Burning the "Wall of Wood"
Estimate of Potential Emissions from Open Burning of Waste Ash Wood

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Introduction: A beautifully iridescent green bug that hitched a ride here from China has become the most destructive and economically costly forest pest ever to invade North America. The Emerald Ash Borer (EAB) infestation threatens every one of the billion ash trees in Minnesota, including the 3 million ash trees in our urban forests.

State action to manage such infestations can be effective. For example, according to the 2008 Minnesota *Forest Protection Plan*, the state invested "nearly $30 million a year for six years in response and replacement funds" to address the Dutch elm disease in the 1970s and 80s.[1] In today's dollars, that would equate to about $106 million.[2] Unfortunately, EAB has not been given this same attention even though the problem is much greater. State support for community forests has been limited to about $8.5 million since the infestation's detection in 2009.[3]

While many communities are following the science-based management approach of *save the best; replace the rest*,[4] all will be faced with massive amounts of dead ash wood, a pressing issue that has been called a "wall of wood." Staff of the Minnesota Pollution Control Agency (MPCA) asked Michael Orange[5] to address an under-researched aspect of the infestation: air pollutants that would be emitted if communities use open burning as a method to manage the waste ash wood. Because there are significant unknowns, this resultant "wall of wood" estimate (WoW Estimate) can, at best, be considered a rough first approximation.

Findings: The WoW Estimate includes the following key components and an accompanying spreadsheet analysis that includes the calculations and data sources:

- **Ash tree amounts:** The WoW Estimate relies on the 2010 statewide survey completed by the Minnesota Department of Natural Resources (DNR) of the trees located within 66 feet of the roadway's edge in residential and commercial areas in 700 communities statewide.[6] The DNR survey predicted a total of about 3 million public and private ash trees. The WoW Estimate

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[1] 2008 MN Forest Protection Plan: http://mn.gov/frc/docs/MFRC_ForestProtectionPlan_2008-01-01_Report.pdf, p.12. However, Professor David French's report, "History of Dutch Elm Disease in Minnesota: A Problem Denied" (1993), asserts that state funding was "an aggregate amount of almost $56 million over several biennium."

[2] Assumes, for simplicity, that the $30 million was invested in 1979. It would be worth $106 million today based on the following inflation calculator: http://www.in2013dollars.com/us/inflation/1979?amount=30

[3] From detection in 2009 to 2018, the state invested approximately $7.5 million in community forests for the management of EAB (including $150,000 in pass through funding from the US Forest Service). The state approved an additional $1 million to be utilized in FY 2020. https://www.echopress.com/news/1633667-dnr-offers-grants-diversify-community-forests-against-pests-disease-and-damage

[4] Professor French's report (above cited) states this same lesson in his history of the Dutch elm disease in Minnesota, "A basic principle overlooked by many is that it is better to save what you have, what is already established, than hope that the newly planted will replace what is being lost."

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[6] Minnesota Department of Natural Resources survey, *DNR 2010 Community Tree Survey*. http://files.dnr.state.mn.us/assistance/backyard/treecare/forest_health/ash_elmRapidAssessment/rapidassessment_AshElm.pdf .

excludes ash trees within the 50 cities that have adopted EAB management plans because most of these cities will likely manage waste ash without open burning. Since a healthy, mature ash tree can be preserved for over 20 years for less than removing and replacing it, the WoW Estimate assumes that 20% of the best quality public and private trees will be preserved (about 195,000 trees statewide). The WoW Estimate "grows" the remaining ash trees to their 2019 sizes and predicts the dry weight of waste wood to total about 1.5 million US tons over the course of the infestation,[7] about 50,000 tons per year on average over the next 30 years (refer to Attachment 2, "Amounts of wood").[8]

- **Management by open burning:** Virtually all of the cities currently managing the infestation have local options for dealing with the waste wood other than via open burning, including 4 energy facilities within range that accept chipped wood as biofuel,[9] adequate storage space within city limits, and end users for wood chips and wood products (e.g., lumber, plywood, particle board, and paper pulp).[10] This, most likely, will not be the case as the infestation spreads throughout the rest of the state.

  Since the 1980 Minnesota Solid Waste Management Act, the state has enforced a municipal solid waste (MSW) hierarchy that prioritizes waste prevention and reuse over composting, waste to energy, and landfilling. Saving the best ash trees with insecticide preserves their natural life and benefits and delays their eventual entry into the waste management system. The 1980 state law bans the open burning of MSW. Logically, the open burning of waste ash wood should be considered the worst management option.

  Studies of the infestation have resulted in an "EAB Death Curve" that predicts the annual percentage of tree losses. The WoW Estimate assumes most cities will be able to manage a *base level* of the loss equal to 10% of their untreated ash trees each year without resorting to open burning. The "EAB Death Curve" predicts that, on average, 71% of the ash tree deaths will occur during the peak years (years 8-11). With the assumed 10% *base level* capacity during the 4 peak years (equaling 40% of the total), the remaining 31% of the waste wood generated during the peak years may be subject to open burning (referred herein as the *eligible portion* of the total amount of ash wood).[11] Since approximately 71% of the total ash deaths will occur during the 4 peak years, the *eligible portion* of the <u>entire</u> amount of waste wood generated by the infestation equals 22% (31% X 71% = 22%). There being no apparent guides to predict the future, the WoW Estimate includes a range of assumptions regarding the actual percentage of this *eligible portion* of waste ash wood managed by open burning: 10%, 20%, and 30% (refer to Attachment 3, "Emission estimates").

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[7] Because pollutant emission rates for open burning are based on the *dry weight* of wood, dry weights are used for the calculations. Since the *green weight* of ash wood is about 18% heavier, cities will have to deal with about 1.8 million tons of ash wood when it is removed.

[8] Although the WoW Estimate did not "grow" the trees over the future study period, the increased tree size is within the estimate's admittedly large margin of error. It is assumed that all below-ground wood will be ground in place or left in place.

