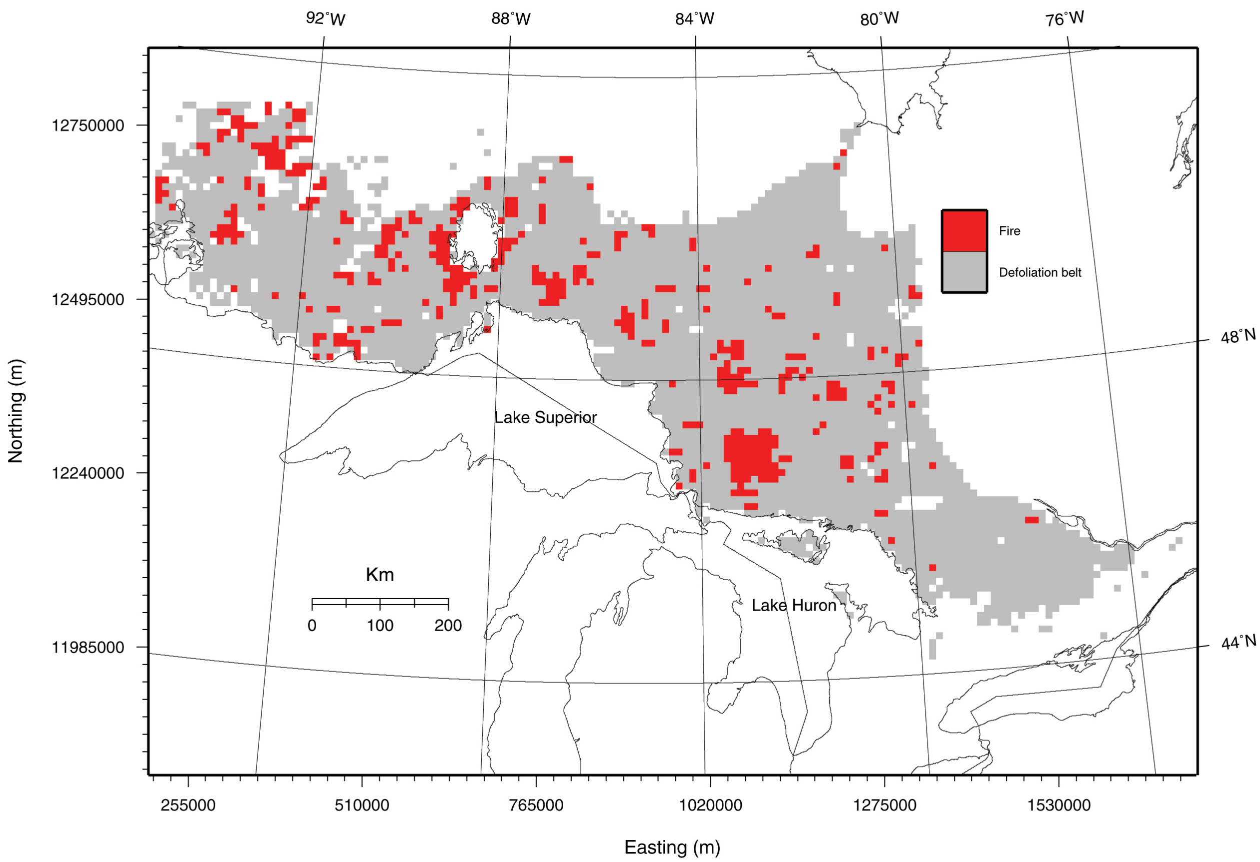

Figure 2. Areas of likely interaction of spruce budworm defoliation and resultant large (>2km^2) fires (red) along the defoliation belt (grey) (Candau et al., 2018).

