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The predicted effect of the polar vortex of 2019 on winter survival of emerald ash borer and mountain pine beetle.

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Abstract

We use simulation models of the winter biology of two forest insects – emerald ash borer and mountain pine beetle – to illustrate the anticipated effect of the polar vortex of the winter of 2019 on overwintering survival. Cold spells in late January and early and mid-February were cool enough that relatively high levels of mortality of both species may be expected in many parts of northern Canada. However the high mortality response is not ubiquitous, and neither is it particularly severe compared to winter weather patterns from earlier decades. Forest insect pest managers will be required to carry on their usual work of population assessment and response. As Earth's climate continues to warm, overwintering survival should, on average, increase in both species. However, the common occurrence a split polar vortex associated with increasingly meridional jet stream flows should bring the odd winter of heavy mortality.

Keywords: insect ecophysiology, cold tolerance, winter mortality, predictive modeling

34 Introduction

35 One of the most important factors that has historically limited the spread and impact of terrestrial
36 invasive species in Canada has been the country's relatively cold climate. This climate causes
37 heavy winter mortality, particularly for invasive species (both plants and animals) from temperate
38 parts of the world, such as China (Jones et al. 2017, Tobin et al. 2017). Even well-adapted, cold-
39 tolerant forest insect species indigenous to North America are occasionally challenged by the
40 severe winter weather conditions of Canada, particularly in northwestern Canada (e.g., Cooke and
41 Roland 2003). However, as the Canadian climate warms, the risk posed by invasive species has
42 risen. A good example is the gypsy moth, *Lymantria dispar dispar* (Régnière et al. 2009). The
43 causal link between enhanced winter survival and rising pest risk has led to a growth in the
44 number and quality of studies devoted to the winter biology of invasive forest insect species (e.g.,
45 Madrid and Stewart 1981, Crosthwaite et al. 2011, Sobek-Swant et al. 2012a, Feng et al. 2016,
46 Bleiker et al. 2017, Elkinton et al. 2017; Rosenberger et al. 2017; Christianson and Venette 2018).

47 One of the more interesting recent results from climate change research is how global warming is
48 predicted – and has been observed – to result in a more “wavy” (i.e., meridional) pattern of jet
49 stream flow in the polar reaches of the northern hemisphere (Francis and Vavrus 2012, 2015).
50 This leads to more frequent intrusions of arctic air into mid-latitudes, sometimes referred to as
51 “Arctic air outbreaks” (Vavrus et al. 2006). Indeed, Overland and Wang (2016) discuss the
52 curious origins of the “split polar vortex” of the winter of 2016, which, coincidentally, Jones et al.
53 (2017) observed, in near real-time, killing emerald ash borer (EAB, *Agrilus planipennis*) in large
54 proportions near Syracuse, NY. The polar vortex of 2019 may have exhibited a similar such
55 pattern (NASA JPL 2019)

In this paper we examine the anticipated effects of the polar vortex of the winter of 2019 in the context of two of the most economically important forest insect species in Canada: the introduced emerald ash borer in eastern North America, and the native mountain pine beetle (MPB, *Dendroctonus ponderosae*) in western Canada. As EAB threatens to spread into Saskatchewan from established populations in the East (specifically: Manitoba), MPB threatens to spread into boreal Saskatchewan from established populations in the West (specifically: boreal Alberta). Both species are known to be vulnerable to extremely cold temperatures (EAB: Crosthwaite et al. 2011, Jones et al. 2017; MPB: Bentz and Mullins 1999, Cooke 2009), and both species have undergone large range expansions northward as a function of climate warming (EAB: Herms and McCullough 2014; MPB: Bentz et al. 2010). These range expansions have been facilitated by the fact that the hosts of both species are present throughout the invaded range. In the case of MPB lodgepole pine (*Pinus contorta*), jack pine (*Pinus banksiana*), and jack pine-lodgepole pine hybrids are susceptible and exist through much of the boreal forest in northern Alberta and Saskatchewan (Cullingham et al. 2011). Ash (*Fraxinus*) is naturally distributed throughout much of eastern Canada and as far west as Saskatchewan (Little 1971), but it is also widely planted in urban forests in western Canada (McKenney et al. 2012).