[9] District Energy in St. Paul, the University of Minnesota, the Koda Energy plant in Shakopee, and Minnesota Power's Hibbard generating station in Duluth.

[10] Staff from various state agencies are developing a report that will provide extensive information regarding the EAB infestation and the various management options available. Expand/replace this footnote when EAB report is ready.

[11] The Minnesota Department of Natural Resources controls open burning permits. The agency's approval process could require applicants to provide evidence that no other viable alternatives are economically feasible.

- **Total emissions:** Using emission factors from the US Environmental Protection Agency and the MPCA for greenhouse gases and 5 of the 6 regulated air pollutants (*criteria* pollutants), the WoW Estimate lists the potential emissions for the range of burning assumptions (Table 1). For example, if local governments managed on average 20% of their total waste ash wood via open burning (about 290,000 tons), emissions would include approximately 600,000 tons of greenhouse gases (GHG), 3,000 tons of fine particulate matter ($PM_{2.5}$), 22,000 tons of carbon monoxide, and nearly 3,000 tons of volatile organic compounds (refer to Attachment 4, "Emission estimates").

Table 1: Total Greenhouse Gas and Criteria Pollutant Emissions from Open Burning of Waste Ash Wood (rounded US tons)

Open Burning %	Tons of Ash Wood and Debris	Biogenic GHG [1]	PM-2.5	CO	SO_2	VOC	NO_x
30%	441,000	901,000	5,000	33,000	90	4,200	600
20%	294,000	601,000	3,000	22,000	60	2,800	400
10%	147,000	300,000	2,000	11,000	30	1,400	200
Notes:							
1	Biogenic GHG results from the combustion or decomposition of biologically-based materials; wood, in this case. Anthropogenic GHG results from the combustion of fossil fuels.						

Table 2: Annual Greenhouse Gas and Criteria Pollutant Emissions from Open Burning of Waste Ash Wood, 2019-2049 (emissions in rounded US tons)

Burning Scenarios		Biogenic GHG Emissions		Selected Criteria Pollutant			Comparisons to Statewide Emissions		
Open Burning %	Annual Tons of Ash Wood and Debris [1]	US Tons	GHG Comparison to Cars (# of cars) [2]	$PM_{2.5}$	VOC	Comparison to Campfires [3]	Share of GHG Emissions [4]	Share of $PM_{2.5}$ Emissions [5]	Share of VOC Emissions [5]
30%	13,000	27,000	6,000	150	120	801,000	0.08%	0.66%	0.20%
20%	9,000	18,000	4,000	100	80	554,000	0.05%	0.44%	0.13%
10%	4,000	9,000	2,000	50	40	246,000	0.03%	0.22%	0.07%
Notes:									
1	Mark Abrahamson, Mn Dept. of Agriculture, predicts that Minnesota will continue to see a spread rate of ~33% of the national average, or about 1.7 counties per year. That translates to another 20-40 years before EAB is in every county. "In southern Minnesota we might be seeing a 12-year cycle [as was the case in Eastern cities], but in the Twin Cities I think it is taking longer." This might be due to our harsher winters and stronger control measures, e.g., sanitation, preemptive removals, and treatments. This analysis adopts the midpoint of the estimate by the MN Dept. of Ag.: 30 years.								
2	The figure lists the number of cars that would emit an equivalent amount of GHG emissions in a year. A typical passenger vehicle emits about 4.6 metric tonnes of carbon dioxide per year (4.17 US tons). Source: EPA, https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle								
3	The Minnesota Pollution Control Agency estimated the amount of wood burned in a typical campfire (32.5 lbs., refer to the "MPCA emission factors" sheet). The above figures show the number of typical campfires that would emit criteria pollutants equal to those from the open burning percentage assumption.								
4	Based on statewide emissions in the "Agriculture, forestry, and land use category" for 2016 (most recent year available, 34.323 million US tons). Source: https://www.pca.state.mn.us/air/greenhouse-gas-emissions-data								
5	Based on statewide emissions for the "Fire" category in 2014 (most recent year available) for $PM_{2.5}$ (45.260 million US tons) and VOC (122.096 US tons) Source: https://www.pca.state.mn.us/air/statewide-and-county-air-emissions								

- **Annual emissions:** It is impossible to know how long it will take for the infestation to kill virtually every unprotected ash tree in Minnesota. With help from the staff of the Minnesota Department of Agriculture, the WoW Estimate assumed it will be another 30 years before most unprotected ash trees will be infested or removed. Table 2 lists the average annual emission estimates for the 3 burning percentage assumptions over this assumed 30-year period, and compares the annual emissions to those from cars and campfires. For example, if 20% of the remaining ash trees are openly burned (about 10,000 tons per year), GHG emissions would be comparable to those from about 5,000 cars and the criteria pollutant emissions would be similar to that of over 600,000 typical campfires over an average year. The table also provides comparisons to annual statewide emissions.

- **Health effects:** Attachment 1 includes information regarding the health effects of the applicable criteria pollutants. A critical pollutant of open burning is fine particulate matter ($PM_{2.5}$). A recent study emphasized that "even moderate levels of [$PM_{2.5}$] can cause lung function impairment that rivals the damage caused by smoking."[12]

GreenStep Cities EAB Calculator: The website for the MPCA's GreenStep Cities program will include a calculator that provides rough approximations of the costs and benefits of saving the best ash trees and replacing the rest based on the total number and average size of ash trees in an urban forest. To address the consequences of open burning, it also calculates the GHG and applicable criteria pollutants from open burning any number of trees, plus the everyday equivalency comparisons included above.

Conclusion: The WoW Estimate demonstrates that massive amounts of ash wood will need management until the infestation runs its course, about 1.5 million tons, and that open-air burning would result in significant local levels of criteria pollutants and GHG emissions annually. Hopefully, the WoW Estimate and subsequent analyses will help lead to increased public action to mitigate the potential environmental, economic, and public health impacts of the infestation.

