Climatic Limitation of Emerald Ash Borer (*Agrilus planipennis*) Impacts on Black Ash (*Fraxinus nigra*) in Canada

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Introduction

a) Overview

Emerald Ash Borer (*Agrilus planipennis*) is an introduced Asian wood boring beetle (family Buprestidae) that is rapidly spreading in North America and poses a significant threat to all North American ash (*Fraxinus*) species (Herms and McCullough 2014; COSEWIC in prep.). In 2016, the Aboriginal Traditional Knowledge (ATK) Subcommittee of the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) solicited the Atlantic Canada Conservation Data Centre (AC CDC) and Donna Hurlburt to co-write a federal status report on Black Ash (*Fraxinus nigra*) (COSEWIC in prep.). Emerald Ash Borer (EAB) is clearly the largest threat to Black Ash in Canada, already having caused 95% to 99+% ash mortality in heavily susceptible areas (Klooster et al. 2013; 2014). There is, however, good evidence from experimental and modeling studies that cold winter temperatures will limit or prevent the establishment of Emerald Ash Borer in the northern part of Black Ash range (Venette and Abrahamson 2010; Crosthwaite et al. 2011; Sobek-Swant et al. 2012; DeSantis et al. 2013). The extent to which Canadian Black Ash may be protected by cold temperatures is thus a crucial question relative to assessing the species' federal status. Relatively fine-scale data on climate and Black Ash abundance exist for most of its Canadian range, but a detailed GIS analysis of climate-related limitation of EAB impacts was beyond the scope of the initial COSEWIC status report contract. The COSEWIC ATK Subcommittee thus solicited AC CDC to conduct the analysis described in this report.

b) EAB Climate Thresholds

EAB typically overwinter within trees, under bark, at the pre-pupae stage (after the fourth larval instar; Crosthwaite et al. 2011). There are differences in cold tolerance across the North American range of EAB associated with local climate and possibly with differing points of origin in Asia (DeSantis pers. comm. 2018). Experimental studies have demonstrated that lethal freezing temperatures in mid-winter for North American EAB near the northern end of their range average between -26°C and -30°C (Sobek-Swant et al. 2012; Venette and Abrahamson 2010; Crosthwaite et al. 2011), although lethal freezing temperatures as low as -35.3°C have been recorded (Crosthwaite et al. 2011). Various factors, especially the insulating effects of bark and snow, mean that the minimum temperatures experienced by EAB in the wild may be significantly warmer than surrounding minimum air temperatures. DeSantis et al. (2013) factored insulating effects of bark and snow into estimates of EAB-experienced minimum temperatures across the eastern North American ranges of Black Ash, White Ash (*Fraxinus americana*) and Red Ash (*Fraxinus pennsylvanica*). They found that all Black Ash range in Manitoba and most of its range north of Sault Ste. Marie, ON and Quebec City, QC are within zones potentially unsuitable for EAB because EAB-experienced temperatures in overwintering sites have typically gone below -30°C in the past (Figure 1). Within those zones EAB were predicted to have poor winter survival, and in the coldest zones they identified (EAB-experienced minimum temperatures below -35.3°C, at air temperature of approximately -41°C) they predicted ash could survive EAB indefinitely. EAB is now established at Winnipeg, Manitoba (CFIA 2018), within the zone for which DeSantis et al. (2013) indicated potentially significant climatic limitations on EAB impacts, but the extent to which EAB-caused ash mortality will occur in the area is not yet understood.

Methods

Ontario and Quebec represent more than 87.8% of the Canadian range of Black Ash (Figure 2; note that some occurrence is known north of the mapped range) and about 95% of the population (Table 1). Ontario and Quebec also include almost all Black Ash range within the coldest climate zones most likely to be protected from EAB (DeSantis et al. 2013; Figures 1 and 2). Populations in Manitoba, Prince Edward Island, Nova Scotia and Newfoundland and Labrador are poorly understood, but based on relatively small ranges and provincial level rarity in each jurisdiction, they are believed to represent a very small portion of the national population that would be unlikely to significantly affect the results of this analysis. Our analysis for this report is thus most detailed for Ontario and Quebec (spatial analysis of Black Ash abundance by climate zone using actual local scale abundance values) with New Brunswick analyzed in less detail (Black Ash abundance assumed equal across all climate zones of the province, as described below under subheading iii).

