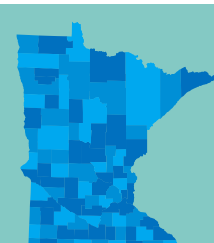
Air quality

December 2022

Minnesota Residential Wood Combustion Survey Results

Recreational Firepit Emissions Testing

MINNESOTA POLLUTION CONTROL AGENCY



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USDA Forest Service, Rocky Mountain Research Station
Missoula Fire Sciences Laboratory
5775 US Highway 10 W
Missoula, MT 59808

Authors

Megan Kuhl-Stennes

Anne Jackson

Azra Kovacevic

Contributors

Minnesota Pollution Control Agency

Chun Yi Wu

Deepa de Alwis

Amherst H. Wilder Foundation

Kelsey M. Imbertson

Kristin A. Dillon

Lisa Sell

Mark A. Anton

Minnesota Pollution Control Agency

520 Lafayette Road North | Saint Paul, MN 55155-4194 |

651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us

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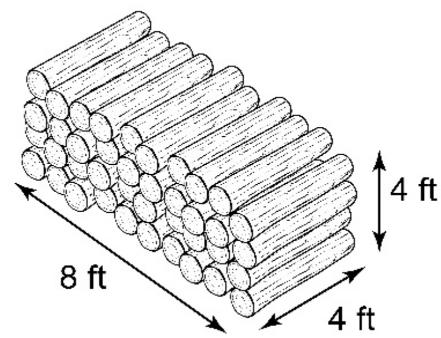
Summary

In 2021, the Minnesota Pollution Control Agency (MPCA) conducted a statewide survey to find out how much wood is harvested and burned annually for heat or pleasure in Minnesota. This survey has been conducted in varying forms every few years since 1960, the previous survey having been conducted in 2018. The most recent study was conducted for the 2020-2021 heating season, May 2020-April 2021.

The MPCA conducts this survey to gather information about residential wood combustion practices. Due to the levels of fine particles ($PM_{2.5}$) in ambient air, it is important to have accurate information about the sources of this pollutant. Residential wood combustion is an important source of fine particle emissions and accounted for 51% of Minnesota's direct fine particle emissions[1] in 2017[2]. This survey provides an improved understanding of residential wood burning in Minnesota by type of equipment, purpose for burning, source of wood fuel, and region of the state. These data have been used by state and federal agencies, as well as trade organizations, to manage forests, inform policymakers and scientists, and assist the hearth and fireplace industry by examining trends in wood burning.

In May 2021, the DNR sent out 7,000 invitations to complete the survey to randomly selected households throughout the state. For purposes of data collection and analysis, the state was divided into five regions. These regions are characterized by their main forest type and the expectation that their populations will have similar wood burning practices. These regions (Northern Pine, Aspen-Birch, Prairie, Metro, and Central Hardwoods; see Figure 2) have been used in past surveys.

Figure 1: One cord of wood



This year's survey showed Minnesota households burned an estimated 1.54 million cords over the course of a year. This amount of wood would completely fill US Bank Stadium in Minneapolis. While caution must be used to interpret the survey over the longer term due to changes in each year's survey, residential wood burning appears to be increasing (see Figure 3).

1 *Direct fine particle emissions are released from pollution sources. Fine particles in the air are a mixture of the directly released fine particles and those that are created in the air by chemical reactions between other pollutants such as the gases released from coal plants and vehicles.*

2 *Minnesota Pollution Control Agency's 2017 Emissions Inventory*

Key findings

- Since 2003, residential wood burning appears to be increasing over time.
- Roughly, 1,170,000 households, about 53% of all Minnesota households, burned some wood between May 2020 and April 2021. This is a 7% increase over the 2018 survey.
- Statewide, the greatest volume of wood burned was for primary heat, but burning for pleasure was the most common reason a household burned wood.
- Unlike previous surveys showing that most wood was burned in wood stoves, this survey shows that the largest amount of wood burned was in outdoor recreational equipment.
- Most wood burned (65% completely or some covered) was stored protected from elements, thus expected to burn more cleanly and efficiently.
- About one third of wood stoves and one fifth of fireplace inserts used were manufactured prior to 1989; these older models pollute significantly more than those manufactured later do. More stoves manufactured after 2015 are being installed.
- The survey was conducted during the COVID-19 pandemic, and Minnesota's Emergency Stay-at-Home order was in effect during this survey period. Results may reflect differences that are unique to other surveys, especially responses about outdoor recreational equipment and burning for pleasure.
- The results of the MPCA's PM emissions testing of firepits is included in this survey report. This test is an initial evaluation of firepits classified as "low smoke". Results are very preliminary, and more testing is needed.
  - Moisture content affects particulate matter emissions. Drier wood emits less PM than wetter wood. Low smoke firepits emit less PM when wood is dry, however when wood was very dry, one popular model was the highest PM emitter. The emission factor developed from this testing is an order of magnitude lower than that used in states' and EPA's National Emissions Inventory for residential wood burning.

Implications

This survey provides data to support the MPCA's air emission inventories for criteria pollutants, criteria pollutant precursors, and hazardous air pollutants. These inventories are released every three years for all air emission sources to support effective air quality tracking for pollution reduction programs and health risk assessments. This survey will inform a more complete picture of the overall impact of wood burning on air quality across the state.

This survey, along with other data on wood burning collected by the MPCA and other agencies, is an important tool to help Minnesota policy planners make informed policy decisions regarding overall forestry management and environmental strategies, especially relating to air emissions in the state. For example, the data collected in this survey help inform the need for appliance change-out incentive programs.

The data collected are also used to estimate the amount of residential fuel wood burned as reported in the annual Minnesota Department of Natural Resources' Forest Resource Report. This report describes Minnesota's forest resources, such as current conditions and trends in forest resources and forest resource industrial use.

Introduction

Project purpose

For more information on wood smoke and wood burning in Minnesota, visit https://www.pca.state.mn.us/air/wood-smoke

Between April and June 2021, the Minnesota Pollution Control Agency (MPCA), assisted by Wilder Research (Wilder), the Minnesota Department of Natural Resources (MDNR), and the U.S. Forest Service (USFS), surveyed randomly selected households across Minnesota to estimate the volume of residential wood burned between May 1, 2020, and April 30, 2021. The State of Minnesota has been surveying wood use since 1960, and now conducts this survey every three years[3]. These surveys are part of a long-term effort to monitor trends in the use and harvesting of Minnesota's wood supply by Minnesota households.

These surveys provide data for Minnesota's air pollutant emission inventories, which are assessed every three years by the MPCA. The MPCA estimates statewide emissions of various air pollutants, such as fine particles ($PM_{2.5}$), volatile organic compounds (VOCs), and other pollutants released from factories, vehicles, residential wood combustion, and other activities. The emission inventories offer valuable information about the activities that contribute to ambient air concentrations of fine particles and other air pollutants. In recent years, Minnesota's emission inventory has indicated that residential wood combustion is a primary source of directly emitted fine particles from combustion processes.

The collected data are used to estimate residential wood fuel burned for DNR's annual Forest Resource Report. The Forest Resource Report describes Minnesota's current forest conditions and trends in forest resource use.

Results of the survey are described in graphic form in the results section of this report. Reference to data tables is provided for some of the figures. These data tables are provided in Appendix B.

Survey objectives

Similar to the previous recent surveys, the objectives for this survey were to:

1. Estimate the total volume and type of residential wood burned from May 1, 2020, through April 30, 2021, by category of equipment used and geographic location.
2. Estimate the amount of wood burned for various purposes, including heat (primary or secondary), pleasure, disposal of wood from residential properties, or more than one of these reasons.
3. Compare with results of previous surveys to identify wood burning trends.
4. Estimate the temporal distribution of wood burning throughout the year.

[3] Similar surveys were conducted for the years of 1960, 1969-1970, 1979-1980, 1984-1985, 1988-1989, 1995-1996, 2002-2003, 2007-2008, 2011-2012, 2014-2015, and 2017-2018.

5. Inform air pollution reduction strategies by understanding the amount and location of wood burned, equipment used to burn wood, and reasons for burning.
6. Estimate the volume and type of fuel wood harvested or obtained, including the amounts harvested from living or dead trees and from land owned by different entities (state, federal, county, forest industry, and private lands).

Results

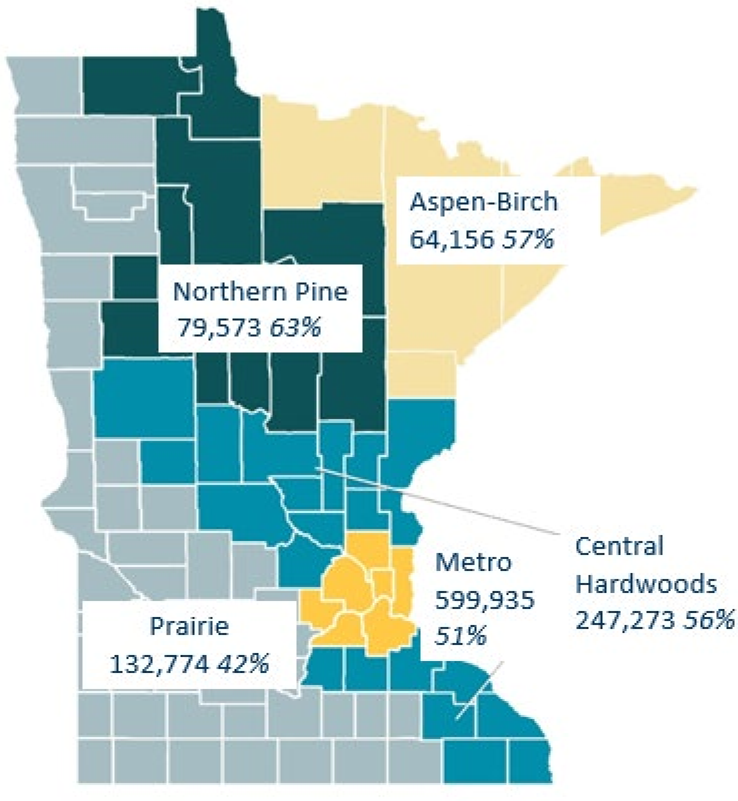
Household burning practices

Between May 1, 2020, and April 30, 2021, an estimated 1,170,000 Minnesota households burned some wood, about 53% of occupied households in the state.

For purposes of data collection and analysis, the state was divided into five regions: Northern Pine, Aspen-Birch, Prairie, Metro, and Central Hardwoods (Figure 2). These regions have been used in analyzing several previous surveys as well. They are characterized mainly by forest type, but also serve to stratify the statewide household population into subgroups that are expected to have similar wood burning practices.

Burning rates (the percentage of all occupied households in a region that burned wood at any location) varied by region. The highest burning rate was in the Northern Pine region, where 63% of households whose primary residence was in the region reported burning wood. The burning rate was lowest in the Prairie region (42%). The Metro region's burning rate was also comparatively low (51%), but because it is more densely populated, it has the greatest number of households estimated to have burned wood (600,000).

Figure 2: Estimated number and percent of household population that burned wood by region



The percentages in Figure 2 are based on the location of the primary residences of the households that reported burning wood in any amount anywhere in the state. Since some households also burned wood in regions outside their region of primary residence (such as at a secondary residence or a campsite), these results do not necessarily reflect the amounts of wood burned in each region.