Attachments:

1. Excerpts from: "America's Children and the Environment," Third Edition, Updated October 2015, *Criteria Air Pollutants, Environments and Contaminants*.
2. Context: Overall Description of the Estimate
3. Amounts of wood
4. Emission estimates
5. Emission factors
6. MPCA emission factors
7. Emission comparison
8. Ash characteristics

[12] "Even moderate air pollution can harm," *Star Tribune*, 7/21/19, SH2.

Attachment 1

Excerpts from: "America's Children and the Environment"

Third Edition, Updated October 2015, *Criteria Air Pollutants, Environments and Contaminants*, US Environmental Protection Agency[13]

Childhood is often identified as a susceptible lifestage in the National Ambient Air Quality Standards reviews, because children's lungs and other organ systems are still developing, because they may have a preexisting disease (e.g., asthma), and because they may experience higher exposures due to their activities, including outdoor play.

Particulate Matter: Particulate matter (PM) is a generic term for a broad class of chemically and physically diverse substances that exist as discrete particles (liquid droplets or solids) over a wide range of sizes. Particles originate from a variety of man-made stationary and mobile sources, as well as from natural sources such as forest fires. Particles may be emitted directly, or may be formed in the atmosphere by transformations of gaseous emissions such as oxides of sulfur (SO_x), oxides of nitrogen (NO_x), and volatile organic compounds (VOCs).

Effects associated with exposures to both [fine particulate matter, $PM_{2.5}$] and $PM_{10-2.5}$ include premature mortality, aggravation of respiratory and cardiovascular disease (as indicated by increased hospital and emergency department visits), and changes in sub-clinical indicators of respiratory and cardiac function. Such health effects have been associated with short- and/or long-term exposure to PM. Exposures to $PM_{2.5}$ are also associated with decreased lung function growth, exacerbation of allergic symptoms, and increased respiratory symptoms. Children, older adults, individuals with preexisting heart and lung disease (including asthma), and persons with lower socioeconomic status are considered to be among the groups most at risk for effects associated with PM exposures. Information is accumulating and currently provides suggestive evidence for associations between long-term $PM_{2.5}$ exposure and developmental effects such as low birth weight and infant mortality due to respiratory causes.

Sulfur Dioxide: People with asthma are especially susceptible to the effects of sulfur dioxide. Short-term exposures of asthmatic individuals to elevated levels of sulfur dioxide while exercising at a moderate level may result in breathing difficulties, accompanied by symptoms such as wheezing, chest tightness, or shortness of breath. Studies also provide consistent evidence of an association between short-term sulfur dioxide exposures and increased respiratory symptoms in children, especially those with asthma or chronic respiratory symptoms. Short-term exposures to sulfur dioxide have also been associated with respiratory- related emergency department visits and hospital admissions, particularly for children and older adults.

Nitrogen Dioxide: Nitric oxide (NO) and nitrogen dioxide (NO_2) are emitted by cars, trucks, buses, power plants, and non-road engines and equipment. Emitted NO is rapidly oxidized into NO_2 in the atmosphere. Exposure to nitrogen dioxide has been associated with a variety of health effects,

[13] Downloaded 8/5/19: https://www.epa.gov/sites/production/files/2015-10/documents/ace3_criteria_air_pollutants.pdf. The final section on volatile organic compounds is from the MPCA website "Volatile Organic Compounds," downloaded 8/5/19: https://www.pca.state.mn.us/air/volatile-organic-compounds-vocs.

including respiratory symptoms, especially among asthmatic children, and respiratory-related emergency department visits and hospital admissions, particularly for children and older adults

Carbon Monoxide: Exposure to carbon monoxide reduces the capacity of the blood to carry oxygen, thereby decreasing the supply of oxygen to tissues and organs such as the heart. People with several types of heart disease already have a reduced capacity for pumping oxygenated blood to the heart, which can cause them to experience myocardial ischemia (reduced oxygen to the heart), often accompanied by chest pain (angina), when exercising or under increased stress. For these people, short-term CO exposure further affects their body's already compromised ability to respond to the increased oxygen demands of exercise or exertion. Other potentially at-risk populations include those with chronic obstructive pulmonary disease, anemia, diabetes, and those in prenatal or elderly lifestages.

The period of fetal development may be one of particular vulnerability for adverse health effects resulting from maternal exposure to some criteria air pollutants. This may occur if maternal exposure to air pollutants is transferred to the fetus during pregnancy; for example, lead and PM have both been shown to cross the placenta and accumulate in fetal tissue during gestation. In addition to the findings noted above regarding associations of prenatal PM exposure and adverse birth outcomes (such as low birth weight), limited studies of prenatal exposure to criteria air pollutants have reported that exposure to PM and oxides of nitrogen and sulfur may increase the risk of developing asthma as well as worsen respiratory outcomes among those children that do develop asthma. However, it is often difficult to distinguish the effects of prenatal and early childhood exposure because exposure to air pollutants is often very similar during both time periods.

Volatile organic compounds:[14] Volatile organic compounds (VOC) play a pivotal role in the creation of ground-level ozone. Ground-level ozone can irritate the eyes, nose, and throat, and can aggravate asthma and other lung diseases, including bronchitis. Exposure to high levels of ground-level ozone can increase the risk of premature death in individuals already suffering from heart or lung disease. Children, whose lungs are still forming and many of whom spend a large amount of time outdoors, are at particular risk under high ozone concentrations.

Exposure to VOCs themselves can cause a variety of health effects, including irritation to the eyes, nose, and throat; headaches and the loss of coordination; nausea; and damage to the liver, kidneys, or central nervous system. Some VOCs are suspected or proven carcinogens.

[14] This section is excerpted from the MPCA website "Volatile Organic Compounds," downloaded 8/5/19: https://www.pca.state.mn.us/air/volatile-organic-compounds-vocs.