i) Forest inventory data and derived local values for Black Ash population

Ontario. Data from the tens of thousands of Forest Inventory Plots spread across Ontario's commercially exploited forest are not in a readily available digital form, and data on species composition and volumes interpreted from aerial photography at the stand scale are not made available to the public, so we received ash volume data compiled by Management Units (MUs), along with GIS polygon data for Ontario MUs, from Larry Watkins, Ontario Ministry of Natural Resources and Forestry (OMNRF). Ontario is divided into 51 management units, and ash volume is available for most of these MUs in the managed forest (from approximately the southern edge of the Canadian Shield north to the limit of commercial forestry; Figure 3). Large protected areas, southern Ontario and northern Ontario beyond the limit of commercial forestry lacked ash values in the OMNRF dataset, as did four northern Ontario MUs in which ash was lumped into an “other hardwoods” category. We filled in missing ash volume values for MUs as noted in Table 1. Different ash species are also not well separated in the OMNRF dataset (Watkins pers. comm. 2018), meaning that using OMNRF total ash volumes overestimates Black Ash volume significantly where other ash species are common. For northern Ontario (all MUs except MU 451 - Algonquin Provincial Park, 360 – French-Severn, 220 – Bancroft-Minden, 140 – Mazinaw-Lanark and 780 – Ottawa Valley) we assumed total ash volumes approximated Black Ash volumes well because White and Red Ash are absent or much less common than Black Ash in the north. This assumption was also made for MU 451 - Algonquin Provincial Park because White and Red Ash are rare overall and represent minimal ash volume (Crins et al. 1998; Blaney pers. obs. 1989-2017). We corrected for inclusion of White and Red Ash in southern Ontario MUs (360 – French-Severn, 220 – Bancroft-Minden, 140 – Mazinaw-Lanark and 780 – Ottawa Valley) by applying the Algonquin Provincial Park ash density value to the area of those MUs to estimate Black Ash volume. This reduced total ash volume in those MUs by 88.9%[1]. The Algonquin density value was also used for MU 5 - Manitoulin Island and for MU 6 - Southern Ontario, but for southern Ontario the density value was only applied to the area classified as upland forest and swamp forest (values from Watkins pers. comm. 2018) to account for extensive deforestation in the south. Although Black Ash is known to occur north of the managed forest in Ontario, we excluded that area from our analysis because the species is very infrequent and seemingly restricted to major river valleys (COSEWIC in prep.), and because we had no way to estimate populations. These northernmost occurrences probably do not contribute very significantly to the national population totals relevant to our analysis here, though they may be especially significant in their climatic resistance to EAB.

<u>Quebec</u>. We downloaded publicly available forest inventory data from 315,289 plots spread throughout Quebec north to the limit of commercial forestry (MFFPQ 2018). These data included numbers of Black Ash stems per plot in various size classes and total volume of Black Ash in each plot.

We considered the Quebec analysis zone to be the range of Black Ash range depicted in the Trees of Canada (Farrar 1995), excluding Anticosti Island (which is known to have very low Black Ash abundance, largely because of extremely high White-tailed Deer populations; see COSEWIC in prep.). Although some Black Ash is known considerably north of the Farrar (1995) range (COSEWIC in prep.), we excluded all areas north of that range because Black Ash is very infrequent (detected in only 6 of 72,266 plots in that region) and because forest inventory information did not extend north to the northernmost known Black Ash, meaning we could not estimate population in those areas. In plots where Black Ash was present, we summed the Black Ash stem density (TIGE_HA) across all DBH classes (range: 10-76). Plot locations where Black Ash was not recorded were assumed to have Black Ash stem densities of 0 stems/ha. To calculate mean density across the analysis range we first decided on a cell size that allowed averaging of at least 100 forest plots for >95% of cells (*Point to Raster* tool, cell assignment type = COUNT). We calculated the mean stem density of all 20 km cells within the analysis range (*Point to raster* cell assignment type = MEAN). To clip the analysis more precisely to analysis range boundaries we

[1] Ash density in the four southern Ontario MUs averaged 7.8 times that in Algonquin Provincial Park. Black Ash density is likely fairly similar in Algonquin and the four surrounding MUs (Blaney pers. obs. 1989-2017) , meaning that the difference in density is probably largely driven by inclusion of other ash species and application of the correction factor is justified.

resampled the raster to a 2 km cell size (*resample* tool) and extracted all cells within the analysis zone (*Extract by mask* tool). After this process, 33% of the area within the Farrar (1995) Black Ash range analysis zone had values of 0 stems/ha. We assumed that these areas would actually have very low Black Ash stem densities. We calculated stems/ha in these areas based on volume/ha in the Ontario Management Units along the northern margin of managed forest (0.008103 m3/ha), [2] where Black Ash is similarly infrequent and near its northern range limit. To translate volume/ha to stems/ha for use in the Quebec analysis, we assessed the relationship between stems/ha (TIGE_HA) and volume/ha (VMB_HA; provided in Quebec forest plot data) within the Quebec analysis zone. Using a power relationship, there was a strong correlation between volume/ha and stems/ha (Figure 4. r = 0.85; volume/ha = 0.0867*stems/ha$^{1.0265}$) which yielded a corresponding stem density of 0.091 stems/ha. Black Ash density by 20 km grid square in Quebec is given in Figure 5.

ii) Climate data

We conducted two separate Black Ash population impact analyses using two different climate data sets:

A) A monthly minimum temperature raster dataset compiled by Dan McKenney, Canadian Forest Service, Natural Resources Canada. Rasters were November to February monthly extreme minimum temperatures for North America for every year from 1950 to 2014 ("North America (CA+US) Historical Monthly Extreme Minimum temperature for 1950-2014,mexmint"; 150 arc-second). We calculated a minimum temperature surface for the region as the minimum temperature across the all monthly rasters (November to February) between 2005 and 2014 (i.e., the overall minimum temperature across these 40 monthly rasters; *Cell Statistics* tool). This was converted to 2x2 km integer raster with 1°C resolution (Figure 2) for the spatial analyses described below.