Computer models have been developed to describe the detailed effects of temperature on cold acclimation and freezing mortality of both species (EAB: Cuddington et al. 2018; MPB: Régnière and Bentz 2007). In this paper we specifically discuss the consequences of the cold winter of 2018-19 on these two invaders by employing the published models to examine the likely large-scale effects of daily temperature fluctuations on overwintering survival of both EAB and MPB. We then compared the predicted mortality for 2019 to predicted mortality in the previous 4 y

period (2015-2018) and to predicted mortality during the previous 30 y climate normal period (1981-2010).

Methods

We used BioSIM version 11.5.9 (Régnière et al. 2017) as a platform for collating temperature data from across Canada in space and time, through the winter of 2018-19, and for providing these temperature data as input to mechanistic models of insect ecophysiology through the overwintering stages of their life cycles. BioSIM simulates weather-driven processes at specific locations based on nearby weather stations, adjusting temperature with local gradients (i.e., latitude, longitude, elevation, and distance to shore) (Régnière 1996; Régnière and St-Amant 2007, Régnière et al. 2014).

We used two different weather databases in the modeling effort, one for MPB in western Canada and second for EAB covering both Canada and the continental United States. Both weather databases were created with the WeatherUpdater tool in BioSIM. For MPB, the database was comprised of data from Environment and Climate Change Canada (2019), and from four publicly available provincial data sets from British Columbia (Pacific Climate Impacts Consortium 2019), Alberta (Alberta Agriculture and Forestry 2019), Saskatchewan and Manitoba. The EAB weather database was created from four sources of weather data: GHCN-D (NOAA 2019a), GSOD (NOAA 2019b), ISD-Lite (NOAA 2019c), and Environment and Climate Change Canada (2019). The database for Canada and the USA, in BioSIM format, is available from Natural Resources Canada (<ftp://ftp.cfl.scf.rncan.gc.ca/regniere/Data11/Weather/Daily/>). We also used two different Digital Elevation Models (DEMs). The MPB DEM was extracted from SRTM30 (USGS 2005) at 30 second resolution and rescaled at 60 seconds. The EAB DEM was extracted from SRTM 4.1

(Jarvis et al. 2008) with a resolution at 3 seconds re-projected into Albers Equal Area and rescaled at 500 meters. We interpolated daily minimum and maximum temperatures for the period 2015–2019 (March) for 10,000 and 15,000 simulation points randomly extracted from the MPB DEM and the EAB DEM respectively. BioSIM was also used to interpolate a surface of cold mortality from simulation points using Universal Kriging with elevation as external drift. Normals generation for period 1981-2010 was done with 30 y and 10 replications. All simulations used the data of the 4 nearest weather stations. Final map was output with QGIS (QGIS Development Team, 2019).

For MPB, we used the only mechanistic model available for simulating overwintering mortality (Régnière and Bentz 2007). This model has been validated as being somewhat accurate, although model improvements may be warranted given the high degree of unexplained variation in observed winter mortality (Cooke 2009). In this model, winter mortality accumulates daily, as insects go through the slow processes of seasonal acclimation and de-acclimation to cold, implying the gain and loss of cold tolerance – processes which are, themselves, temperature-dependent. We terminated the daily simulation at March 10, 2019 to begin writing this report. The BioSIM model settings and associated files for the MPB model are available on GitHub (<https://github.com/RNCan/WeatherBasedSimulationFramework/tree/master/wbsModels/MPB/CTModel>).

For EAB, we implemented the logistic regression procedure of Cuddington et al. (2018) to model the temperature dose-response relationship for overwintering prepupae (Fig. 1B). We determined mortality using the equation:

$$M = 1 - \frac{1}{1 + e^{-\lambda(T^3 - T_o)}} \quad (1)$$

121 where M is mortality, T is temperature, λ and T_o are shape parameters determined by fitting the
 122 model to the data. These were determined to be 2.013×10^{-4} and -2.418×10^4 , respectively. Our
 123 EAB model does not simulate the processes of cold acclimation and de-acclimation (Sobek-Swant
 124 et al. 2012a) but we report on predicted overwintering mortality nonetheless because it is a
 125 relatively safe assumption that when the cold weather struck in January and February 2019, the
 126 insects had acclimated, i.e., were in their most cold-hardy state. Moreover, given the time of year
 127 and weather conditions proceeding January and February 2019 de-acclimation was unlikely to
 128 have occurred in the regions most affected by the polar vortex, due to the stability of cold
 129 temperatures through those months, when the models predict mortality was accruing. However,
 130 our model does take into account the buffering effects of the tree on temperature. Cuddington et
 131 al. (2018) provide both nonlinear and linear submodels that predict under bark temperature given
 132 air temperature (their Fig. 3) and that also incorporate a random effect for ‘city’. We extracted the
 133 data from Cuddington et al. (2018) Fig. 3 and re-fit their nonlinear model,