Minnesota Statewide "Wall of Wood" Estimate

Updated: 8/7/19

Context: Overall Description of the Estimate

Purpose: Preemptive removals and deaths of ash trees from the Emerald Ash Borer infestation in Minnesota will result in what some describe as a "wall of wood" debris. Some of this wood will be used by the wood products industry, some will help fuel energy plants (e.g., District Energy in St. Paul, the University of Minnesota, the Koda Energy plant in Shakopee, and Minnesota Power's Hibbard generating station in Duluth), and some will be chipped and used as mulch or for paper pulp. However, for most of the debris, an end use may not be available or economical and instead it may be managed by open burning or landfilling. The Minnesota Pollution Control Agency is interested in estimating the potential environmental impacts associated with managing this ash wood stream. The purpose of this analysis is to estimate the tons of ash wood that will be available in the future and the potential greenhouse gas (GHG) and criteria pollutant emissions from open burning. Accompanying this spreadsheet analysis is a report (in Word) that summarizes the findings.

Primary data sources: According to the Minnesota Department of Natural Resources (DNR), Minnesota has about a billion ash trees statewide (source: *Rapid Assessment of Ash and Elm Resources in Minnesota Communities*, 1/5/07, Minnesota Department of Natural Resources). The estimates in this analysis rely primarily on the statewide survey of urban trees completed in 2010 by the DNR (*DNR 2010 Community Tree Survey*, http://files.dnr.state.mn.us/assistance/backyard/treecare/forest_health/ash_elmRapidAssessment/rapidassessment_AshElm.pdf). The DNR's statewide, tree estimates are based on survey results of trees located within 66 feet of the roadway's edge in residential and commercial areas. The figures include both public and private ash trees. The survey will be an under-estimate of total trees to be managed because it did not include trees beyond the survey boundary. It did not include trees in non-managed areas; however, these trees are likely to die in place rather than be managed. The emission factors for open burning come from the MN Pollution Control Agency.

Methodology for "Amounts of Wood" sheet: Table 2 includes the DNR's urban, ash tree data for 2010 and "grows" the trees for 9 years to get current likely sizes. Table 1 addresses the urban forests already decimated by preemptive removals or EAB-related tree deaths in the 50 Minnesota cities that have adopted EAB management plans. Since virtually all of this wood is coming from cities with nearby facilities that will process the wood into usable mulch, energy plant fuel, or other product, it is assumed that none will be openly burned. This wood is subtracted from Table 2 before the table estimates the weight of the remaining wood debris. This analysis does not estimate how these future amounts of wood debris will be processed. Because data is lacking, the analysis relies on very rough estimates in Table 1 and 2 (refer to highlighted cells). However, the estimates would have to be off by factors of 2 to 4 before they would have a significant effect (+/- 10%) on the total ton estimate (refer to Table 3, the sensitivity analysis).

Methodology for estimating the *eligible portion* of the total waste stream: Studies of the infestation have resulted in an "EAB Death Curve" that predicts the annual percentage of tree losses. Table 1 on the "Emission estimates" sheet assumes most cities will be able to manage a base level of the loss equal to 10% of their untreated ash trees each year without resorting to open burning. The "EAB Death Curve" predicts that, on average, 71% of the ash tree deaths will occur during the peak years (years 8-11). With the assumed 10% base level capacity during the 4 peak years, 31% of the waste wood generated during the peak years may be subject to open burning (referred herein as the *eligible portion* of the total amount of ash wood). Since approximately 71% of the total ash deaths will occur during the 4 peak years, the eligible portion of the entire amount of waste wood generated by the infestation equals 22% (31% X 71% = 22%). There being no apparent guides to predict the future, the WoW Estimate includes a range of assumptions regarding the actual percentage of this *eligible portion* of waste ash wood managed by open burning: 10%, 20%, and 30% (refer to the "Emission estimates" attachment).

Methodology for "Emission estimates" sheet: Table 2 uses a variety of emission factors (listed on the "Emission factors" and "MPCA emission factors" sheets) to estimate the potential GHG and criteria pollutant emissions from open burning based on a range of assumptions regarding the percent of the total amount of wood to be burned. Table 4 includes an estimate of the likely annual emissions. It is impossible to know how long it will take for the infestation to kill virtually every unprotected ash tree in Minnesota. With help from the staff of the Minnesota Department of Agriculture, the estimate assumed it will be another 30 years before most unprotected ash trees will be infested or removed (Table 3).

Emission comparisons: In order to make the scale of the emission estimates easier to understand, Table 2 on the "Emission estimates" sheet lists the average annual emission estimates for the 3 burning percentage assumptions over this assumed 30-year period, and compares the annual emissions to those from cars, campfires, and statewide emissions. The sources and assumptions for these comparisons are noted on the "Emission comparisons" sheet.

Minnesota Statewide "Wall of Wood" Estimate

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Amounts of Waste Ash Wood

Table 1: Estimate of ash trees lost to EAB or preemptive removal for cities implementing EAB management plans

Categories	Source	Trees prior to Infestation
Minneapolis trees (city-owned)	1	38,000
Minneapolis trees (non-city owned)	1	162,000
St. Paul trees (city-owned)	2	26,000
St. Paul trees (non-city owned)	2	110,000
Trees in other cities	3	192,000
Total		**528,000**