B) A minimum EAB-experienced temperature raster dataset compiled by Dale Gormanson, in which moderating effects of snow cover and tree bark were modeled on top of temperature data extrapolated from 179 United States and 315 Canadian weather stations. Detailed description of methods by which this dataset was derived is given in DeSantis et al. (2013). This was converted to 2x2 km integer raster with 1°C resolution (Figure 2) for the spatial analyses described below.

iii) Determination of Black Ash populations within climate zones

The proportion of provincial Black Ash population falling in each 1°C zone for each of the two climate datasets above was calculated separately for Ontario and Quebec in GIS using the *Tabulate Area* tool with our modified Ontario MU layer, and our Quebec stems/ha layer as analysis zones. Values were converted to proportion of national population based on an Ontario population of 82,809,273, a Quebec population of 71,321,192, and a New Brunswick population of 8,300,000[3]. Nova Scotia and Prince

[2] This is the average volume/ha of Ontario Management Units 110 Abitibi River, 120 Trout Lake, 350 Kenogami, 415 Ogoki, 438 Gordon Cosens, and 601 Hearst.

[3] Ontario and Quebec populations came from provincial government volume estimates (with some modifications as noted in Table 1) using the formula derived in Figure 4: stems = (volume/0.0867)^(1/1.0265). Ontario population was based on a total volume of 11,639,308 m^3 (the extrapolated total provincial volume value developed during the current analysis as described under subheading 1 above). Quebec population was based on a

Edward Island populations are very small (low thousands) and were not considered in the analysis. Manitoba and Newfoundland and Labrador populations are unknown and although likely considerably larger than Nova Scotia and Prince Edward Island, are also small relative to the national population, so they too were not considered within the analysis. Fine scale New Brunswick distribution data for Black Ash was unavailable in time for this report and we assumed that the total volume of Black Ash was evenly distributed across the province, meaning that population by climate zone was assumed to be proportional to the area of the climate zone. This assumption is known to be false, but the bias it introduces is probably limited even for New Brunswick alone. In New Brunswick, Black Ash is more abundant in the north and west of the province, which includes both some of the coldest zones and some of the warmest zones. Any bias this assumption introduces for Canada would be much smaller, as the New Brunswick population only represents about 5% of the national population.

Results and Discussion

All analysis discussed below assumes no dispersal limitation of EAB over a one generation (60 year) time scale. This is based on 20 km per generation (one year) dispersal potential for EAB (Taylor et al. 2005; Prasad et al. 2010, plus intermittent human-aided dispersal over larger distances, and no Black Ash population more than 1,200 km from current EAB range (see COSEWIC in prep.).

Table 3 shows our estimates of the cumulative proportions of Black Ash in Ontario, Quebec, New Brunswick and Canada within each 1°C minimum temperature zone, based on the minimum air temperature layer from Dan McKenney, CFS (Table 2) and on the EAB-experienced temperature layer that factors in insulating effects of snow and bark, from DeSantis et al. (2013). Most Black Ash in Canada likely experiences some degree of protection from EAB because of cold temperatures. Significant EAB cold-related mortality has been documented at minimum air temperatures of -25°C to -30°C and -30°C is a typical average temperature of lethal freezing for EAB in mid-winter (Venette and Abrahamson 2010; Crosthwaite et al. 2011; Sobek-Swant et al. 2012). Our analysis suggests that 98.75% of the Canadian population of Black Ash is within zones that have experienced air temperatures below -30°C since 2005 and 78.04% of the Canadian population of Black Ash have experienced air temperatures below -35.3°C (the lowest recorded lethal freezing temperature for EAB, Crosthwaite et al. [2011]) since 2005. If those temperatures were sufficient to protect Black Ash from EAB, we would thus expect to lose no more than 1.25% to 21.96% of the Canadian population to EAB.

We know, however, that insulating effects of snow and bark mean EAB-experienced minimum temperatures are moderated relative to outside air temperatures. Vermunt et al. (2012) found minimum temperatures under bark were frequently 2°C to 4°C warmer than air temperatures. DeSantis et al. (2013) modeled effects of snow cover and bark on minimum temperatures experienced by EAB across northeastern North America. The zone mapped by DeSantis et al. (2013) in which EAB-experienced minimum temperatures were below -30°C and ash was expected to survive EAB indefinitely includes the Manitoba and northwestern Ontario range of Black Ash and a fairly narrow zone along the

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total volume of 9,984,998 m^3 (the total provincial volume calculated by the Quebec government, Mercier pers. comm. 2016). New Brunswick population was calculated by NB DERD and provided to AC CDC (Sabine pers. comm. 2016).

northern margin of Black Ash range across the rest of Ontario and into Quebec (Figure 1). Our analysis using the DeSantis et al. (2013) data suggests 72.82% of the Canadian population of Black Ash is susceptible to EAB if -30°C is the minimum survivable EAB-experienced temperature (Table 3). If the minimum survivable EAB-experienced temperature is -35°C, 100% of the Canadian population of Black Ash is EAB-susceptible (Table 3). Susceptibility to EAB does not necessarily equal ash mortality because there will likely be a gradient from complete EAB-caused mortality to zero EAB-caused mortality as EAB spreads into colder climate zones. The extent of EAB mortality from cold minimum temperatures that would be necessary to significantly reduce ash mortality is not yet well understood.