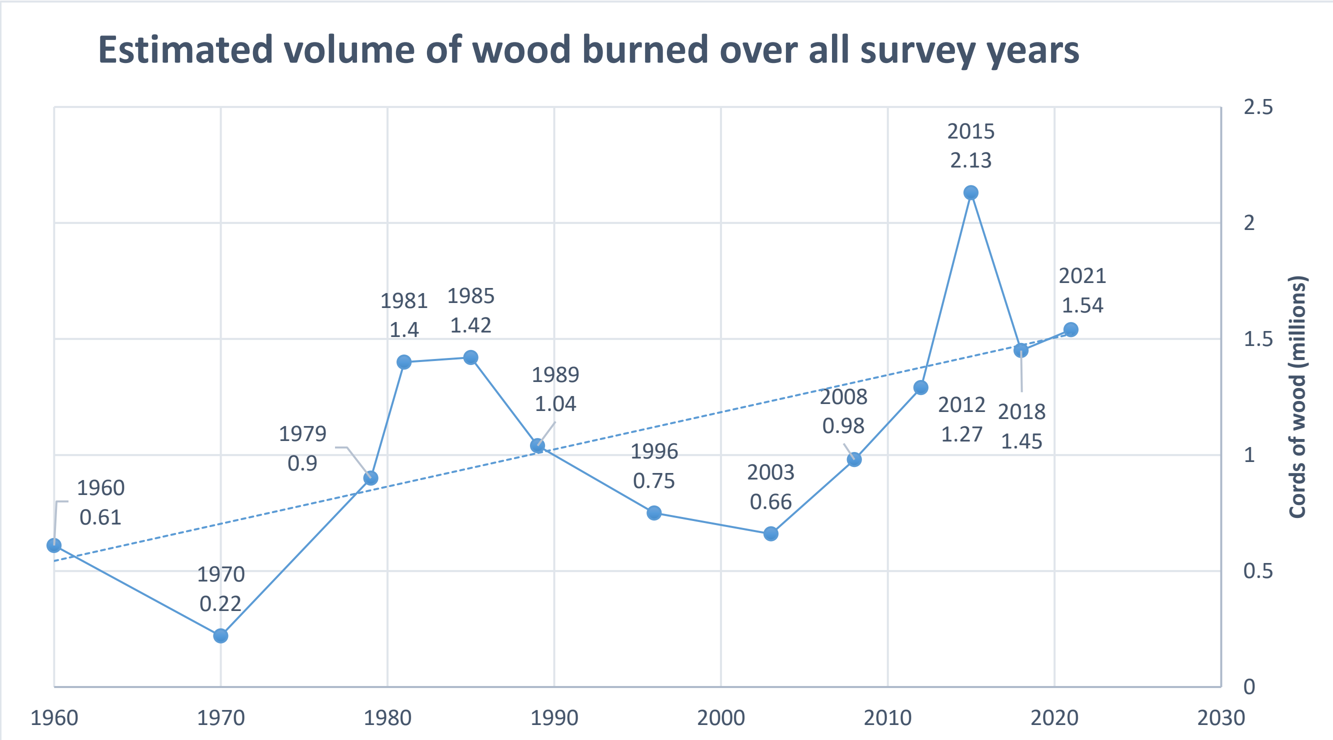
Volume of wood fuel burned

Total volume

Between May 1, 2020, and April 30, 2021, Minnesota households burned an estimated 1.54 million cords of wood. [4] This is a 6% increase from 2018 (Figure 3). the estimated amount of wood burned over all survey years has increased by an average of about 15,300 cords per year. Since 2003, the estimated amount of wood burned has increased by about 75,000 cords per year. Despite varying differences between years, wood burning in general appears to be increasing over time.

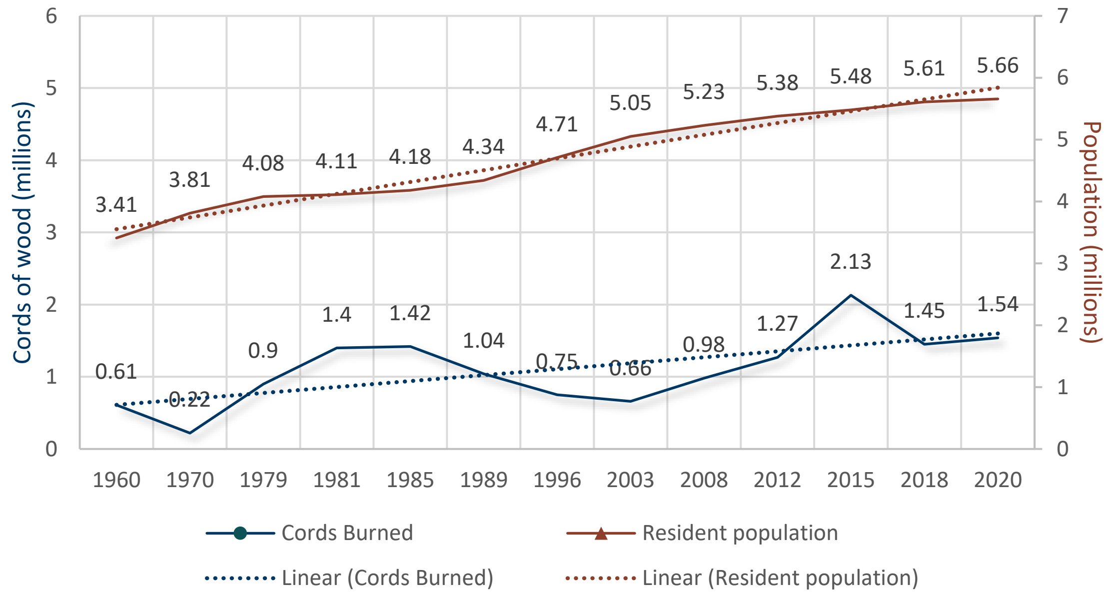
[4] *One cord of wood measures 8 x 4 x 4 feet (Figure 1). Unless otherwise noted, "wood" may include wax logs, wood reported in cords, face cords or bundles, wood pellets, pallets, slabs, and tree branches and woody brush. Table 1 describes the breakdown.*

Figure 3: Estimated volume of wood burned over all survey years



Concurrent to the general increase in the amount of wood burned over all survey years, Minnesota's resident population has been increasing at a rate of approximately 39,000 per year (Figure 4), corresponding to a 0.86% average annual growth rate. However, the average annual growth rate of wood burned over the same time period, at 1.5%, exceeds that of population. Since 2003, the volume of wood burned has been increasing by an average growth rate of 5.3% annually, while population has only increased by 0.7% per year since then. These estimates give a general idea of how growth in wood burning has compared to population growth, rather than a precise estimate.

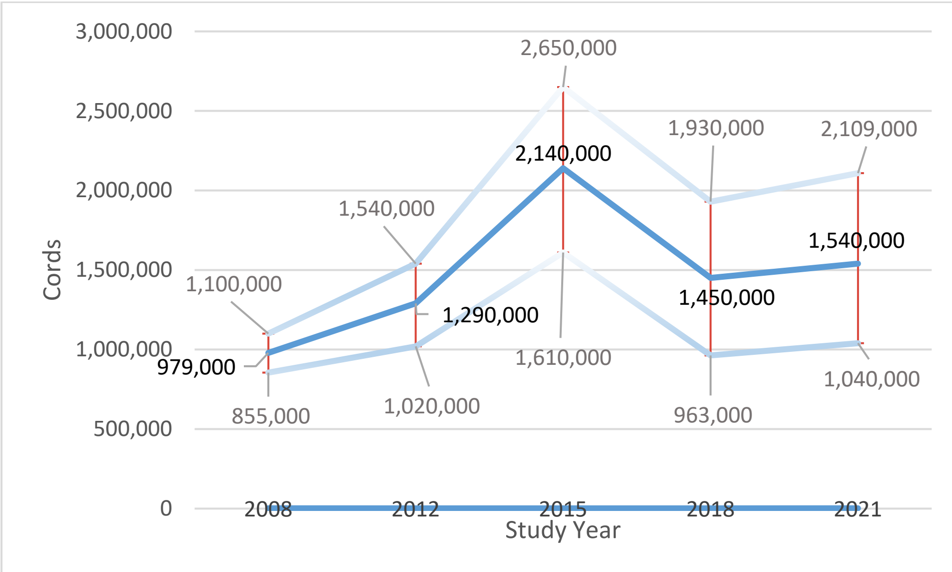
Figure 4: Estimated volume of wood burned and resident population over all survey years[5]



When applying a 95% confidence interval around the estimation of total wood burned in the 2021 survey, the result ranges from 1.04 to 2.11 million cords (Figure 5). In the 2018 report, the 95% confidence interval yielded a range between 0.96 and 1.93 million cords. The considerable overlap between these two intervals suggests that there was not a statistically significant increase in wood burning between the two surveys.

[5] *US Census Data collated https://www.statista.com/statistics/206236/resident-population-in-minnesota/*

Figure 5: Estimated volume of wood burned by survey year with 95% confidence interval



Minimal changes in survey design between 2018 and 2021 surveys and similar response rates are important, but comparisons between 2018 and 2021 should be made with caution. Observed trends over multiple survey years may also be affected by changes in survey design, which have not been tested for statistical significance. The occurrence of this survey during the COVID-19 pandemic may impact the results and burning rates. Survey selection bias, error in respondents' self-reporting, and changes to the survey tool and administration may also affect estimated burning rates and comparisons over time.

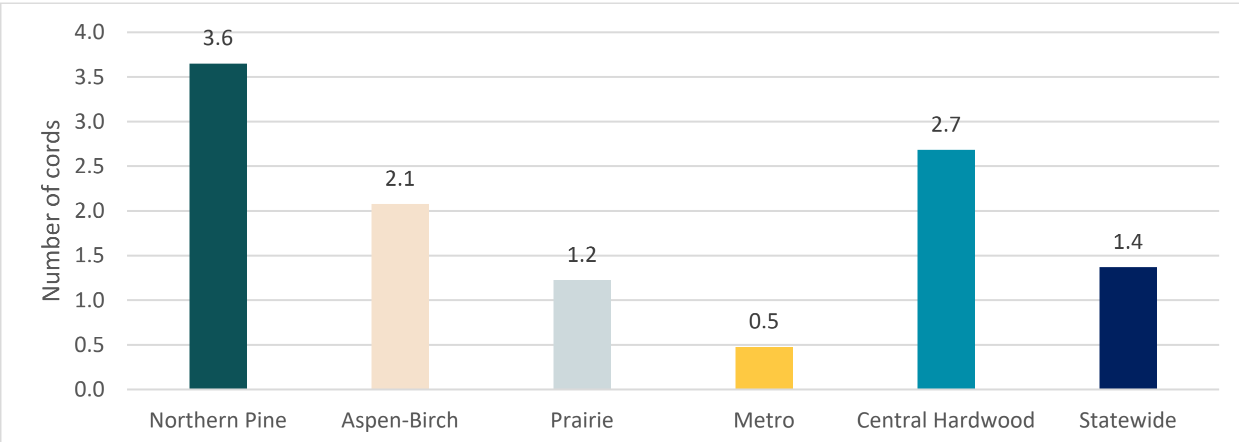
Wood burning by region

The greatest amount of wood burned in any of the five regions was in the Central Hardwoods region. Of the estimated 1.54 million cords burned statewide, an estimated 43%, about 660,000 cords, was burned in the Central Hardwoods region (Figure 6). The Metro region had (290,000 cords) or 19% of all wood burned. The fewest estimated number of cords burned were in the Prairie and Aspen-Birch regions, with 10% and 8% of all wood burned, respectively. These totals include all wood burned in each region at primary residences, secondary residences, or campsites. Both the Metro and Central Hardwoods regions increased wood burning over the 2018 survey. The Metro and Central Hardwoods regions also have the highest populations in the state. These increases could impact health issues considering the population density and increased potential exposure to wood smoke in these regions.

Figure 6: Estimated volume of wood burned in each region

Statewide, households that burned wood burned an estimated average of 1.4 cords of wood per household, regardless of property type (primary or secondary residences or campsites). However, the average varies considerably among regions. Households in the Northern Pine region on average burned the most amount of wood per household, 3.6 cords (Figure 7). Households in the Central Hardwoods region burned the next highest estimated amount of wood, at 2.7 cords per household. Metro households that burned wood averaged 0.5 cords burned per household.