$$T_{under\ bark} = -44.6 + 62.4e^{0.0398T_{air}} \quad (2)$$

134 where T_{air} is the observed air temperature and $T_{under\ bark}$ is the predicted under bark temperature,
 135 and their linear model,

$$T_{under\ bark} = -2.38 + 0.747T_{air} \quad (3)$$

136 to determine new parameters that exclude the effect of ‘city, as shown in equations 1 and 2. In
 137 general our model fits are slightly different than those presented in Cuddington et al. (2018) (Fig.

1A; black vs. gray lines). For our subsequent predictions of EAB mortality we chose the nonlinear model over the linear model because we found the RSS for the nonlinear fit (RSS=81.04; broken black line in Fig. 1A) was lower than for the linear fit (RSS=96.85; black line in Fig. 1A). As with MPB, we terminated the simulation on March 10, 2019. The BioSIM model settings and associated files for the EAB model are available on GitHub (<https://github.com/RNCan/WeatherBasedSimulationFramework/tree/master/wbsModels/EmeraldAshBorer>)

Results

The winter of 2018-19 in context

In the second half of January 2019 there were two waves of cold that affected most cities in east central North America (Fig. 2, black line). Although temperatures below -20°C in Detroit, MI and Syracuse, NY may have felt unusually cold compared to weather during previous winters, these daily minimum temperatures were not that different from historical minimum values from the period of 1980-2016 (Fig. 2, grey line) or the average minimum temperatures for the same day over the same period (Fig 2, grey band). This was even more true in Canadian cities such as Sault Ste. Marie, ON, Thunder Bay, ON, and Winnipeg, MB, where temperature in late January may have dropped below -30°C, but did not approach historical minima, which were below -35°C (Fig. 2). Of all these cities, Québec, QC's late January cold snaps were least anomalous, being roughly 10°C warmer than the extreme minima observed through the 1980-2016 period.

The previous polar vortex of 2016 (Overland and Wang 2016) was implicated in causing severe mortality to overwintering EAB in at least one site (Jones et al. 2017). When we looked for the presence of 2016 records in the extreme minimum temperature data we found only four records

(Fig 2, black dots). Notably two of those are in the Syracuse, NY data, which is the closest centre to the sites examined by Jones et al. (2017).

In early February the deep cold that was in the East shifted West, producing two cold snaps, Feb 4-5 and Feb 10-12, where temperatures dropped to roughly -40°C , and a stretch of 14 days where daily maximum temperatures in places such as Grande Prairie did not exceed -20°C . The lowest temperature in western Canada south of 60°N was observed at Grande Prairie, where the night-time minimum on Feb. 4 2019 dropped to -43.7°C .

In summary, the polar vortex of 2019 produced cold winter weather that is reminiscent of winter weather from earlier decades, when Earth's climate was a fraction of a degree cooler.

Mountain pine beetle simulation

The MPB model predicted a moderately high level of winter mortality resulting from the cold snaps of Feb 3-4 and Feb 17-18, 2019 in the areas where MPB are currently causing damage to lodgepole pine (i.e., northwestern Alberta; Fig 3A). In the Jasper and Hinton areas west of Edmonton the level of predicted mortality is higher than 80% and closer to 90% (Fig. 3A).

Despite the overall cold in northern Saskatchewan, there are predicted to be warm islands of high survival is the Meadow Lakes area of western Saskatchewan, north and west of Saskatoon. We verified that numerous weather stations in this part of Saskatchewan, oddly, failed to record temperatures colder than -34.3°C on any date.

The MPB model suggested that 2019 was also a significant mortality year compared to the four previous winters. We compared predicted mortality from early 2019 (Fig 3A) to average predicted mortality over the previous four-year period (2015-2018; Fig 3B) we see a substantial positive

difference in predicted mortality (blue shaded areas in Fig 3B). This suggests that during the winter of early 2019 MPB experienced more mortality than they had in the recent past. We see a somewhat-similar pattern when we compared the 2019 mortality to average predicted mortality over the previous climate normal period (1980–2010; Fig. S1A). However, the differences between 2019 and this period are less stark, and we see that predicted mortality is actually greater in the normal period (red shaded areas in Fig. S1A) for places such as northern British Columbia and the Cypress Hills region of southern Saskatchewan and Alberta.