The expectation of a warming climate (IPCC 2014) complicates interpretation, especially over the one to three generation time scale (60 to 180 years) for Black Ash. IPCC (2014) climate predictions for 2100, including error bars, range between about 1°C and 4°C above current temperatures. If that level of warming equated to a corresponding increase in minimum annual temperatures, there would be very little Black Ash with any climatic protection from EAB. For example, if temperature zones shifted northward such that the zones with current EAB-experienced minima between -31°C and -34°C became survivable for EAB, that would leave 85.99% to 99.99% of Canadian Black Ash susceptible to EAB. Actual effects of a warming climate are much less predictable. Among many possible interacting effects, annual minimum temperatures could remain stable within a warming climate; warmer fall temperatures and increased freeze-thaw cycles in a warming climate could reduce EAB tolerance to rare cold extremes; or snow levels could increase in some regions, increasing insulating effects. If warming climate increased EAB-caused mortality of Black Ash, this would occur on top of potentially significant declines directly related to less suitable climate for Black Ash in the southern part of the Canadian range (Morin et al. 2008; Iverson et al. 2016)

It is interesting to note that EAB is now established at Winnipeg, MB (CFIA 2018). The long-term persistence of EAB and the effects of EAB on ash in Winnipeg are still unclear, but Winnipeg is within the zone for which DeSantis et al. (2013) indicated potentially significant climatic limitations on EAB impacts, associated with typical minimum annual air temperatures in the range of -35°C. The previous three winters (2015-2017) in Winnipeg have not had any air temperatures below -31°C (based on The Forks weather station, roughly 1 km from the Winnipeg site of EAB infestation; ECCC 2018), and thus could resemble a future, warmer climate.

In summary, the balance of evidence suggests that although cold temperatures will likely protect some Black Ash in Canada and may limit the severity of effects elsewhere, EAB is still likely to cause a significant decline in the Canadian population of Black Ash over the next 60 years. We cannot say with certainty whether population declines associated with EAB will exceed the 50% population decline threshold that is especially important for COSEWIC assessment. Loss exceeding 50% may, however, be most likely, given that our analysis suggests 72.8% of Canadian Black Ash is within zones in which EAB-experienced minimum temperatures average warmer than the most widely cited minimum survivable temperature of -30°C (Table 3). Even if the minimum EAB-experienced survivable temperature was only -26°C, that would still leave 50.39% of the Canadian population of Black Ash potentially susceptible to EAB (Table 3).

Table 1. Derivation of Black Ash volume estimates for Ontario Management Units (MUs) for which Black Ash volume was not directly available in the OMNRF data we received. Volume / ha values were applied to the entire MU area except for MU 6 (Southern Ontario).

MU#	MU Name	Black Ash Volume Derived as [area (ha) of the MU] x [volume / ha] of:	Reason
67	Big Pic	Average of 965 Pic River, 60 White River	No value available from OMNRF
175	Caribou	702 Lac Seul	No value available from OMNRF
280	Temiskaming	Average of 898 Temagami, 930 Romeo Malette, 110 Abitibi River	No value available from OMNRF
994	Whitefeather	Average of 840 Red Lake, 425 Ogoki	No value available from OMNRF
3	Woodland Caribou Provincial Park	840 Red Lake	No value available from OMNRF
2	Quetico Provincial Park	Average of 796 Lakehead, 405 Crossroute	No value available from OMNRF
4	Pukaskwa	Average of 615 Algoma, 60 White River	No value available from OMNRF
5	Manitoulin Island	451 Algonquin	No value available from OMNRF
6	Southern Ontario	451 Algonquin, applied only to the area of forest	No value available from OMNRF; volume / ha value applied to forested area only because of heavy deforestation
7	Lake Superior Provincial Park	615 Algoma	No value available from OMNRF
140	Mazinaw-Lanark	451 Algonquin	All ash spp. lumped, thus overestimating Black Ash volume
220	Bancroft-Minden	451 Algonquin	All ash spp. lumped, thus overestimating Black Ash volume
360	French-Severn	451 Algonquin	All ash spp. lumped, thus overestimating Black Ash volume
780	Ottawa Valley	451 Algonquin	All ash spp. lumped, thus overestimating Black Ash volume
8	Northern Ontario (north of commercial forestry)	[excluded from analysis]	Population of Black Ash north of zone of commercial forestry is believed to be very small relative to Canadian total, and is not possible to estimate

Table 2. Proportional Black Ash susceptibility to EAB by province and nationally, within temperature zones representing theoretical minimum survivable temperatures for EAB. For example, the value for Canada under -37C indicates that if -37°C is the minimum survivable temperature for EAB, 27.87% of Canadian Black Ash are susceptible to EAB and 72.13% of Canadian Black Ash are protected from EAB by climate. The climatic layer used for this analysis was the minimum monthly air temperature raster dataset from Dan McKenney (Canadian Forest Service) for 2005-2014.

Minimum Annual EAB-experienced temperature zone, and percentage of Black Ash susceptible to EAB if given temperature represents the minimum survivable temperature for EAB

	-45C	-44C	-43C	-42C	-41C	-40C	-39C	-38C	-37C	-36C	-35C	-34C	-33C	-32C	-31C	-30C	-29C	-28C	-27C	-26C	-25C	-24C	-23C	-22C	-21C
Ontario	100	99.97	89.68	76.85	65.59	51.19	41.74	33.23	18.85	14.14	10.91	8.74	6.88	4.43	2.97	2.56	2.25	1.73	1.26	0.72	0.41	0.14	0.03	0.01	0.00
Quebec	99.75	96.90	90.51	82.25	74.46	66.75	56.47	45.28	33.25	26.31	20.79	12.45	7.82	4.26	2.75	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
New Brunswick	100	100	100	100	100	98.80	91.00	82.53	71.52	62.62	54.32	43.90	32.96	24.25	15.72	6.69	2.05	0.87	0.36	0.04	0.00	0.00	0.00	0.00	0.00
CANADA	99.89	98.62	90.57	80.40	71.24	60.45	50.73	41.04	27.87	21.96	17.47	12.16	8.62	5.37	3.53	1.66	1.25	0.93	0.66	0.37	0.21	0.07	0.02	0.01	0.00

Table 3. Proportional Black Ash susceptibility to EAB by province and nationally, within temperature zones representing theoretical minimum survivable temperatures for EAB. The climatic layer used for this analysis was the minimum EAB-experienced temperature raster dataset compiled by DeSantis et al. (2013).