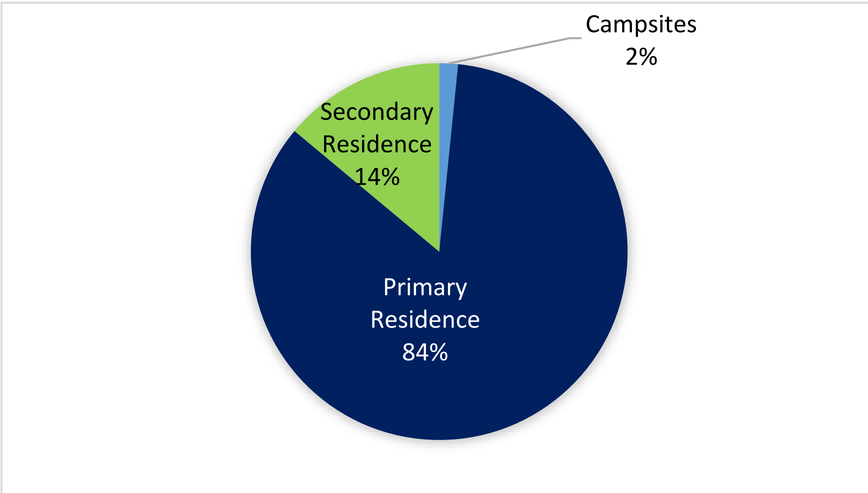
Figure 7: Estimated average volume of wood burned per household anywhere in the state by region



Location of wood burning by region

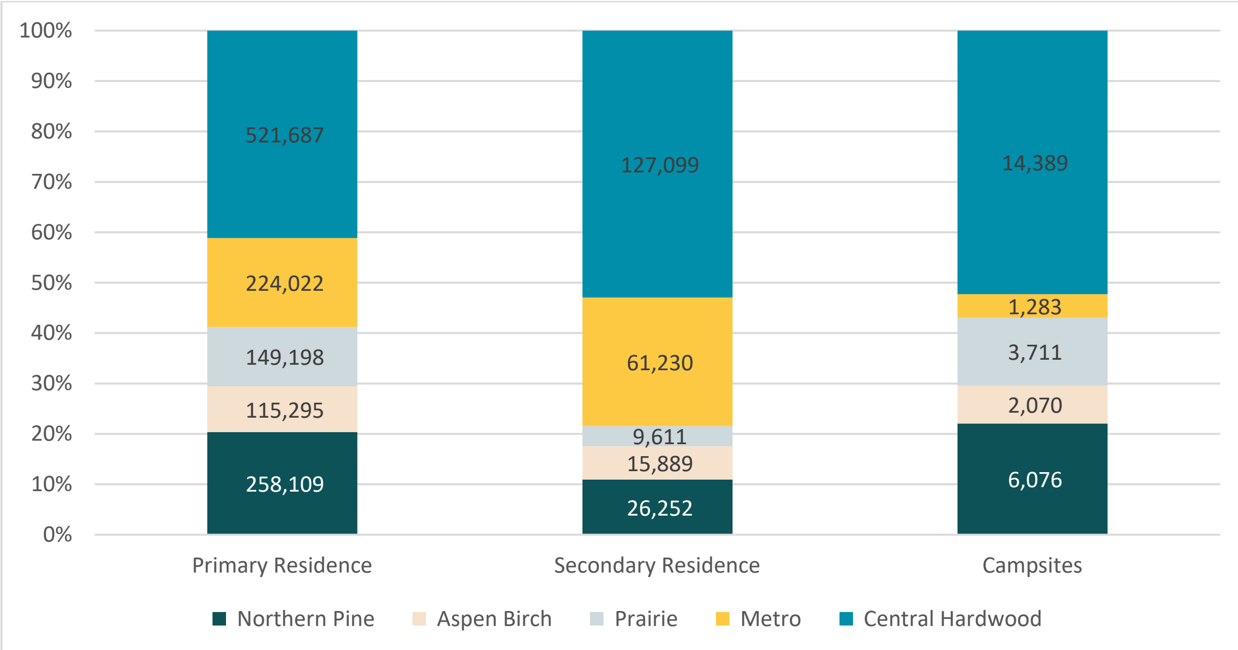
The majority of estimated wood burned statewide was at primary residences (1.27 million cords, 84%), followed by secondary residences (240,000 cords, 14%), and campsites (28,000 cords, 2%; Figure 8).

Figure 8: Estimated wood burned by property type



The greatest total estimated volume of wood burned at primary residences, secondary residences, and at campsites was in the Central Hardwoods region. Wood burned at primary residences in the Central Hardwoods region was 41% of all the wood burned in primary residences. (Figure 9). Over half of all the wood burned (53%) at secondary residences was in the Central Hardwoods region (127,000 cords). Of all the wood that was burned at campsites, more than one-half was burned at campsites in the Central Hardwoods region (14,000 cords).

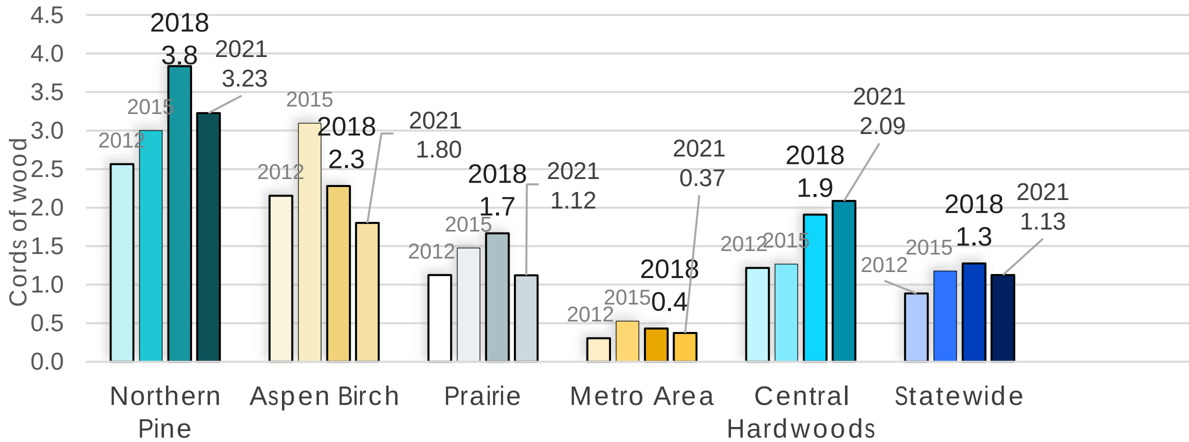
Figure 9: Estimated volume of wood burned by property type and region



Volume of wood burned per household

[Figure 10](#) shows the average wood burned per household by region over the past four surveys. Statewide, the overall amount of wood burned per household has stayed relatively flat with a slight decrease over the previous survey. In general, while more people are burning wood, the total amount of wood burned is not increasing significantly, each household is burning a little less.

Figure 10: Estimated cords burned per household by region and year



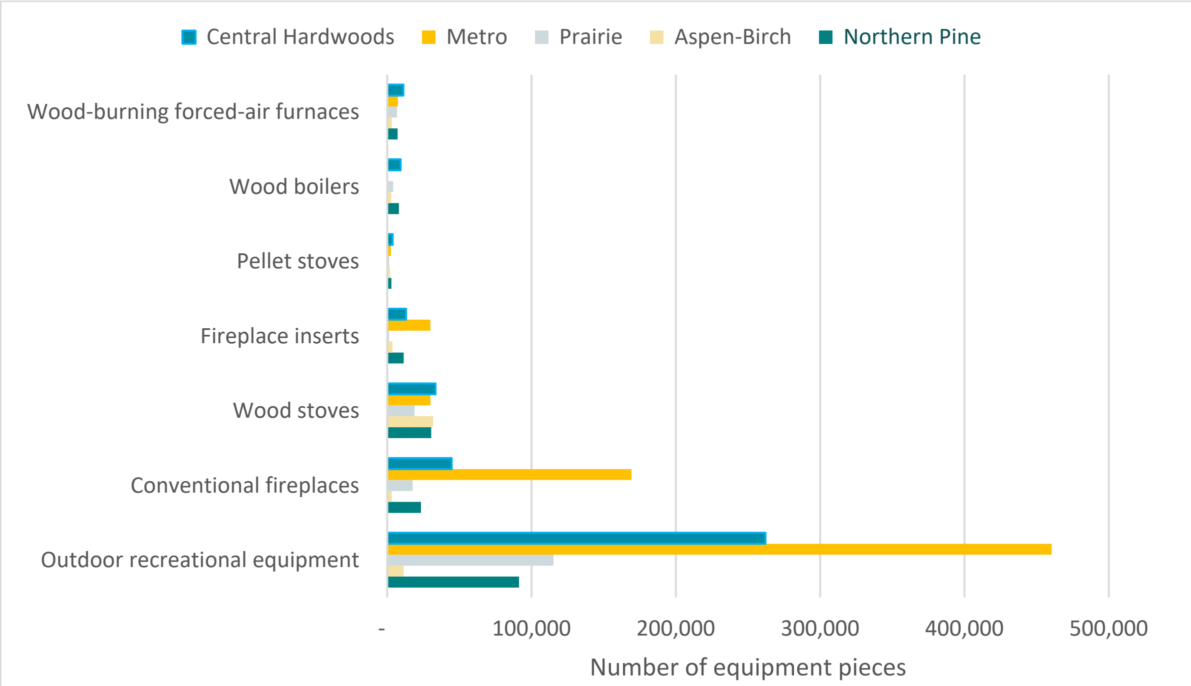
Equipment used for wood burning

Numbers of equipment pieces used

Between May 1, 2020, and April 30, 2021, Minnesota households used an estimated 2.2 million pieces of wood-burning equipment. The most common type of equipment owned at primary and secondary residences statewide was outdoor recreational equipment (fire pits, fire rings, chimineas, etc.), making up over 40% of all equipment used (not including equipment at campsites). The next most common pieces of equipment used were conventional fireplaces (14%) and wood stoves (8.6%). Less frequently reported equipment included fireplace inserts (1.8%), wood boilers (1.6%), wood furnaces (0.8%), and pellet stoves (0.4%).

Figure 11 shows the estimated number of equipment in each region by equipment type. Thirty-one percent of all equipment used was located in the Metro region, due to the region's large household population. The Metro had the most outdoor recreation equipment (360,000), conventional fireplaces (190,000), and fireplace inserts (12,000). Woodstoves were most commonly used in the Central Hardwoods (53,000) and Northern Pine (46,000) regions, as were furnaces, boilers, and pellet stoves.