Emerald ash borer simulation

The EAB model predicted a wide range of survival across the known invaded range in North America (Figure 4A). In most of the United States overwintering mortality was predicted to be negligible, with the exception of the upper Midwest (Minnesota, Wisconsin) and the Dakotas, where predicted mortality was >85%. In Canada, predicted mortality was low throughout the contiguous EAB range in southern Ontario and eastern Quebec. The newly-discovered satellite populations in New Brunswick and Nova Scotia (Canadian Food Inspection Agency 2019) also are predicted to have experienced little overwintering mortality. Populations in northern Ontario (Sault Ste. Marie and the Algoma region, Thunder Bay) are predicted to have experienced high mortality, as is the population in Winnipeg, MB.

The EAB model also suggested that 2019 was also a significant mortality year compared to the four previous winters. Predicted mortality from early 2019 (Fig 4A) was greater than the average predicted mortality over the previous four-year period (2015-2018; Fig 4B) and, as with MPB, we observed more predicted mortality (blue shaded areas in Fig 3B). However, we see a different pattern when we compared the 2019 mortality to average predicted mortality over the previous

climate normal period (1980–2010; Fig. S1B). In that comparison, we see that mortality in 2019 was similar in the normal period to that observed in 2019, in particular in the region of Detroit, MI and Windsor, ON where EAB is thought to have first established sometime in the mid-1990s (Siegert et al. 2014; Circled region in Fig. S1B).

Discussion

We show that the polar vortex of 2019 should have significant effects on both MPB and EAB, in particular in the expanding range of both species in western Canada. For EAB, a reduction in the population in places such as Minneapolis, MN, Winnipeg, MB and Thunder Bay, ON would compliment management efforts to limit the impact of the beetle on urban tree populations. However, cold is not predicted to have a limiting impact on EAB in the rest of the invaded range of eastern North America. For MPB, we predict that widespread mortality throughout northeastern Alberta, if confirmed, would assist in the present efforts to manage the expanding front of MPB in that region. Moderately high levels of predicted mortality in the range of 80-90%, if supported by subsequent observations, would be welcome news to foresters in the Hinton district of western Alberta, because this predicted mortality would be higher than what has been observed in the region for the last several years (Hodge et al. 2017, Alberta Agriculture and Forestry, unpublished data). However this observed mortality is still lower than what used to be typical for the region in the 1990s and early 2000s (Cooke 2009; Figure S1A), and it is also not sufficient on its own to cause populations to decline. With a sex ratio of 2:1 female:male and a rate of fecundity of 60 eggs per female, this means that 39 of 40, or 97.5%, of all females must die for a MPB population to maintain a stable state. The pools of high survival predicted in western Saskatchewan are a concern because there are MPB known to exist in that area on the Cold Lake Air Weapons Range (Hodge et al. 2017). Temperatures of -34°C typically cause less than 50% mortality in lab

experiments, (Cooke 2009), which agrees with our model predictions for these islands of anomalously higher temperature.

Our effort to develop a rapid prediction of overwintering mortality in an insect population is unique. Traditionally, estimates of overwintering mortality will be made in the spring and summer following a significant cold event (e.g., EAB: Jones et al. 2017; MPB: Dooley et al 2015) with the results arriving a year or more after the event. These estimates are usually very accurate, but may come too late to assist managers with deriving operational plans that incorporate the effect of stochastic weather events. Here, we have merged a modelling platform (BioSIM) with freely-available daily weather data and insect mortality models to produce a snapshot assessment of the fate of these insects following an important weather event. Given that similar overwintering survival models exist for other important pest insect species (e.g., Elkinton et al. 2017) we suggest that similar rapid estimates could be produced to assist managers with integrating cold events into management plans.