Minimum Annual EAB-experienced temperature zone, and percentage of Black Ash susceptible to EAB if given temperature represents the minimum survivable temperature for EAB

	-35C	-34C	-33C	-32C	-31C	-30C	-29C	-28C	-27C	-26C	-25C	-24C	-23C	-22C	-21C	-20C	-19C	-18C	-17C	-16C	-15C
Ontario	100.00	99.98	99.81	97.40	78.16	53.41	48.36	47.03	40.26	30.39	25.01	19.11	14.40	11.03	8.13	4.59	2.95	2.26	1.84	1.04	0.30
Quebec	100.00	100.00	99.75	95.63	93.45	92.18	90.90	86.02	80.89	69.23	46.63	17.57	1.46	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
New Brunswick	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.34	88.11	76.78	64.23	45.16	24.71	7.81	3.32	0.00	0.00	0.00	0.00	0.00
CANADA	100.00	99.99	99.79	96.76	85.99	72.82	69.68	66.86	61.12	50.39	37.15	20.74	10.29	6.94	4.55	2.51	1.51	1.15	0.94	0.53	0.15

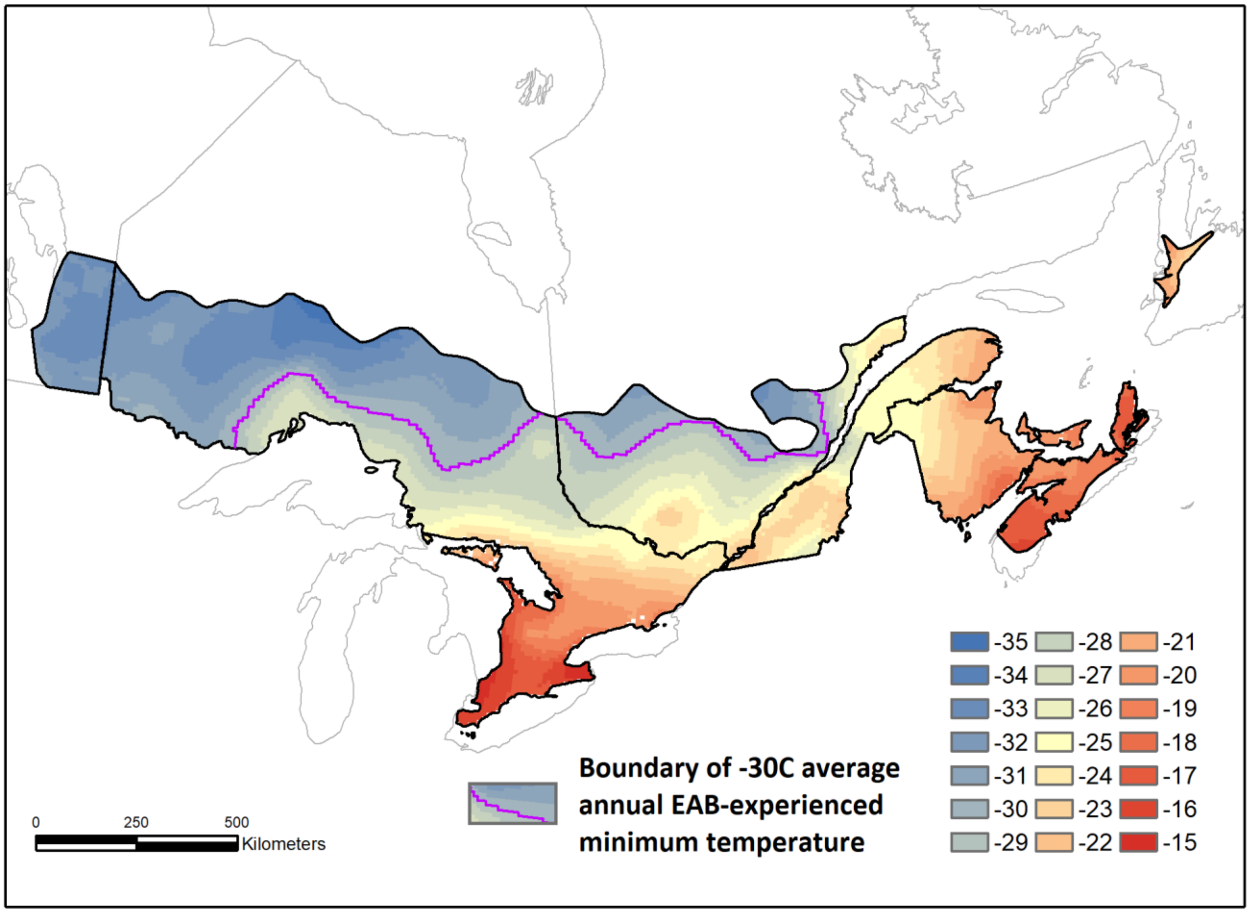

Figure 1. Coldest estimated Emerald Ash Borer-experienced temperatures (accounting for insulating effects of snow and bark) within the range of Black Ash in Canada as given in Farrar (1995). The purple line at the -30°C thermocline marks the expected average northern limit of EAB overwintering (DeSantis et al. 2013). Temperature zone derivation is described in DeSantis et al. (2013).