Figure 10: Estimated number of pieces of wood burning equipment used by region[6]



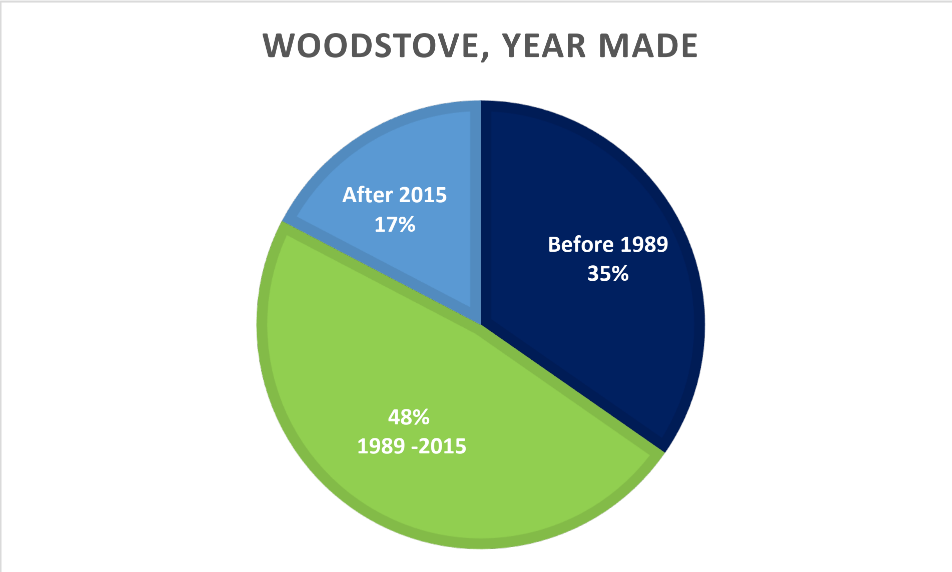
Age of wood stoves and fireplace inserts

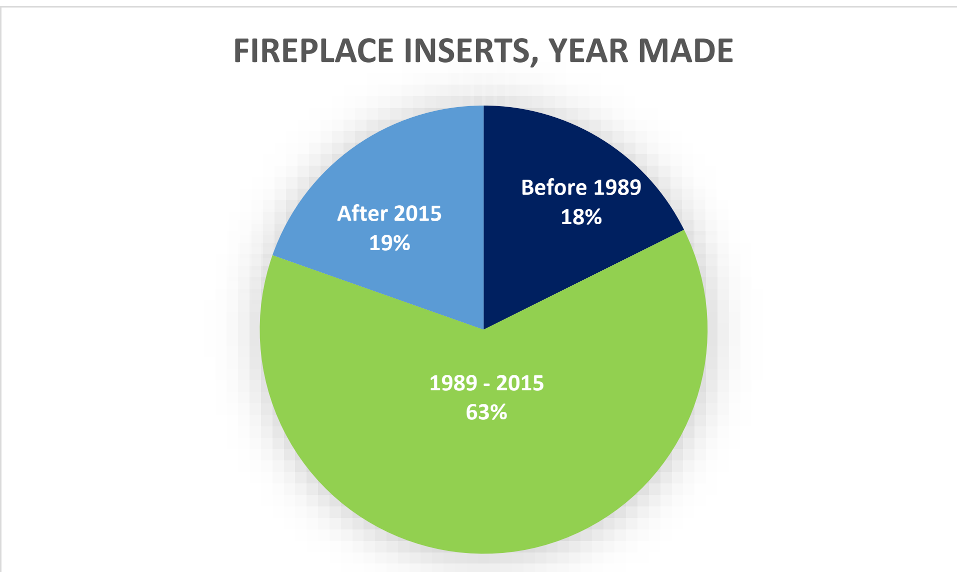
Federal standards to limit the amount of air pollution from wood stoves and inserts were initially adopted in 1989. In 2015, the U.S. Environmental Protection Agency (EPA) updated the standards to reduce air emissions, reflecting emissions and efficiency technology advances in the wood stove industry. The EPA further updated standards in 2020. Survey respondents were asked to report the age of their wood stoves and whether or not the stoves had a catalyst.

There were an estimated 54,429 wood stoves and 10,430 fireplace inserts used that were manufactured before 1989, compared with 26,437 wood stoves and 11,010 fireplace inserts manufactured since 2015 (Figure 12). These estimates inform an understanding of the potential quality of air emissions and the potential emission reductions that could be achieved from stove replacement programs. We know these are estimates because fireplace inserts and wood stoves may have worn or hidden tags where it is not accessible to view the manufacture date.

6 *Does not include outdoor recreation equipment at campsites, since they are not owned by Minnesota households. See Appendix C, Table 10 for unrounded estimated values.*

Figure 11: Equipment age of wood stoves and fireplace inserts



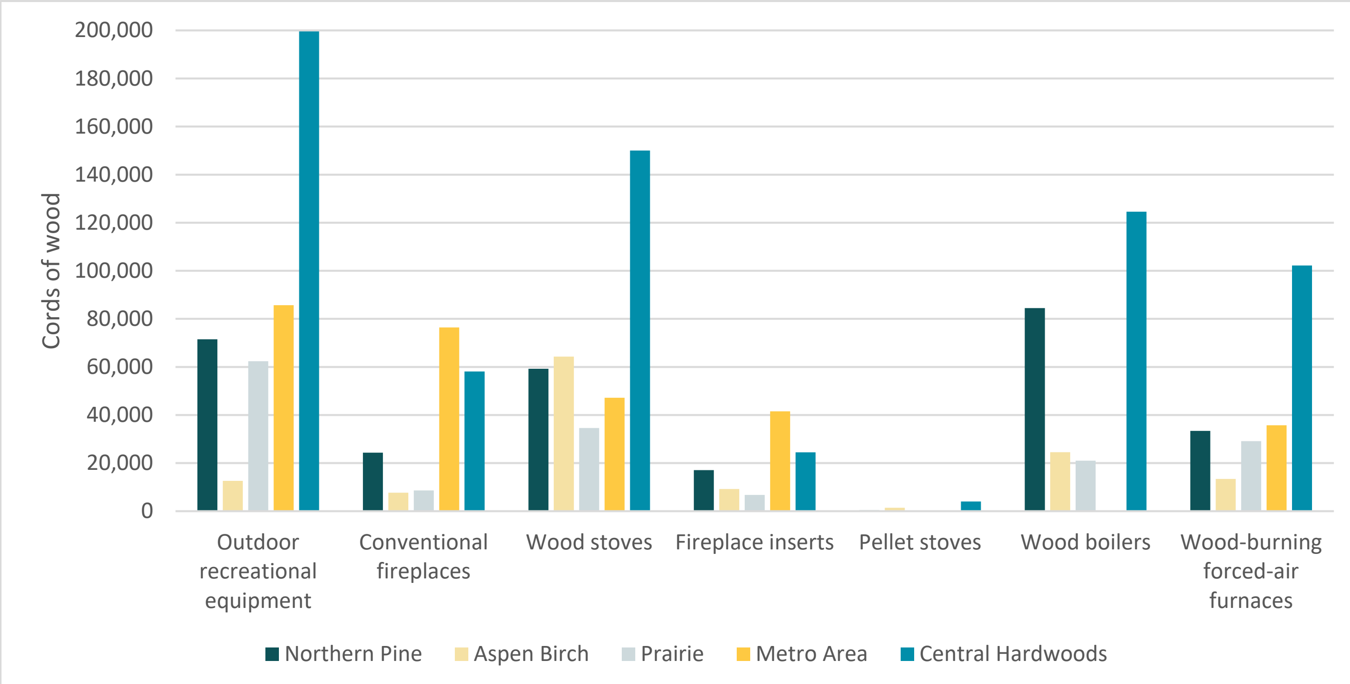


Wood burning by equipment and burn location

With 43% of the wood burned in the Central Hardwoods region, Figure 13 once again displays large quantities of wood burned in each type of equipment. Central Hardwoods burned the most wood in each type of equipment except conventional fireplaces, in which the Metro region burned the largest amount of wood.

In past surveys, these data have often shown extremely large quantities of wood burned in wood boilers and wood stoves. This year, outdoor recreational equipment shows the greatest amount of wood burned across regions.

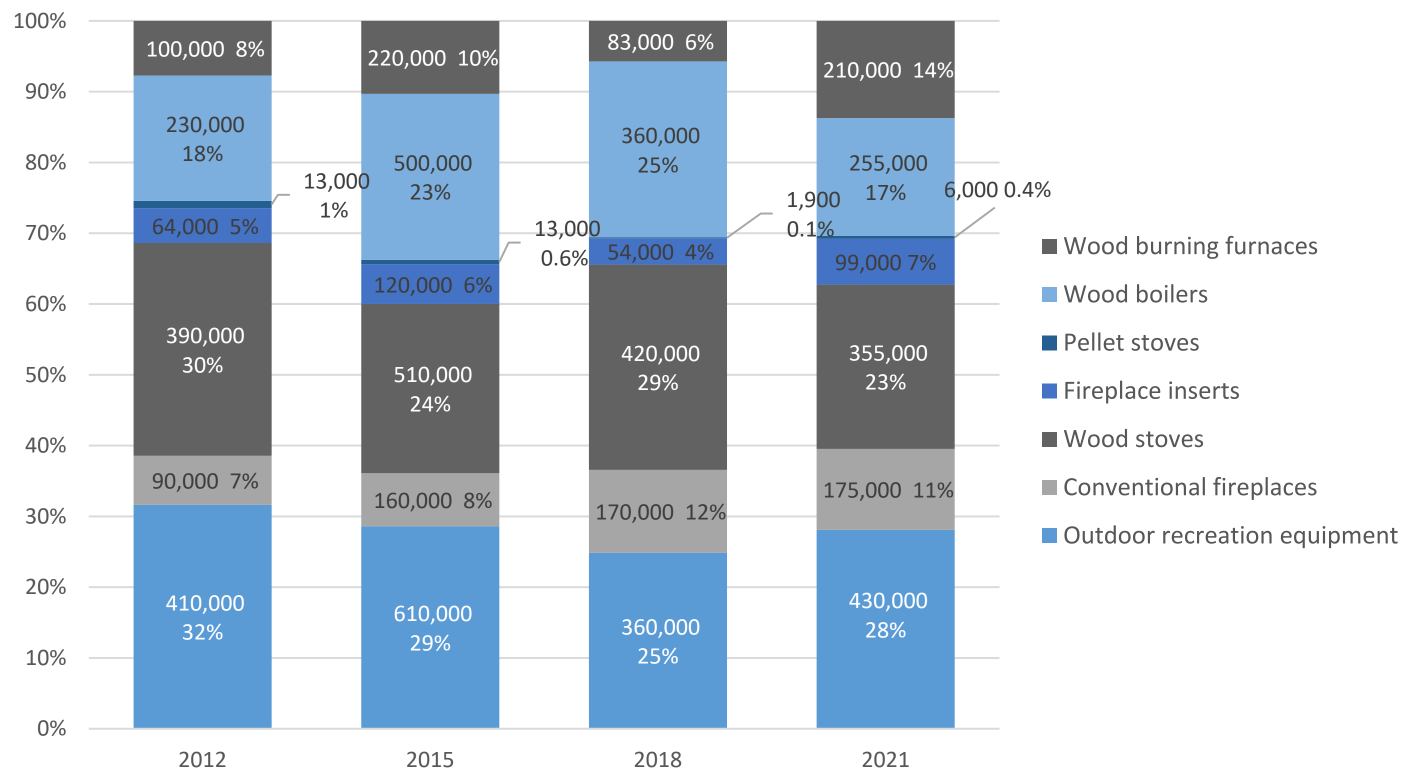
Figure 12: Estimated volume of wood burned by equipment type and region



Wood burning by equipment over time

The estimated proportions of all wood burned in each type of equipment have varied slightly between 2012 and 2021 (Figure 14). While wood burned in outdoor recreational equipment decreased from 2012 to 2018, it has increased in the 2021 survey. Fireplace inserts also increased between 2018 and 2021 surveys. The percentage of wood burned in wood boilers decreased, the percentage of wood burned in wood furnaces increased rather significantly.