Table 2: Estimate of statewide impacts

Urban Ash Population Estimates	Source	All Ash Trees			Diameter at Breast Height (DBH) 1"-5"			Diameter at Breast Height (DBH) 5"-12"			Diameter at Breast Height (DBH) >12"		
		Total	Healthy	Low Quality	Total	Healthy	Low Quality	Total	Healthy	Low Quality	Total	Healthy	Low Quality
Ash trees from 2010 DNR survey	4	2,968,513	2,865,361	103,147	655,958	644,991	10,967	1,125,961	1,081,811	44,150	1,186,589	1,138,559	48,030
Percent of Total		100%	97%	3%	100%	98%	2%	100%	96%	4%	100%	96%	4%
Estimated average 2010 DBH	5	10.6	10.5	11.8	3.0			8.5			17.0		
Estimated average 2019 DBH	6	15.5	15.4	16.1	6.8			13.4			21.2		
Trees from Table 1		528,000											
Net estimate of ash trees, 2019	7 & 8	2,440,513	2,355,708	84,801	539,285	530,268	9,016	925,690	889,393	36,297	975,534	936,047	39,487
Estimated future removals:													
Estimated removal percentage	9	92.0%	91.7%	100%		100%	100%		99%	100%		80%	100%
Estimated number of trees, 2019		2,244,406	2,159,605	84,801	539,285	530,268	9,016	916,796	880,499	36,297	788,325	748,838	39,487
Estimated DBH, 2019		32,664,687	31,279,869	1,384,819	3,667,137	3,605,826	61,311	12,285,066	11,798,684	486,382	16,712,485	15,875,359	837,126
Average DBH		14.6	14.5	16.3									
Average height (ft.)	10				27			32			47		
Estimated ave. *dry weight* per tree to be removed (lbs.)	11	1,155			352			586			2,367		
Estimated total weight to be removed (US tons)	11	1,296,611			94,991			268,606			933,014	886,280	
Estimated total annual weight to be removed (US tons rounded to nearest thousand)	12	43,000			3,000			9,000			31,000		
Estimated trees assumed to be preserved		196,103	196,103						8,894			187,209	
Estimated trees assumed to be preserved as a % of total trees		8%											

Table 3: Sensitivity Analysis

Considerations	Current Total Tons	Change by +10%	Change by -10%
Significance of estimates in Table 1:			
Estimates on Table 1 include very rough guesses. What if off by + / - 10% (refer to highlighted cell)? Resultant total ton estimate.	1,296,611	1,324,663	1,268,559
Percent effect on total ton estimate.		2.2%	-2.2%
Factor Table 1 could be off to result in a significant effect (+/- 10%) total ton estimate.		4.6	(4.6)
Conclusion: The accuracy of the estimates in Table 1 have minor effects on the total ton estimate. Table 1 estimates could be off by a factor of 4 before having a +/- 10% effect on the total ton estimate.			
Significance of treatment estimates in Table 2:			
Table 2 includes very rough guesses of the removal percentages for mature ash trees (refer to highlighted cells). What if off by + / - 10%? Resultant total ton estimate.	1,296,611	1,207,983	1,385,239
Percent effect on total ton estimate.		-6.8%	6.8%
Factor Table 2 estimate could be off to result in a significant effect (+/- 10%) total ton estimate.		(1.5)	1.5
Conclusion: The accuracy of the treatment estimate in Table 2 has a fairly significant effect on the total ton estimate. The treatment estimates could be off +/- 50% before having a +/- 10% effect on the total ton estimate.			

Sources:

1	Source for the number of trees: City of Minneapolis. https://www.minneapolisparks.org/park_care__improvements/invasive_species/terrestrial__invasive_species/emerald_ash_borer/	
2	Source for the number of city-owned trees: https://www.stpaul.gov/sites/default/files/Media%20Root/Parks%20%26%20Recreation/2017%20EAB%20Annual%20Report_2018%20Mgmt%20Recs_FINAL_.pdf. Private trees are assumed to be at the same ratio as for Minneapolis.	
3	More than 50 communities have adopted EAB management plans in Minnesota. It is assumed that none of the trees from these cities will be managed via the open burning of removed trees and that, on average, the cities contain about 4,000 ash trees each within the same 66-foot zone used for the MN DNR 2010 Community Tree Survey.	
4	Source: Minnesota Department of Natural Resources survey, *DNR 2010 Community Tree Survey*. The tree estimates are based on survey results of ash trees located within 66 feet of the roadway's edge in residential and commercial areas. The figures include public and private ash trees. Source: http://files.dnr.state.mn.us/assistance/backyard/treecare/forest_health/ash_elmRapidAssessment/rapidassessment_AshElm.pdf .	
5	Assumed averages are the median DBH for the first 2 categories and 17 for the third.	
6	Trees are "grown" for 9 additional years per the following source: "Predicting Dimensional Relationships For Twin Cities Shade Trees," Lee E. Frelich, Department of Forest Resources, University of Minnesota, June 1992 (refer to "Ash	
7	Derived proportionately from the DNR survey data	
8	Virtually all of the wood debris from cities currently implementing EAB management plans is in quarantined counties that have nearby facilities that will either process the wood into usable mulch or for energy plant fuel. Therefore, it is subtracted from the 2019 statewide amounts. The net amount is proportionately estimated for the 3 DBH categories.	
9	The estimate assumes a very small percentage of healthy mature trees with a 10-12 DBH and only 20% of large healthy trees would be treated. This is based on a consultation with Jeff Hafner, Consulting Arborist with Rainbow Treecare,	
10	Average height is from the "Ash characteristics" sheet.	
11	Below-ground wood is assumed to be ground in place and not removed for further processing. The green weight of ash is generally about 18% higher than the dry weight (source: https://www.fpl.fs.fed.us/documnts/fpltn/fpltn-218-1931.pdf). Since the emission factors are based the dry weight of wood and theb following equations are based on the green weight, the average weight calculations have been decreased by 18% to make the emission calculations more	
	< 11 DBH	(0.26153(D^2)^1.12422*Height^0.93871
	>11 DBH	(0.10743(D^2))^1.12422*Height^0.93871
	Average of both formula	(0.18448(D^2))^1.12422*Height^0.93871
12	Assumes it will take an additional 30 years for most unprotected urban trees to die or be removed (refer to the "Emission estimates sheet).	