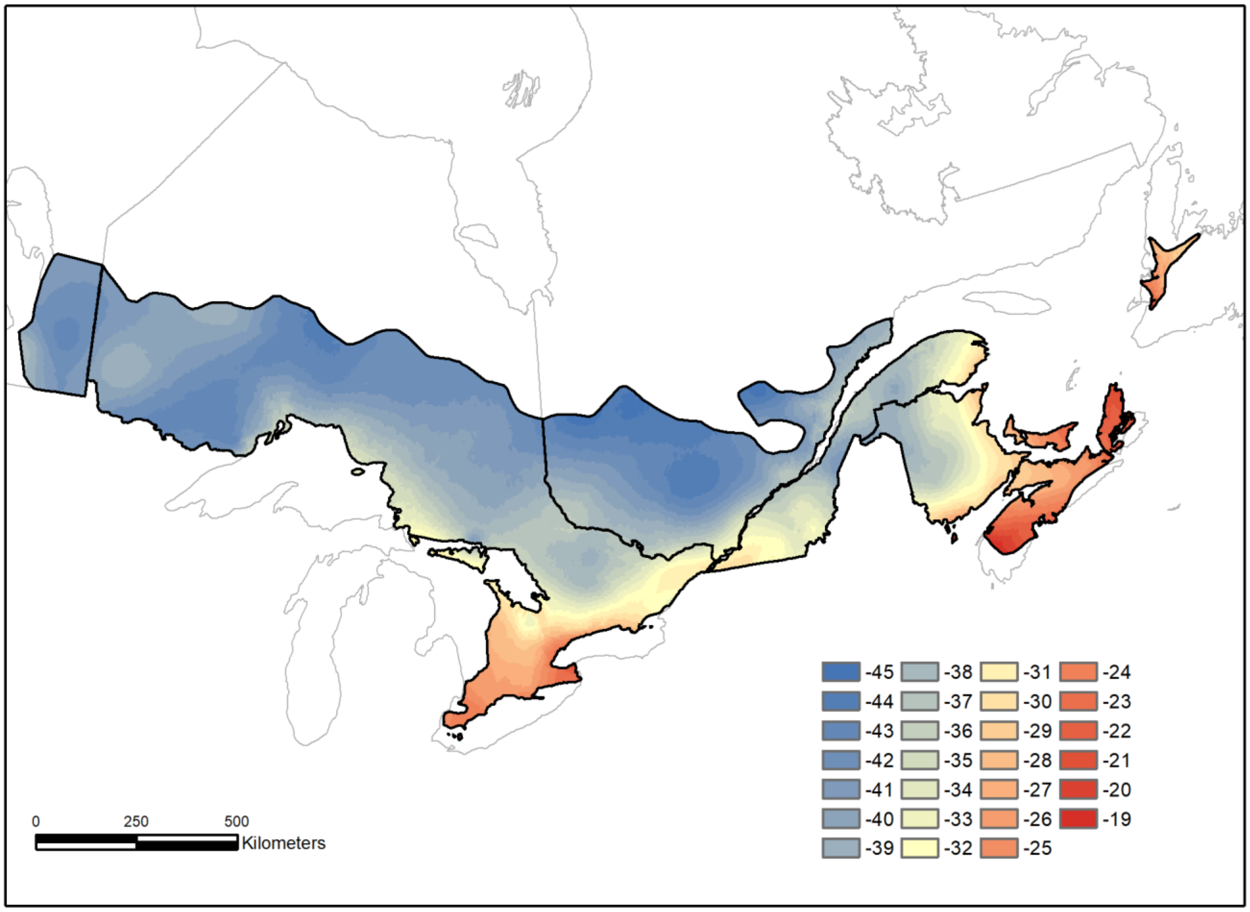

Figure 2. Average minimum winter air temperature within the Canadian range of Black Ash as used in this analysis (COSEWIC in prep., primarily from Farrar 1995).