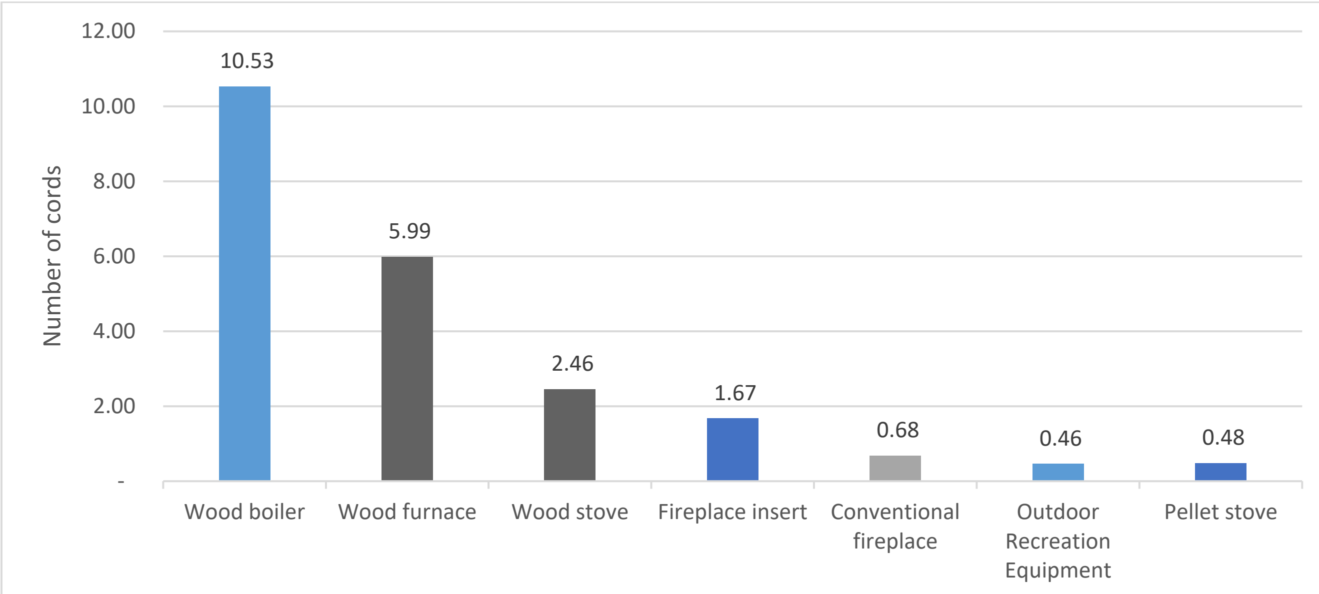
Figure 13: Estimated cords of wood burned as percent of total wood burned by equipment type and survey year



Wood burning rate by equipment type

On average, wood boilers and wood furnaces typically burned much higher quantities of wood than other types. Figure 15 shows the estimated average number of cords burned per type of equipment in 2021. Wood boilers burned more wood per unit than all other types and this has been consistent between 2018 and 2021. The statewide estimated average quantity burned in a wood boiler was about 10½ cords per year. Pellet stoves burned the least wood for heat, which is understandable given their higher heating efficiency and that they generally require less wood than other heaters (see conversion factor in Appendix A). Outdoor recreational equipment also burned very small amounts of wood since this type of equipment is generally used for pleasure and disposal of woody yard waste.

Figure 14: Average estimated volume of wood burned annually by equipment type[7]



Characteristics of wood fuel users

Reasons for wood burning

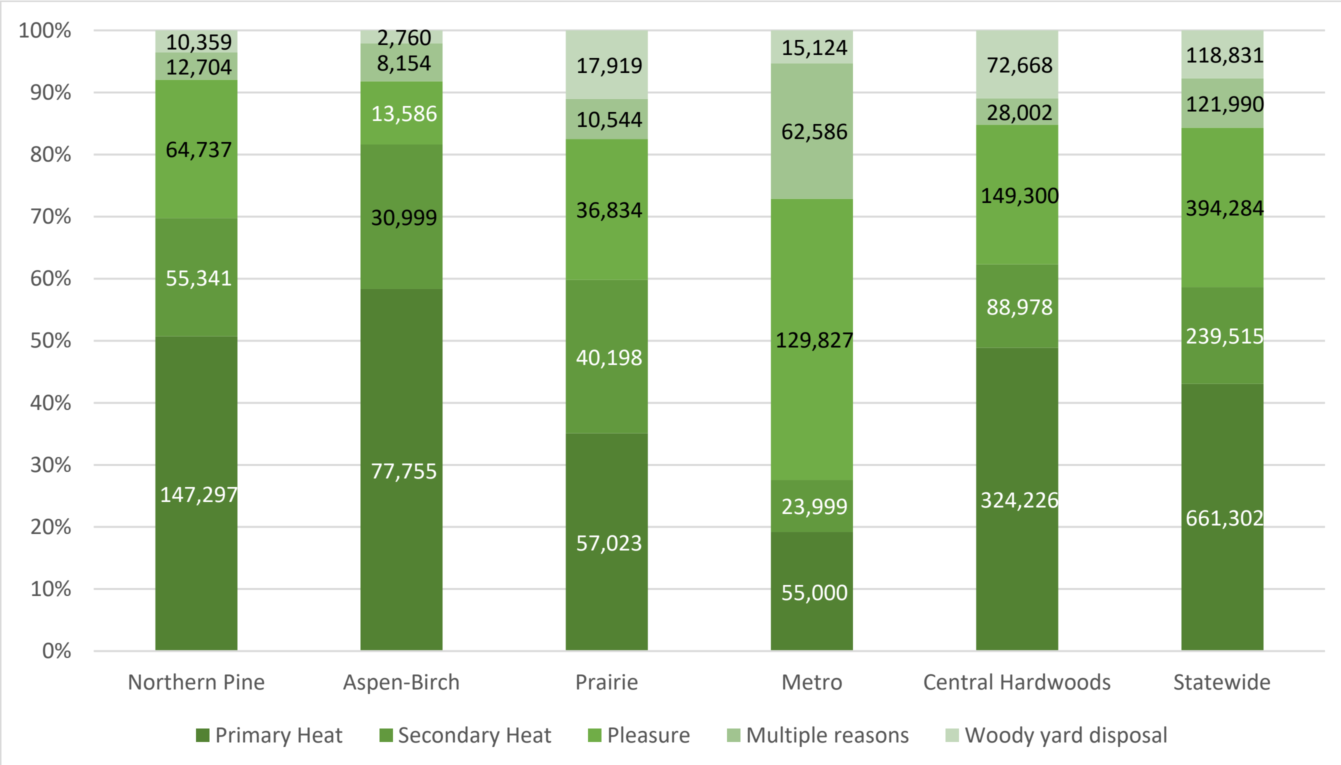
Survey respondents were asked to report their reason(s) for burning wood in each type of equipment they used. For each type, respondents could select from the following five options: pleasure, primary heat source, secondary heat source, multiple reasons, or disposal of woody yard materials.

Statewide, the greatest estimated volume of wood was burned for primary heat (43%), followed by burning for pleasure (26%), and secondary heat (16%). Disposal of woody yard materials and multiple reasons each accounted for an estimated 8% of the amount burned.

In 2021, the estimated distribution and purpose for wood burning varied between the regions (Figure 16). The greatest estimated volumes of wood burned for heat — both primary and secondary — were in the Central Hardwoods region (324,226 cords and 88,978 cords respectively), as well as the greatest estimated volume of wood burned for pleasure (149,300 cords) and woody yard disposal (72,668 cords). The Metro region had the greatest estimated proportion of wood burned for pleasure among all regions, accounting for approximately 45% of wood burned in the region, up from 29% in the 2018 survey.

7 *Does not include wood burned in outdoor recreation equipment at campsites.*

Figure 15: Estimated cords of wood burned as a percent of total wood burned by reason and region



Households in the Northern Pine region burned the highest average volume of wood per household for primary heat, at an estimated average of 1.72 cords per household (Figure 17). The Northern Pine and Central Hardwoods regions also had the highest estimated averages per household for wood burned for pleasure. All the non-Metro regions burned more wood for primary heat than for pleasure.

Figure 16: Average estimated volume of wood burned per household by burn purpose[8]

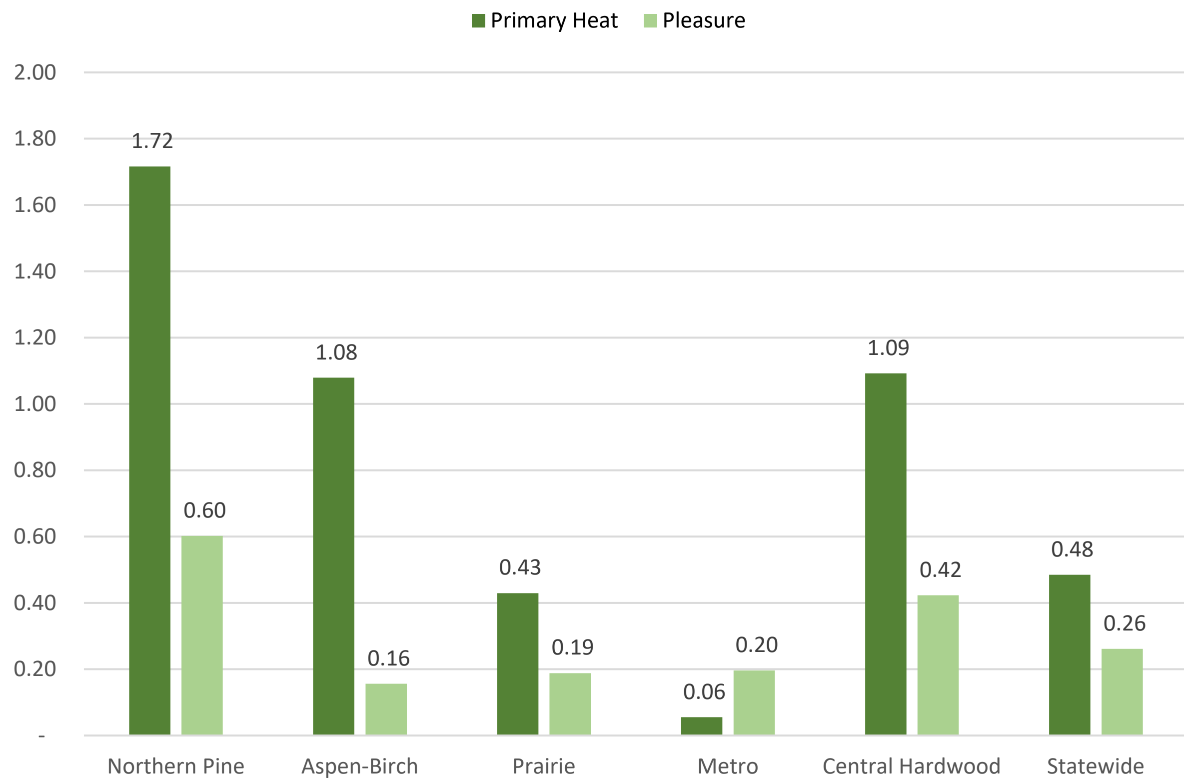
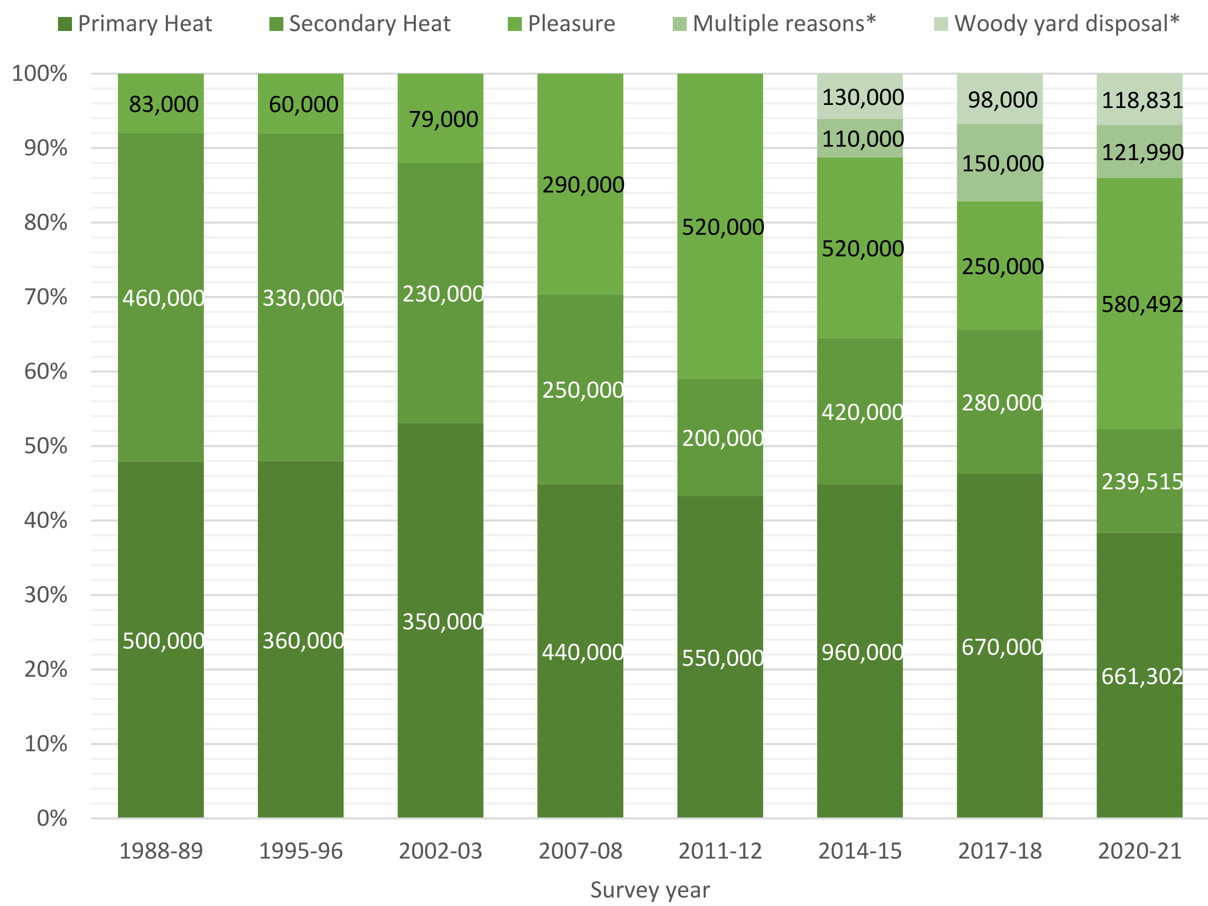