Minnesota Statewide "Wall of Wood" Estimate

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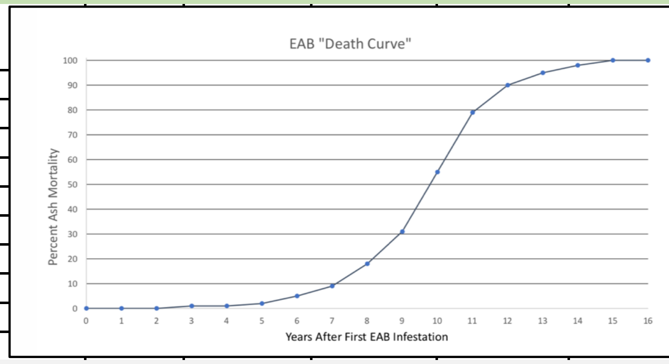
Emission Estimates

Table 1: Estimated peak-period removals and open burning percentages

Year [1]	% Deaths [1]	Tree Deaths per City [2]	Possible % Burned [3]
8	11.5%	423	1.5%
9	24.5%	902	14.5%
10	24.5%	902	14.5%
11	10.5%	386	0.5%
8 to 10	71.0%	2,613	31%
1 to 16	100%	3,680	22%



Notes:

1. Peak years and the annual percentage of ash tree deaths are from the "EAB Death Curve." Source: Minnesota Department of Agriculture. Downloaded 7/1/19: https://www.mda.state.mn.us/sites/default/files/inline-
2. Assumes 4,000 ash trees per average community and 8% treatment rate (refer to "Amounts of wood" sheet).
3. Assumes cities can handle without open burning the removals during early years (years 1-7) and final years when all unprotected trees will need removal (years 12-16). During the 4 peak years (years 8-11), it is assumed that a city can manage 10% of removals without burning (this equals about 370 trees for an average city with 4,000 ash trees and an 8% treatment rate), and that the remainder might be openly burned.

Table 2: Total estimated emissions from open burning of ash wood debris (US tons rounded)

Open Burning %	Tons of Ash Wood and Debris	Biogenic GHG [1]	PM-2.5	CO	SO_2	VOC	NO_x
30%	389,000	795,000	5,000	29,000	80	3,700	500
20%	259,000	529,000	3,000	19,000	50	2,500	300
10%	130,000	266,000	2,000	10,000	30	1,200	200

Notes:

1. Biogenic GHG results from the combustion or decomposition of biologically-based materials; wood, in this case. Anthropogenic GHG results from the combustion of fossil fuels.

Table 3: Estimate of selected annual emissions (emissions in US tons rounded)

Burning Scenarios		Biogenic GHG Emissions		Selected Criteria Pollutant			Comparisons to Statewide Emissions		
Open Burning %	Annual Tons of Ash Wood and Debris [1]	US Tons	GHG Comparison to Cars (# of cars) [2]	$PM_{2.5}$	VOC	Compariso n to Campfires [3]	Share of GHG Emissions [4]	Share of $PM_{2.5}$ Emissions [5]	Share of VOC Emissions [5]
30%	13,000	27,000	6,000	150	120	801,000	0.08%	0.66%	0.20%
20%	9,000	18,000	4,000	100	80	554,000	0.05%	0.44%	0.13%
10%	4,000	9,000	2,000	50	40	246,000	0.03%	0.22%	0.07%

Notes:

1. Mark Abrahamson, Mn Dept. of Agriculture, predicts that Minnesota will continue to see a spread rate of ~33% of the national average, or about 1.7 counties per year. That translates to another 20-40 years before EAB is in every county. "In southern Minnesota we might be seeing a 12-year cycle [as was the case in Eastern cities], but in the Twin Cities I think it is taking longer." This might be due to our harsher winters and stronger control measures, e.g., sanitation, preemptive removals, and treatments. This analysis adopts the midpoint of the estimate by the MN Dept. of Ag.: 30 years.
2. The figure lists the number of cars that would emit an equivalent amount of GHG emissions in a year. A typical passenger vehicle emits about 4.6 metric tonnes of carbon dioxide per year (4.17 US tons). Source: EPA, https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
3. The Minnesota Pollution Control Agency estimated the amount of wood burned in a typical campfire (32.5 lbs., refer to the "MPCA emission factors" sheet). The above figures show the number of typical campfires that would emit criteria pollutants equal to those from the open burning percentage assumption.
4. Based on statewide emissions in the "Agriculture, forestry, and land use category" for 2016 (most recent year available, 34.323 million US tons). Source: https://www.pca.state.mn.us/air/greenhouse-gas-emissions-data
5. Based on statewide emissions for the "Fire" category in 2014 (most recent year available) for $PM_{2.5}$ (45.260 million US tons) and VOC (122.096 US tons) Source: https://www.pca.state.mn.us/air/statewide-and-county-air-emissions

Minnesota Statewide "Wall of Wood" Estimate

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Emission Factors

Emission Factors	CO_2 [1]	CH_4 [2]	N_2O [3]	Total GHG [4]	PM-2.5 [2]	CO [2]	SO_2 [2]	VOC [2]	NOx [2]
Wood as biomass fuel: [5]									
Wood as biomass fuel (g/US ton)	1,640,000								
Wood as biomass fuel (lbs./US ton)	3,616								
Open burning of wood: [5]									
Open burning of wood (g/kg)			0.19						
Open burning of wood (lbs./US ton)		14.4	0.38		23.6	149	0.4	18.9	2.6
Open burning of wood (lbs./short ton)				**4,088**	**23.6**	**149**	**0.4**	**18.9**	**2.6**

Emission factor sources:

1. *Emission Factors for Greenhouse Gas Inventories*, USEPA, 11/19/2015, Table 1: https://www.epa.gov/sites/production/files/2015-11/documents/emission-factors_nov_2015.pdf
2. Data from the "MPCA emission factors" sheet.
3. Source: "Temperate Forest" emission factor from Table 1 below. The emission factor on Table 1 below is based on green wood and the total amount of wood on Table 2 on the "Amounts of wood" sheet is dry wood, the the emission factor in the above table has been increased by 18% to enable a more accurate dry-wood-to-dry-wood comparison. Refer to footnote 5 below.
4. Biogenic greenhouse gases. Incorporates global warming factors: CH_4 = 25, N_2O = 298. Source: Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/lraq-2sy19.pdf
5. The green weight of ash is generally about 18% higher than the dry weight. The total weights of trees on the "Amounts of wood" sheet have been decreased by 18% to make them compatible with the above dry-wood emission factors. The exception is the emission factor for N_2O.