There are some caveats that should be applied to the interpretation of both the EAB and MPB results. It is important to emphasize that these maps are most appropriately taken as regional scale assessments of mortality that could be subject to significant variability at smaller spatial scales. For EAB in particular, the tree-cooling model was developed using data from urban trees (Vermunt et al. 2012) and there still can exist significant variation within a city in observed temperatures (e.g., the urban heat island effect: Oke 1973). For EAB as well, the predicted survival is based on supercooling points developed for prepupae (Crosthwaite et al. 2011, Sobek-Swant et al. 2012a). To our knowledge, there are no overwintering mortality estimates available for other life stages. This is potentially important to address, as in all EAB populations some individuals have a two-year life cycle and thus spend the winter as larvae (Cappaert et al. 2005).

The frequency of this two-year life cycle varies across Canada (MacQuarrie, unpublished) and is hypothesized to increase in frequency with increasing latitude. Addressing this gap would be an important step towards generating better overwintering survivorship estimates that would aid in generating more accurate invasion risk predictions (e.g., Sobek-Swant et al. 2012b, DeSantis et al. 2013, Cuddington et al. 2018) and assessing mortality following future severe cold events. Both assessments also include regions where, to our knowledge, the insects do not yet occur (e.g., EAB: western Canada, the southwest United states; MPB: northwestern Saskatchewan) and for regions where there may not be susceptible host (e.g., southern Saskatchewan). The inclusion of these areas in our assessments should not be taken as evidence that we think the insects are introduced to those areas.

For MPB it must be emphasized that the model output relates to the above-snow populations of MPB larvae. Populations below the snow-line are well-insulated from sharp drops in temperature and will suffer much lower rates of mortality than what this model predicts. Also, some factors that are known to affect on survival have been neglected, such as tree-size and attack density, which are tree-level variables typically not available for landscape-wide forecasting. Additionally, it is possible that survival rate increases with larval age (Cooke 2009), an effect also not captured in the model of Régnière and Bentz (2007).

Global climate change is predicted to cause significant increases in global temperatures but also result in more variability in extreme weather events. Some have referred to this process as ‘global weirding’ (Hayhoe 2016). The polar vortex event of 2019 (and the earlier event of 2016) are exemplars of the predictions of global weirding. The management of native and invasive pest species has, so far, been done under the assumption of a stable climate where significant events occur at predictable frequencies. Events like the polar vortex are a consequence of anthropogenic

climate change which itself is predicted to have overall negative implications on forests and managed ecosystems because of the increased activities of both familiar and novel pests. However, events like the polar vortex can, perhaps, also assist with the management of pest outbreaks by causing wide scale mortality far greater than managers can typically achieve. The challenge though, will be for managers to be able to recognize, detect and quickly adapt management plans to take advantage of stochastically weird events.

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Figure Captions

Figure 1. A: Relationship between minimum annual air temperature and minimum annual under bark temperature for ash trees fit by linear (solid lines) and nonlinear (broken lines) models (see eq. 2 & 3) using parameters derived by fitting models to data (black) and using parameters given in Cuddington et al. (2018) (gray); black circles show data digitized from Cuddington et al. (2018; Fig 3). B: Modelled temperature dose-response for emerald ash borer according to a logistic regression (solid line; equation 1) fit to the data (grey circles) of Crosthwaite et al. (2011), as per Cuddington et al. (2018); black circles show cumulative mortality.

Figure 2. Daily minimum temperatures for the winter of 2018-19 (black) compared to the record minimum temperature (gray) for the same day for the period 1980-2016, for six key weather stations across east central North America. The grey band shows the 95% confidence intervals of the mean minimum daily temperature for each day during the same period. Black circles show extreme minimum temperatures that occurred during 2016, the year with the last significant polar vortex to impact North America.

Figure 3. Predicted percent winter mortality of mountain pine beetle (A), as of March 10, 2019, according to the model of Régnière and Bentz (2007) and difference in predicted mortality between 2019 and the average predicted mortality for the same region for 2015–2018 (B). In A blue implies colder temperatures and higher mortality, in B blue implies higher mortality in 2019 compared to the previous four years.

Figure 4. Predicted percent winter mortality of emerald ash borer (A), as of March 10, 2019, according to the logistic regression model of Cuddington et al. (2018) as implemented herein (see text for details), and difference in predicted mortality between 2019 and the average predicted

447 mortality for 2015–2018 (B). Blue implies colder temperatures and higher mortality. In A blue
448 implies colder temperatures and higher mortality, in B blue implies higher mortality in 2019
449 compared to the previous four years.

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Figure 1.

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