Figure 18 shows this distribution of reasons for burning wood from the last eight surveys conducted. Note that "woody yard disposal" and "multiple reasons" were first added to the survey in 2015. The estimated proportion of wood burned for primary heat has remained relatively consistent over the last three decades, accounting for about half of all wood burned. Beginning after 2003, the proportion and total amount of wood burned for pleasure began to increase rapidly over the following decade, accounting for 12% of wood burned in the 2003 survey and 41% in 2012. In the 2021 survey, burning wood for pleasure accounted for 38% of the all the wood burned. This significant increase (17% of wood burned for pleasure in the 2018 survey) could be explained by the increase of people being home and using home wood burning equipment for pleasure burning in both outdoor recreational equipment and fireplaces. Amounts of wood burned for reasons other than pleasure decreased but stayed relatively consistent between the 2018 and 2021 surveys, but the amount of wood burned for pleasure more than doubled between survey years. The 2021 survey indicates the most wood ever has been burned in Minnesota for pleasure.

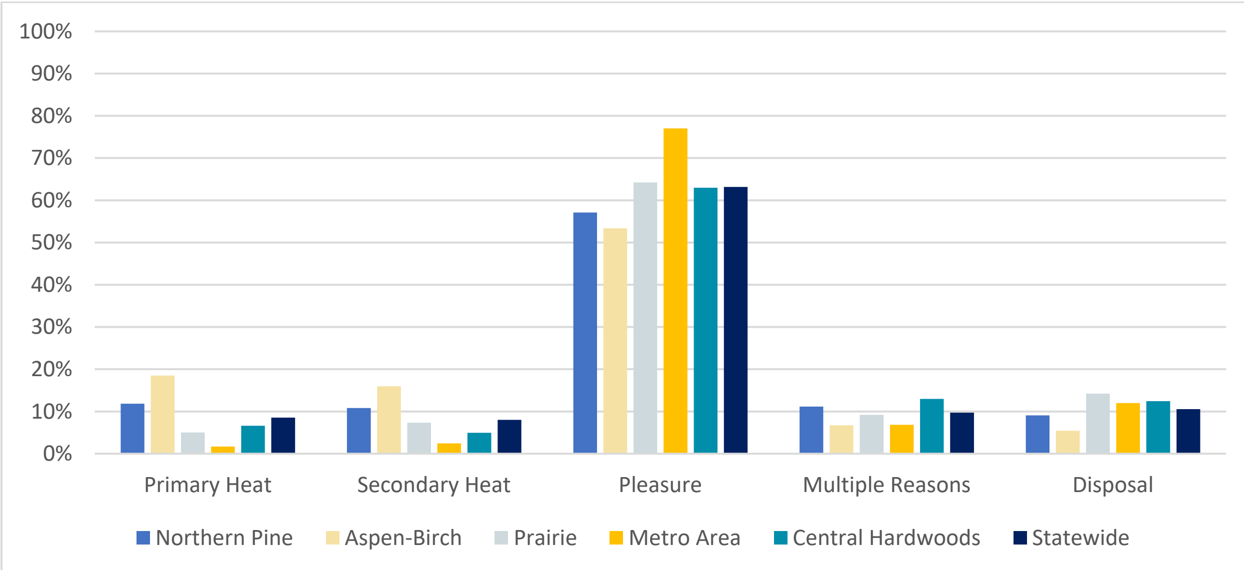
[8] *Based on number of cords burned at primary residences.*

Figure 17: Estimated cords of wood burned by reason for burning, as percent of total wood burned by survey year



Statewide the greatest estimated volume of wood was burned for primary heat (661,302 cords) but burning for pleasure was the most common reason a household burned wood. As illustrated in Figure 19, this held true across all regions, with the greatest percent of households burning for pleasure (27-39% of total households by region). Statewide, 34% of all occupied households burned for pleasure. Comparatively, only 5% burned for primary heat. Wood burned for primary heat made up 43% of all wood burned in the state. The estimated percentage of total households that burned for primary heat varied among regions from 1% of all households in the Metro to 18% of all households in the Aspen-Birch region.

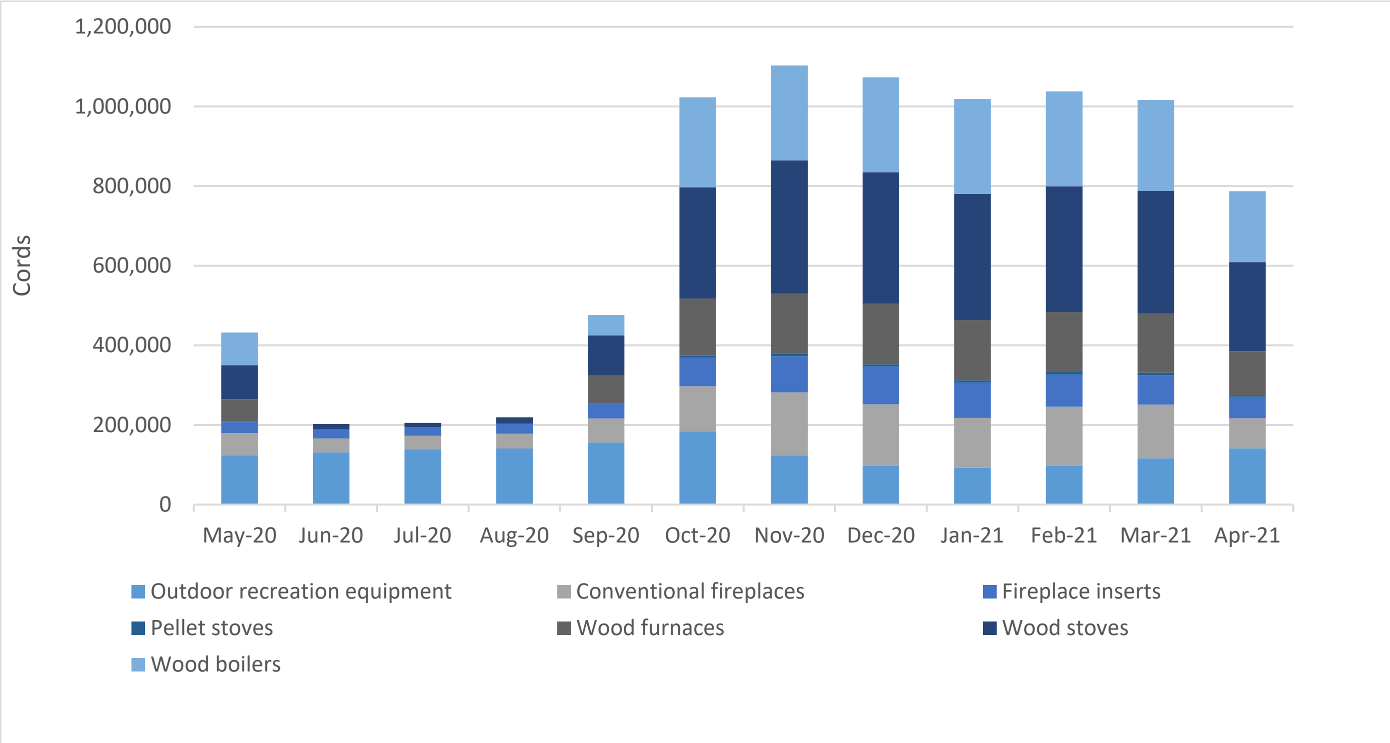
Figure 18: Estimated percent of total household population in each region by reason for burning



Time of year

Survey respondents were asked to report the months of the year in which they burned wood. Most was burned from September to May, reflecting the use of wood for heating purposes (Figure 20). Outdoor recreational burning occurred throughout the year, but primarily in spring, summer, and fall. Some wood boilers were also operated throughout the year, indicating their use in the summer months for purposes other than space heating, including to heat domestic water supply for washing, cooking, etc. Wood stoves and conventional fireplaces were also operated in all months of the year.

Figure 19: Estimated volume of wood burned each month by equipment type[9]



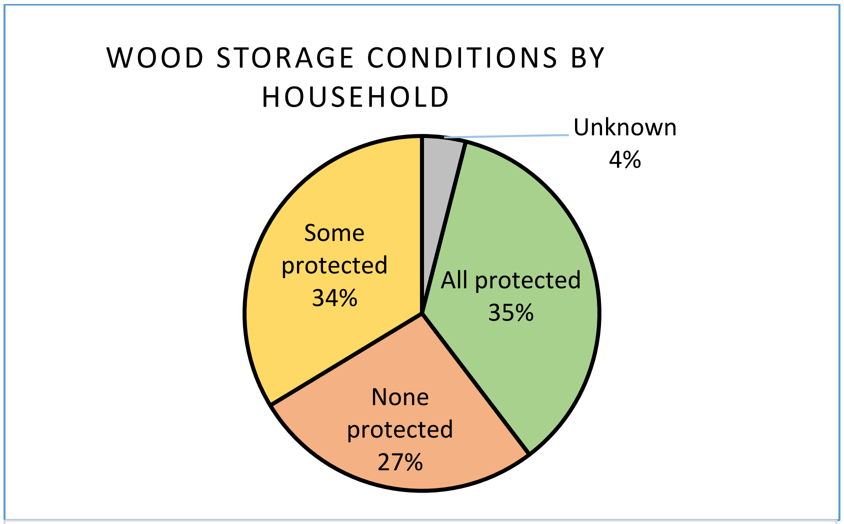
Wood storage practices

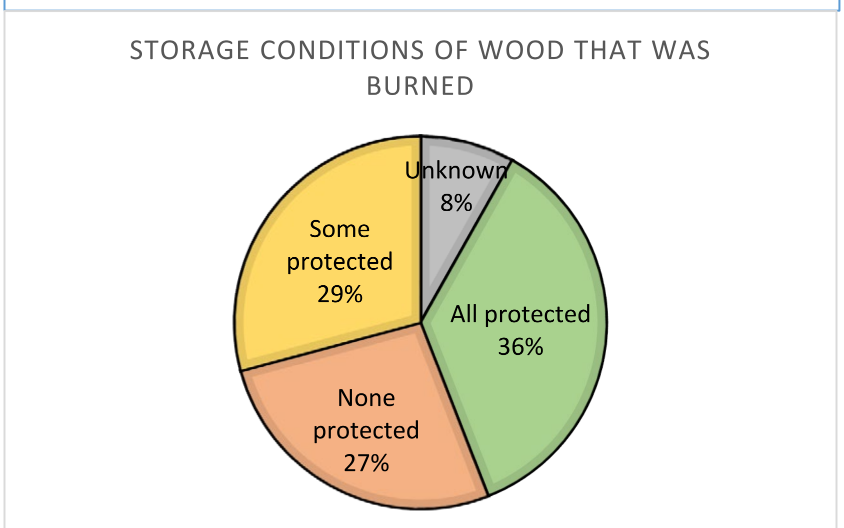
Survey respondents were asked to report whether their wood was stored protected from the elements, such as rain, at primary and secondary residences. This aspect of wood use is important in addressing air quality since burning dry wood emits fewer air pollutants than burning wet wood.