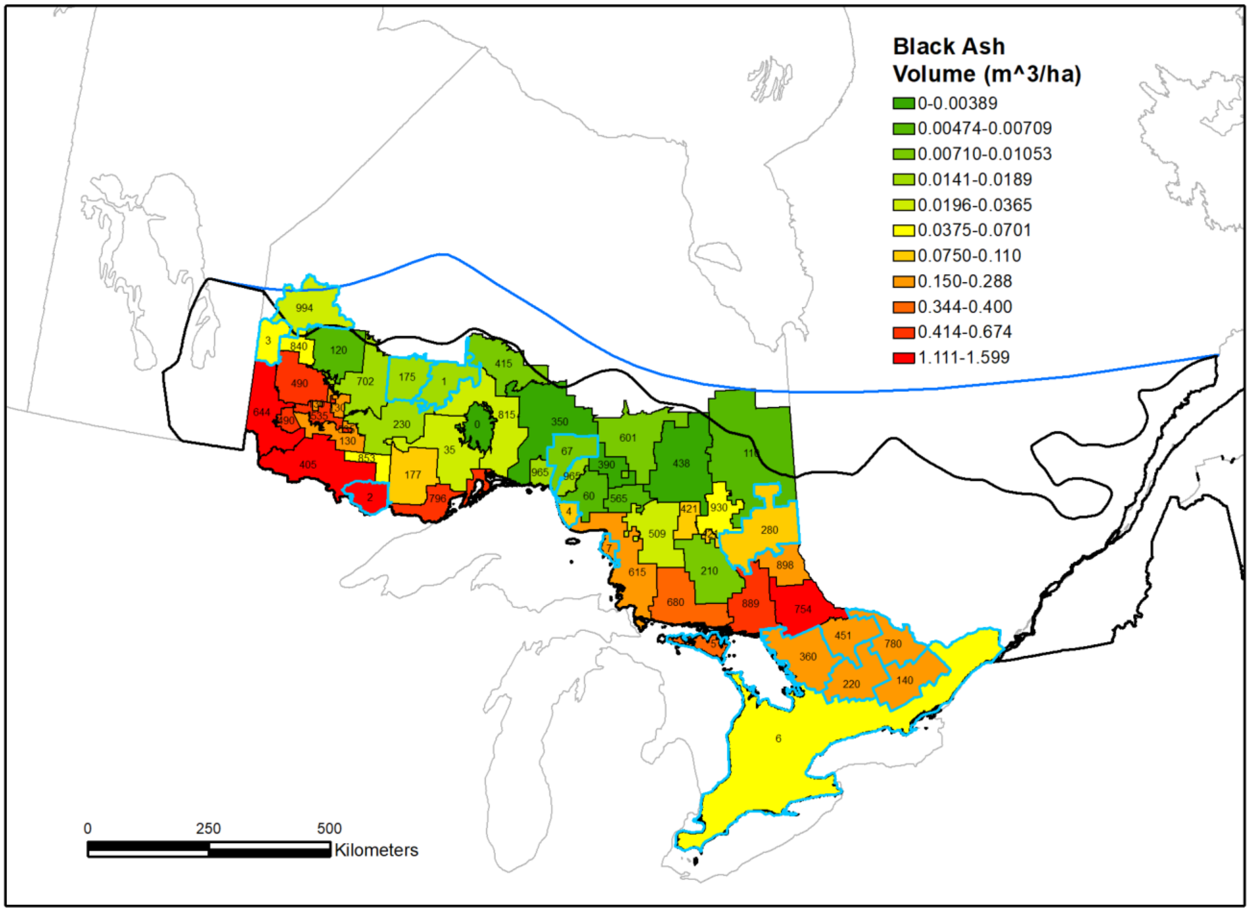

Figure 3. Ontario Ministry of Natural Resources Forest Management Units (MUs) with relative Black Ash volumes. Black Ash volumes for MUs with blue borders were unavailable and were derived as noted in Table 1. The black line through northern Ontario is the northern limit of Black Ash as given in Farrar (1995). The blue line north of that is an approximate northern range limit based on records compiled for COSEWIC (in prep.). Occurrence north of the range mapped in Farrar (1995) is very sparse.