IMPLICATIONS OF CLIMATE CHANGE

It is likely that climate change will influence the key biotic and abiotic factors that impact spruce budworm, wildfire, and their interaction. The boreal biome is expected to experience the largest temperature increase of all forest types and a likely increase in biotic and abiotic disturbances (Gauthier et al., 2015). Using six climate change scenarios over 2011-2040, Candau and Fleming (2011) showed increases in key spruce budworm defoliation variables of maximum winter temperature and minimum May temperature, but changes in precipitation would generally be small. While these scenarios predict defoliation will become less frequent, they also predict that the defoliation limit will shift northward, resulting in an increase in total defoliation of almost 3% for the period 2011-2040. However, when vegetation dynamics are considered it is expected that balsam fir and white spruce may shift northward and be replaced in the south by deciduous forests, grasslands, or shrublands. These changes may not occur during the considered timeframe (2011-2040) but may develop over a longer period. Climate change is expected to negatively impact coniferous biomass, with a reduction in balsam fir of nearly 83% and of black spruce of over 92% (Tremblay et al., 2018). Additionally, global warming trends are likely to disrupt the phenological synchrony of spruce budworm with its hosts (Pureswaran et al., 2019): spruce budworm may emerge from diapause or hatch too early for budburst, or the window for spruce budworm to defoliate black spruce may widen during an outbreak cycle after balsam fir has been defoliated (Pureswaran et al., 2019).

Most changes in the boreal forests are expected to result from changes in the fire regime (Tremblay et al., 2018). Fires are expected to be bigger with more crown fires under climate change conditions (Wotton et al., 2017), with spread days (i.e., the few days of high or extreme fire weather when most of the area is burned) increasing by 35-400% by 2050 (Wang et al., 2015). The largest increases in burning rates (i.e., percent of area burned annually) are expected to occur in northern Ontario, northern Quebec, and central Canada (Boulanger et al., 2018). With an increase in wildfires, smoke particles will cause less solar radiation to reach the ground and interact with clouds, resulting in cooler surface temperatures and lower precipitation levels, however the long-term effects of increased CO_2 emissions will still result in higher temperatures (Liu et al., 2014).

Long-term trends show an increase in precipitation and higher temperatures in the boreal forest. However, the increase in temperature will negate any effect of the increase in precipitation, causing drought conditions to occur more frequently (Wang et al., 2014). Since fire size and occurrence are affected by moisture content of deep and top layers of soil respectively (Portier et al., 2019), the changes in temperature and precipitation are likely to affect these layers, in turn resulting in dryer, more flammable conditions. The resulting changes in fire regime and defoliation could shift where spruce budworm – fire interactions occur. Should a spruce budworm outbreak or large fire occur during the transient period when forests are responding to climate change, there could be a total collapse of the system (Candau and Fleming 2011). Under such a scenario, the increased magnitude of wildfires could be enough to cause a negative feedback loop. This loop is described in models of vegetation dynamics that predict an increase of almost 50% in area burned leading to a rise in less flammable, aspen-dominated forests and more recently burned forests in the boreal forest (Krawchuk and Cumming 2011). One consequence of this prediction would be less frequent fires, and a forest that would no longer support spruce budworm outbreaks.

CONCLUSION

The interaction between spruce budworm defoliation and wildfire is driven by the accumulation of ladder fuels that allow surface fires to reach the canopy (Candau et al., 2018). Climate, defoliation frequency, and forest composition best predict which areas are more likely to fall in the spruce budworm – fire interaction period. Understanding that areas of moderate defoliation frequency are more likely to have subsequent fires will help foresters and fire managers anticipate potential large fires and allocate resources.

Although it is nearly impossible to definitively predict how climate change will impact spruce budworm defoliation, wildfires, and their interactions in central Canada, the warming trend and increase in drought does indicate that spruce budworm outbreak cycles and wildfires could occur more frequently, cause spatio-temporal shifts in both regimes, or cause a complete collapse of both important disturbance regimes. As disturbance regimes change, forest management techniques will need to adapt.

RESEARCH AT GLFC

The existence of a relationship between spruce budworm defoliation and wildfire in central Canada is supported by an increasing number of experimental and statistical results. They suggest that an interaction between spruce budworm defoliation triggered fire activity is modulated by three key factors: (1) the severity and the duration of the defoliation, (2) forest characteristics (e.g., age, composition), and (3) climatic conditions. GLFC is conducting research on the impact of these factors on the interactions between defoliation and fire to improve predictions of the impact of climate change on these interactions. They are also currently developing a landscape-scale tool that implements our current knowledge of the processes involved in these interactions to provide estimates of the amount and characteristics of budworm-related fuel. Such a tool will likely improve landscape-scale assessments of fire risk in the period following spruce budworm outbreaks.

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