While less than half of Minnesota households stored their wood protected from the elements, more than half of the estimated wood burned was stored dry (Figure 21). This was because households that burn large quantities of wood for the purposes of heating are likely more careful about storing their wood protected.

[9] *Does not include wood burned at campsites. Some respondents did not indicate in which months they used their equipment.*

Figure 20: Wood storage conditions[10]





Types and sources of wood burned

Survey respondents reported the volume of wood they burned in units of cords, face cords, bundles, and bags of branches. Depending on the equipment type, they could also report the volume of wood in the form of pallets, slabs, wood pellets, and wax logs. These volumes were converted to full cords for analysis. Nearly all wood burned in the state was in the form of "wood" logs and split wood (99%). Pallets (<1%), wood pellets (0.4%), and wax logs (<1%) accounted for much smaller proportions of all the wood burned. No slabs of wood were reported burned (Table 1).

[10] *Only includes wood burned at primary and secondary residences, not campsites.*

Table 1: Estimated volume of wood burned by fuel type

Fuel type	Cords	Percent of total
Wood (cords, face cords, and bundles)	1,526,335	99.38%
Pallets	1,456	<0.1%
Wood pellets	5,891	0.38%
Wax logs	2,239	0.15%
Total	**1,535,921**	

Types of wood burned

The distribution of types of wood burned in 2018 was similar to distribution in previous surveys. The greatest estimated known percent of wood burned was oak (37%), followed by ash (12%). Pine was burned as the third greatest species of wood, but this was less than the previous survey. (Table 2). Trends are difficult to determine because of the addition and deletion of types and groupings.

Table 2: Estimated percent of wood burned by species type

	Percent of statewide total							
Type	**1988-89**	**1995-96**	**2002-03**	**2007-08**	**2011-12**	**2014-15**	**2017-18**	**2020-21**
Oak	32%	27%	38%	29%	29%	27%	22%	37%
Unknown species	N/A	N/A	N/A	N/A	N/A	14%	17%	14%
Ash	8%	4%	10%	17%	11%	11%	9%	12%
Maple	8%	4%	8%	10%	9%	6%	9%	9%
Pine	N/A	N/A	N/A	N/A	6%	7%	11%	8%
Birch	13%	14%	13%	9%	11%	11%	10%	7%
Aspen	7%	10%	8%	12%	7%	9%	5%	5%
Elm	14%	3%	5%	9%	6%	5%	5%	4%
Basswood	N/A	N/A	N/A	N/A	1%	2%	3%	4%
Other hardwoods	N/A	N/A	N/A	N/A	N/A	5%	6%	N/A
Other softwoods	N/A	N/A	N/A	N/A	N/A	3%	4%	N/A
Cedar	N/A	N/A	N/A	N/A	<1%	N/A	N/A	N/A
Mixed species	N/A	N/A	N/A	N/A	16%	N/A	N/A	N/A
Other species	3%	6%	9%	10%	4%	N/A	N/A	N/A
Slabs and scrap lumber	15%	32%	8%	4%	N/A	N/A	N/A	N/A

Note: Changes over time should be interpreted with caution due to changes in the survey design, methodology, response rate, and conversion rates for different types of wood.

N/A: Minimal or not asked on the survey

Procurement of wood for burning

The survey asked respondents to report how and where they procured the wood they burned. About 57% of the wood Minnesota residents burned was self-harvested by the household or an immediate family member, while 36% was purchased or received for free (Table 3). A significant portion (7%) came from an unknown source. The total cords of wood harvested does not include wood gathered during yard clean-up or maintenance.

Table 3: Estimated amount and percent of wood burned by procurement method

Procurement method	Percent of state total	Cords
Self-harvested	57%	875,349
Purchased or received for free	36%	549,416
Unknown	7%	111,157
Total		**1,535,921**

Wood harvesting

The survey asked respondents how much firewood they harvested for the purpose of burning over the course of the year, not including wood gathered during yard clean-up or maintenance.

Amount of wood harvested

Results of the survey indicated an estimated 1.2 million cords of wood were harvested by Minnesotans between May 2020 and April 2021. This is greater than the 875,000 total cords reported as self-harvested in Table 3 because the total in Table 3 refers to amount of wood burned that was procured via harvesting. This may be because respondents harvested more wood than they ended up burning, accounting for the discrepancy between these two values.

Types of wood harvested

Similar to the distribution of wood burned, the greatest percent of wood harvested was oak (31%), followed by ash (12%) and aspen, basswood, and elm (all 9%). (Table 4).

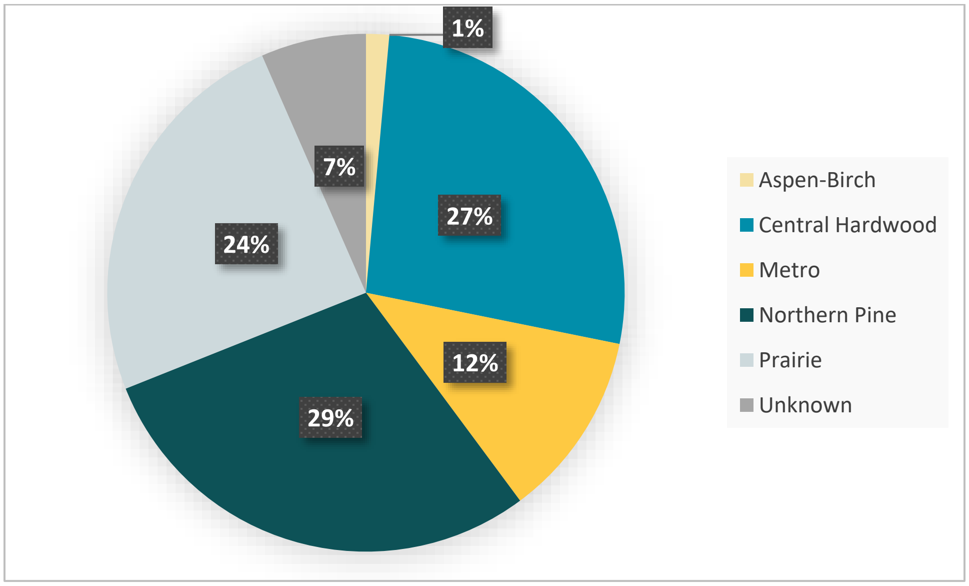
Table 4: Estimated percent of wood harvested by species

Type	Percent of total
Oak	31%
Ash	12%
Aspen	9%
Basswood	9%
Elm	9%
Maple	7%
Pine	7%
Birch	5%
Unknown species	10%

Location of wood harvesting

The Northern Pine region had the greatest reported amount harvested from the region with 29% of the total (Figure 22), followed closely by Central Hardwoods at 27%. Prairie residents reported harvesting a significant amount of wood in this survey at 24% of the wood harvested. This question was redesigned from the 2018 survey which listed "Unknown" as the first option. Over half of the respondents chose that answer in the 2018 survey. Moving the "unknown" response as the last option may have resulted in more accurate answers for the 2021 survey.

Figure 21: Estimated percent of wood harvested by region



The majority of harvested wood was from private land (76%). Small proportions were harvested from county land (5%), state land (<1%), and national forestland (<1%). A larger portion of the wood harvested was from unknown land (18%) in this survey than in the previous survey. (Table 5)

Table 5: Estimated amount and percent of wood harvested by property type

Harvest location	Cords	Percent of total
Private land	891,709	76%
Unknown	211,505	18%
County land	60,855	5%
State land	3,808	<1%
National land	3,864	<1%
Municipal land	622	<1%
Total	**1,172,363**	

An estimated 36% of the wood harvested came from dead trees from forestland which is an increase over the past survey. Wood harvested from live or dead trees from yards inside city limits, or other non-forest land (35%) was the second greatest source of harvested wood; 14% came from cut trees and/or tops and branches after a timber harvest; 8% unknown; and 7% live or dead trees from pasture land and/or cropland. Less than 1% came from live trees from forestland (Table 6).

Table 6: Estimated amount and percent of wood harvested by type of harvest source

Harvest source	Cords	Percent of total
Dead trees from forestland	424,478	36%
Live or dead trees from yards, inside city limits, or other non-forestland	404,726	35%
Cut trees and-or tops and branches after a timber harvest	164,593	14%
Unknown	93,884	8%
Live or dead trees from pasture land and/or cropland	82,386	7%
Live trees from forestland	2,296	<1%
Total	**1,172,363**	

Recreational firepit emissions testing

Introduction

The MPCA contracted with the U.S. Forest Service Fire Sciences Laboratory in Missoula, Montana, to measure fine particulate matter ($PM_{2.5}$) from firepits. The Missoula Fire Sciences Laboratory in Montana conducts research into the fundamentals of fire behavior, extensive modeling of fire behavior, studies of soil heating, determination of fire effects and ecosystem response to fire, estimation of fire danger, as well as measurements of smoke emissions, dispersion, and chemical content. The laboratory hosts a large-scale combustion facility where firepit emissions testing was conducted.

The project goal was to provide data for estimating $PM_{2.5}$ emissions from conventional and those marketed as "low smoke" outdoor recreational firepit use in Minnesota. As this wood use survey indicates, a significant amount of wood is burned in backyard fires or campgrounds, and the MPCA was interested in learning if the growing popularity of low-smoke campfire stoves represent an opportunity for reducing the amount of PM associated with backyard fires.

The study asked:

- Do PM emission rates differ among firepits?
- How does firewood moisture content affect PM emissions?

Summary of findings

1. The limited number of tests for each stove and moisture content condition along with high variability in results makes conclusions about the influence of moisture content on PM emissions uncertain. As a general conclusion, it appears that with increasing moisture content, the low smoke firepits emit less PM than the traditional firepit.
2. When PM emissions are normalized to radiant heat flux, PM emission factors increase with moisture content.
3. The PM emission factor derived from this study overall is 2.2 g/kg. The default emission factor in the National Emissions Inventory for this activity (Res. Heating: Outdoor woodburning device,

NEC) is 11.8 g/kg. The results of this study are probably a better estimate for appliances of similar design (barrel style, burning split wood at a moisture content of less than 35%) than this NEI emissions factor.

4. The results of this study indicate that further testing would be beneficial to address the influence of variability on final results.

The full report can be found in Appendix D.

Firepits tested

Three firepits were tested. Breeo and Solo stoves were identified as "low smoke" firepits, while the MPCA selected the firepit ring installed at Minnesota DNR-operated campground to represent a traditional firepit ring. This ring is manufactured by Pilot Rock. Figure 23 below provides visuals of the three firepits.