Conversions:

pounds per gram	0.002205
US ton per kilogram	0.001102
kilogram per US ton	907.185

Table 1. Emission factors ($g\,kg^{-1}$) for species emitted from different types of biomass burning[a].

	Tropical Forest	Savanna	Crop Residue	Pasture Maintenance	Boreal Forest	Temperate Forest	Extratropical Forest[b]
Nitrogen Oxides (NO_x as NO)	2.55 (1.40)	3.9 (0.80)	3.11 (1.57)	0.75 (0.59)	0.90 (0.69)	2.51 (1.02)	1.12 (0.69)
Nitrous Oxide (N_2O)	–	–	–	–	0.41	0.16 (0.21)	0.38 (0.35)

Source: "Emission factors for open and domestic biomass burning for use in atmospheric models,"
S. K. Akagi1, R. J. Yokelson1, C. Wiedinmyer2, M. J. Alvarado3, J. S. Reid4, T. Karl2, J. D. Crounse5, and P. O. Wennberg6, Published in *Atmos*. Chem. Phys. Discuss.: 12 November 2010 Revised: 14 April 2011 – Accepted: 15 April 2011 – Published: 3 May 2011. Downloaded 7/17/19:

Minnesota Statewide "Wall of Wood" Estimate								
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MPCA Emission Factors								
Data from the Minnesota Pollution Control Agency								
Typical fire is 2 bundles of wood.								
There are 170 bundles per cord								
Per MN analysis each cord is 1.38 tons of wood during 2014/2015 heating season.								
Typical fire		0.011764706	0.008525149	tons/wood				
Type	**SCC**	**Pollutant**	**Amount**	**Units**	**Throughput Material**	**Units**	**Emission Estimates**	**Units**
E	2104008700	CO	149	LB	WOOD	TON	1.270247229	LBS
E	2104008700	PM10-PRI	23.6	LB	WOOD	TON	0.201193521	LBS
E	2104008700	PM25-PRI	23.6	LB	WOOD	TON	0.201193521	LBS
E	2104008700	VOC	18.9	LB	WOOD	TON	0.16112532	LBS
E	2104008700	METHANE	14.4	LB	WOOD	TON	0.122762148	LBS
E	2104008700	NOX	2.6	LB	WOOD	TON	0.022165388	LBS
E	2104008700	AMMONIA	1.8	LB	WOOD	TON	0.015345269	LBS
E	2104008700	FORMALDEHYDE	1.79	LB	WOOD	TON	0.015260017	LBS
E	2104008700	ACETALDEHYDE	1.07	LB	WOOD	TON	0.00912191	LBS
E	2104008700	BENZENE	0.686	LB	WOOD	TON	0.005848252	LBS
E	2104008700	PHENOL	0.472	LB	WOOD	TON	0.00402387	LBS
E	2104008700	SO2	0.4	LB	WOOD	TON	0.00341006	LBS
E	2104008700	CRESOL MX IS	0.357	LB	WOOD	TON	0.003043478	LBS
E	2104008700	NAPHTHALENE	0.265	LB	WOOD	TON	0.002259165	LBS
E	2104008700	BUTADIENE,13	0.157	LB	WOOD	TON	0.001338448	LBS
E	2104008700	ACROLEIN	0.123	LB	WOOD	TON	0.001048593	LBS
E	2104008700	BENZO(A)PYRE	0.001	LB	WOOD	TON	8.52515E-06	LBS
E	2104008700	MERCURY	5.36E-06	LB	WOOD	TON	4.56948E-08	LBS
E	2104008700	TCDF,2378	1.25E-09	LB	WOOD	TON	1.06546E-11	LBS
E	2104008700	OCDD,TOT	6.66E-10	LB	WOOD	TON	5.67681E-12	LBS
E	2104008700	PECDF,23478	6.44E-10	LB	WOOD	TON	5.48929E-12	LBS
E	2104008700	PECDF,12378	4.56E-10	LB	WOOD	TON	3.88683E-12	LBS
E	2104008700	HXCDF,123478	3.56E-10	LB	WOOD	TON	3.03445E-12	LBS
E	2104008700	HPCDD1234678	3.16E-10	LB	WOOD	TON	2.6935E-12	LBS
E	2104008700	HPCDF1234678	3.00E-10	LB	WOOD	TON	2.55754E-12	LBS
E	2104008700	PECDD,12378	2.58E-10	LB	WOOD	TON	2.19912E-12	LBS
E	2104008700	HXCDD,123478	2.50E-10	LB	WOOD	TON	2.13094E-12	LBS
E	2104008700	HXCDD,123678	2.50E-10	LB	WOOD	TON	2.13094E-12	LBS
E	2104008700	HXCDD,123789	2.50E-10	LB	WOOD	TON	2.13094E-12	LBS
E	2104008700	HPCDF1234789	2.34E-10	LB	WOOD	TON	1.99455E-12	LBS
E	2104008700	TCDD,2378	2.28E-10	LB	WOOD	TON	1.94341E-12	LBS
E	2104008700	HXCDF,123678	2.20E-10	LB	WOOD	TON	1.87523E-12	LBS
E	2104008700	HXCDF,123789	1.98E-10	LB	WOOD	TON	1.69111E-12	LBS
E	2104008700	OCDF,TOT	1.67E-10	LB	WOOD	TON	1.42006E-12	LBS
E	2104008700	HXCDF,234678	1.65E-10	LB	WOOD	TON	1.40642E-12	LBS
Email source:								
From: Kuhl-Stennes, Megan (MPCA) <Megan.KuhlStennes@state.mn.us>								
Sent: Friday, May 24, 2019 11:16 AM								
To: Muessig, Philipp (MPCA) <philipp.muessig@state.mn.us>								
Subject: emissions factors for wood								
Attached are two versions of a spreadsheet Azra shared with me around wood burning emissions factors. The latter is the sample one she did for me for a “backyard fire” with some assumptions at the top. It is based on the 2014 emissions inventory. I know this is based on tons of wood burned so the figures should be correct.								
Campfire weight								
Typical weight of a wood for a campfire (lbs.)			32.5					