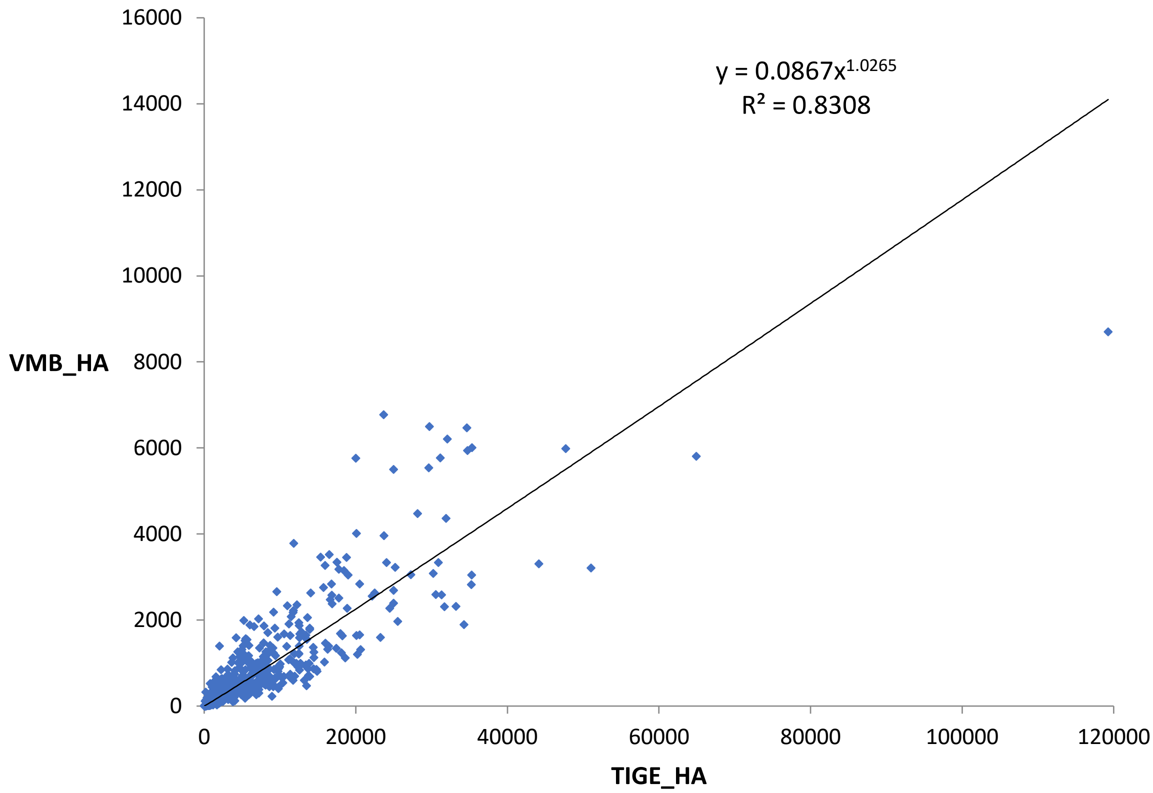

Figure 4. Relationship between Black Ash volume/ha and stems/ha for all cells in which Black Ash was recorded within the Quebec Black Ash analysis zone.

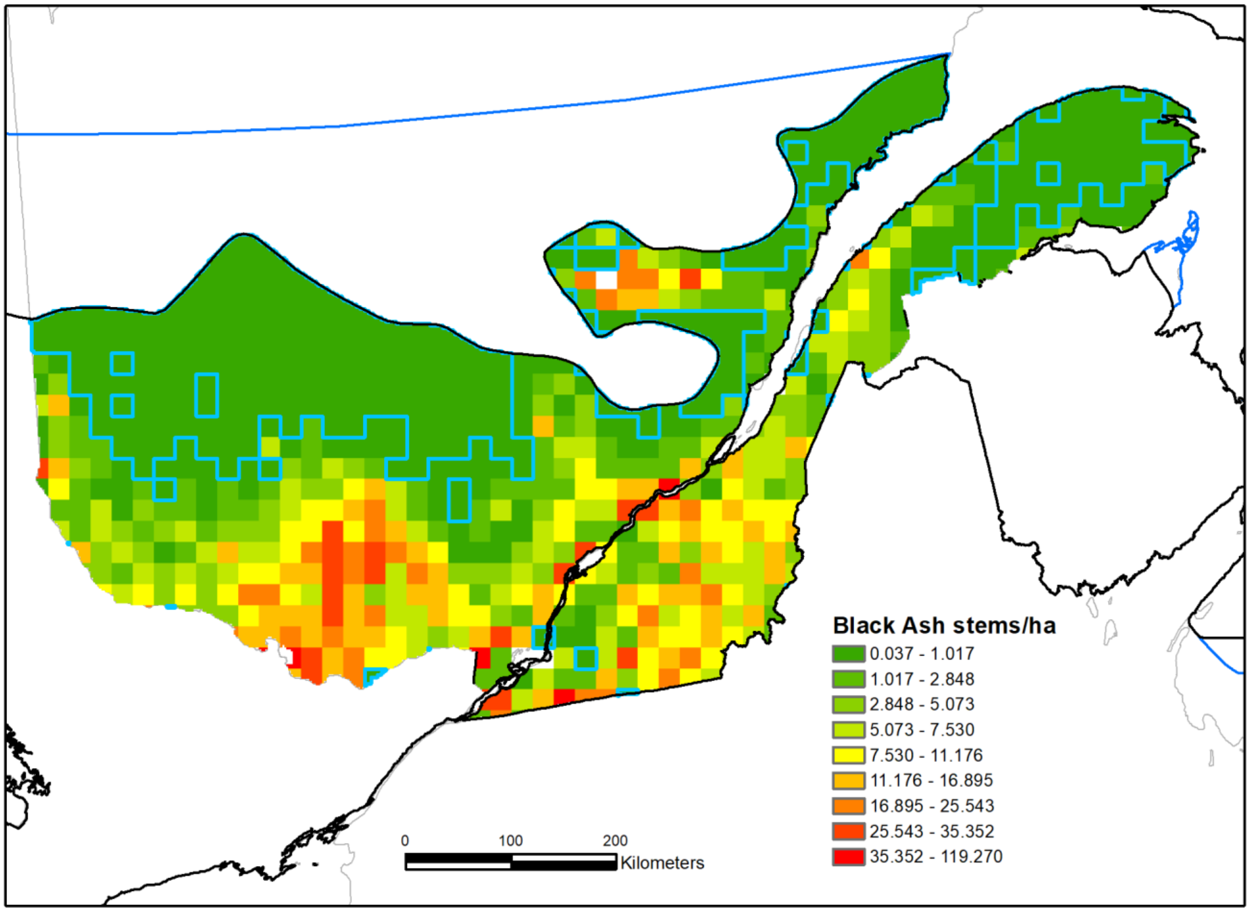

Figure 5. Relative Black Ash density in Quebec by 20 km x 20 km grid square, derived from provincial forestry plot data (MFFPQ 2018) as described in Methods. The blue outlines indicate areas for which stems / ha values were zero in MFFPQ (2018) but where a small population is believed to be present based on mapped range in Farrar (1995) and sparse occurrence known north the blue line (COSEWIC in prep.). Stems / ha for this zone were derived based on broad scale densities at the northern range margin in Ontario, as noted in Methods. Thus the large, uniform, green areas toward the northern margin of the range and in the central Gaspe Peninsula are almost all derived values, as are a few grid squares around Montreal and Ottawa. The blue-outlined squares within solid green areas northward are based on actual Black Ash presence in MFFPQ (2018) data.

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