Minnesota Statewide "Wall of Wood" Estimate

Updated: 8/7/19

Ash Characteristics

Table 6 from *Predicting Dimensional Relationships For Twin Cities Shade Trees*, Lee E. Frelich, Department of Forest Resources, University of Minnesota, June 1992.
https://www.forestry.umn.edu/sites/forestry.umn.edu/files/cfans_asset_249769.pdf

DBH	Height
5.9	24.4
6.8	27.0
7.5	29.0
8.6	31.7
9.7	34.2
10.8	36.4
11.4	37.6
12.4	39.5
13.4	41.1
14.6	43.0
15.6	44.6
16.6	46.1
17.6	47.4
18.5	48.7
19.4	49.9
20.3	51.0
21.2	52.1
22.0	53.1

Table 6. Predicted dimensions for green ash.

Age	Dbh	Ht	Htw	Htb	Cw	Ca
6	1.5	3.5	3.9	2.4	2.9	19.4
7	1.9	6.6	4.9	3.0	4.4	28.7
8	2.4	9.5	5.9	3.6	5.9	40.1
9	2.8	12.1	6.8	4.1	7.3	53.7
10	3.3	14.5	7.7	4.6	8.6	69.3
11	3.8	16.8	8.6	5.1	9.9	86.9
12	4.3	18.9	9.4	5.5	11.2	106.5
13	4.8	20.8	10.3	5.9	12.5	128.0
14	5.3	22.6	11.1	6.3	13.7	151.3
15	5.9	24.4	11.9	6.7	14.9	176.3
16	6.4	26.0	12.6	7.1	16.1	202.9
17	7.0	27.5	13.4	7.4	17.2	230.9
18	7.5	29.0	14.1	7.7	18.3	260.3
19	8.1	30.4	14.8	8.1	19.4	290.9
20	8.6	31.7	15.5	8.4	20.4	322.6
21	9.2	33.0	16.1	8.6	21.5	355.4
22	9.7	34.2	16.8	8.9	22.5	389.0
23	10.3	35.3	17.4	9.2	23.4	423.4
24	10.8	36.4	18.0	9.5	24.4	458.5
25	11.4	37.5	18.6	9.7	25.3	494.2
26	11.9	38.5	19.2	9.9	26.2	530.4
27	12.4	39.5	19.8	10.2	27.1	567.0
28	13.0	40.4	20.3	10.4	27.9	603.9
29	13.5	41.3	20.9	10.6	28.8	641.1
30	14.0	42.2	21.4	10.8	29.6	678.4
31	14.6	43.0	21.9	11.0	30.4	715.8
32	15.1	43.8	22.4	11.2	31.2	753.2
33	15.6	44.6	22.9	11.4	31.9	790.6
34	16.1	45.4	23.4	11.6	32.6	828.0
35	16.6	46.1	23.8	11.8	33.4	865.2
36	17.1	46.8	24.3	12.0	34.1	902.2
37	17.6	47.4	24.7	12.1	34.7	939.0
38	18.0	48.1	25.2	12.3	35.4	975.6
39	18.5	48.7	25.6	12.4	36.1	1011.8
40	19.0	49.3	26.0	12.6	36.7	1047.8
41	19.4	49.9	26.4	12.7	37.3	1083.3
42	19.9	50.5	26.8	12.9	37.9	1118.5
43	20.3	51.0	27.1	13.0	38.5	1153.3
44	20.8	51.6	27.5	13.2	39.1	1187.7
45	21.2	52.1	27.9	13.3	39.6	1221.6
46	21.6	52.6	28.2	13.4	40.2	1255.1
47	22.0	53.1	28.5	13.5	40.7	1288.1

Table from *How to Weigh a Tree*, Shodor Education Foundation, Inc., 2002, https://www.shodor.org/succeedhi/succeedhi/weightree/math1-content.html

Tree species	Size	Algorithm (calculates weight in pounds)
Southern Pine Coastal plane	< 5 inches	$0.32214(D^2H)^{0.91330}$
	≥ 5 inches	$0.19821\ (D^2)^{1.06419}\ (H)^{0.91330}$
Southern Pine Piedmont	< 5 inches	$0.28557\ (D^2H)^{0.92236}$
	≥ 5 inches	$0.18703\ (D^2)^{1.05385}(H)^{0.92236}$
Hard Hardwoods	< 11 inches	$0.38315\ (D^2H)^{0.92045}$
	≥ 11 inches	$0.11710\ (D^2)^{1.16763}(H)^{0.92045}$
Soft Hardwoods	< 11 inches	$0.26153(D^2)^{1.12422}(H)^{0.93871}$
	≥ 11 inches	$0.10743(D^2)^{1.12422}(H)^{0.93871}$
Sweet gum	< 11 inches	$0.24512(D^2H)^{0.95220}$
	≥ 11 inches	$0.09605(D^2)^{1.14754}(H)^{0.95220}$
Yellow Poplar	< 11 inches	$0.16258(D^2H)^{0.99008}$
	≥ 11 inches	$0.12701(D^2)^{1.04157}(H)^{0.99008}$