Figure 23: Firepits tested

Assumptions about firepit use/operation in setting up the experiment

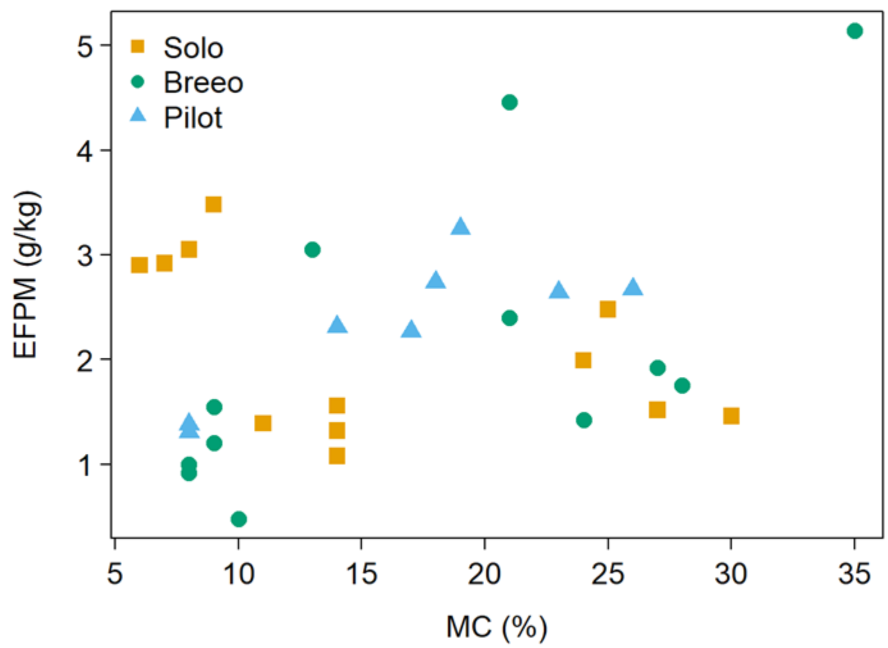
Pollutant yield from burning wood in a firepit typically increases with moisture content, while radiant heat yield decreases with moisture content. Recognizing that wood consumption is largely dependent on user behavior, the experiment was designed to use a fueling cycle that applies to a range of user behaviors. If we assume firewood input is driven by user desire for radiant heat, wood is added to the fire when more heat is needed. Therefore, radiant heat was measured during each test and wood added to sustain a robust, steady fire.

Wood from Minnesota that is typically preferred for firepits (oak, maple, birch) was prepared in standard dimension to fit the firepits, and then conditioned to specific moisture content. The MPCA advises that wood is dry if its moisture content is less than 20%.

Results

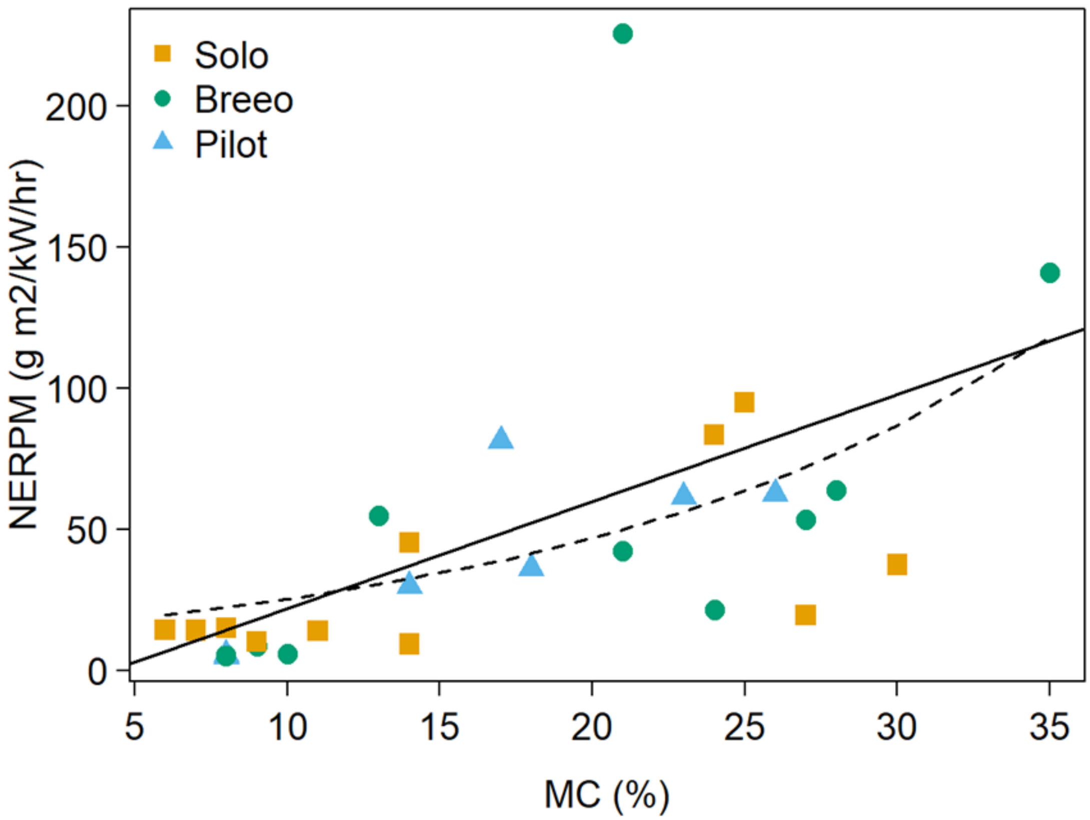
$PM_{2.5}$ emissions were measured and reported in two ways: on a mass basis (EFPM) and normalized to radiant heat flux (NE). Figure 24 below shows the PM emission factor on a g/kg basis. Results discussed are from the steady state operating conditions. Limited test number and high variability of emission results make conclusions on the influence of moisture content uncertain. However, as a general observation, particulate matter from the low smoke firepits increases with moisture content, but in this experiment, the low smoke firepits PM emissions are not significantly lower than the conventional firepit as assumed. At conditions assumed to be very dry (moisture content less than 10%), PM emissions from one low smoke firepit were significantly higher than the other firepits, including the traditional firepit.

Figure 24: Particulate matter emission rate versus wood fuel moisture content (EFPM), mass basis



However, when results are normalized to radiant heat flux, that is, heat demand, emission profile changes; PM emissions showed a more dramatic rise as moisture content increases, increasing by factors of 14.7 and 12.1 for the Breeo and Pilot Rock Firepits (Figure 25).

Figure 25: PM emissions normalized to radiant heat flux during steady burn phase



Conclusions

Key findings

Since 2003, residential wood burning appears be increasing over time. An estimated 1.54 million cords were burned between May 1, 2020, and April 30, 2021.

Roughly 1,170,000 households, or about 53% of all Minnesotan households, burned wood in some amount during this time period. This proportion varies between the five survey regions. The Northern Pine region had the highest estimated proportion of households that burned wood, at 63% of the region's total households, while the Prairie region had the lowest, at 42%.

Statewide, the greatest volume of wood burned was for primary heat, but burning for pleasure was the most common reason a household burned wood. Statewide, an estimated 43% of all wood burned was burned for primary heat. However, only 9% of households statewide burned for primary heat, while 63% of households burned for pleasure.

Unlike past surveys that showed wood stoves burned the largest amount of wood, this survey show that **the largest amount of wood was burned in outdoor recreational equipment.** An estimated 430,000 cords of wood was burned in outdoor recreational equipment statewide.

More than half of the wood burned was stored protected from the elements. Wet wood burns less efficiently than dry wood and releases more smoke.

New, certified stoves and fireplace inserts are being installed, but stoves and inserts older than 1989 are not being removed. **About one third of wood stoves and one fifth of fireplace inserts in use were manufactured prior to 1989.** These older models pollute significantly more than those manufactured later do.

The survey was **conducted during the COVID-19 pandemic, and Minnesota's Emergency Stay-at-Home order** was in effect during this survey period. Results may reflect differences that are unique to other surveys, especially responses about outdoor recreational equipment and burning for pleasure as a common social activity during this time was to gather around an outdoor recreational fire.

The results of the MPCA's PM emissions testing of firepits is included in this survey report. This test is an initial evaluation of firepits classified as "low smoke". Results are very preliminary, and more testing is needed.

- **Moisture content affects particulate matter emissions**. Drier wood emits less PM than wetter wood. Low smoke firepits emit less PM when wood is dry, however when wood was very dry, one popular model was the highest PM emitter. **The emission factor developed from this testing is an order of magnitude lower than that used** in states' and EPA's National Emissions Inventory for residential wood burning.

Implications

Opportunities still exist for wood-burning equipment change-out programs. Information about the number, location, and types of old, dirty wood burning equipment still being used will be useful for efforts such as Environmental Initiative's Project Stove Swap[11] in designing those incentive programs.

The Metro region covers a much smaller geographic area than any other region, but its households burned a comparable amount of wood. On average, **the Metro region burns more cords of wood per acre than any other region**.

More wood burning translates to more air pollution. The amount of air pollution released from the different types of wood-burning equipment varies depending on the air pollution controls. Outdoor recreational residential fires, which have no controls, account for 30% of the wood burned in the Metro region and 28% of the wood burned statewide, suggesting that information campaigns about how to build clean-burning backyard fires will be useful throughout Minnesota, especially in more densely populated neighborhoods. These data will inform the MPCA's partners in Clean Air Minnesota[12] who are working on voluntary measures to reduce air pollution from sources such as residential wood burning.

Estimates from this study indicate residents use their backyard recreational equipment to dispose of woody materials from their yards. If other methods for disposing of branches and brush from residential properties were convenient and widely available, this air pollution source could be reduced.

Additional analysis and possible future research

This report provides initial data analyses. The data set is robust, allowing the MPCA to conduct additional analyses of the data. For example, further analysis is in progress on the increasing trend of wood burning especially compared to population, external factors such as propane and other fuel prices, and better understanding of the reasons for use of specific equipment. The data set will be available from MPCA on request.

In February 2015 and again in 2020, EPA revised the standard for new wood stoves and fireplace inserts as well as boilers (hydronic heaters) and forced-air furnaces. As the survey data show, we are already seeing more households using these cleaner-burning units. We are concerned that people may be keeping old devices in use, as well. The MPCA will be evaluating how to incorporate the increasing use of these newer devices into its emissions inventory estimates, and how to encourage recycling of older units.

The MPCA could consider ways to better understand the use of wood burning in commercial establishments such as restaurants, since it seems, at least anecdotally, use of wood-burning ovens, smokers, and grills seems to be increasing in popularity.

Other factors have been speculated as affecting wood use trends and need further evaluation, specifically whether non-wood energy prices influence wood use and quantities. Wood use, particularly as a heating fuel, will have a role in addressing and adapting to climate change. Survey results will need to be valuated through this lens.

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11 *Environmental Initiative* *https://environmental-initiative.org/work/project-stove-swap/*

12 *Clean Air Minnesota* *https://environmental-initiative.org/work/clean-air-minnesota/*

Survey methods

2021 methods

Study regions

As in prior surveys, Minnesota households were independently sampled from five geographic regions. Surveys stratify the population into subgroups expected to have similar behaviors as a way to cost-effectively improve the precision of the estimates. These five survey regions, depicted in Figure 1, are based on four U.S. Forest Service survey units for Minnesota forests. The Aspen-Birch and Northern Pine survey regions contain most of the state's boreal forest. The Aspen-Birch region has Minnesota's largest area of reserved forest land including the Boundary Waters Canoe Area Wilderness and Voyageurs National Park. The Central Hardwoods survey region is dominated by hardwoods. The more densely populated seven-county Twin Cities Metro region was sampled separately from the less densely populated portion of the Central Hardwoods region. The Prairie survey region is dominated by croplands.

Based on recent census data, the Metro region is geographically the smallest region, but contains just over half of Minnesota's occupied households (54.3%). The Aspen-Birch (5.2%) and Northern Pine (5.7%) regions are the least densely populated. The Prairie (14.4%) and Central Hardwoods (20.3%) regions are also much less densely populated than the Metro region. See Figure 2 for the numbers of households in each region.

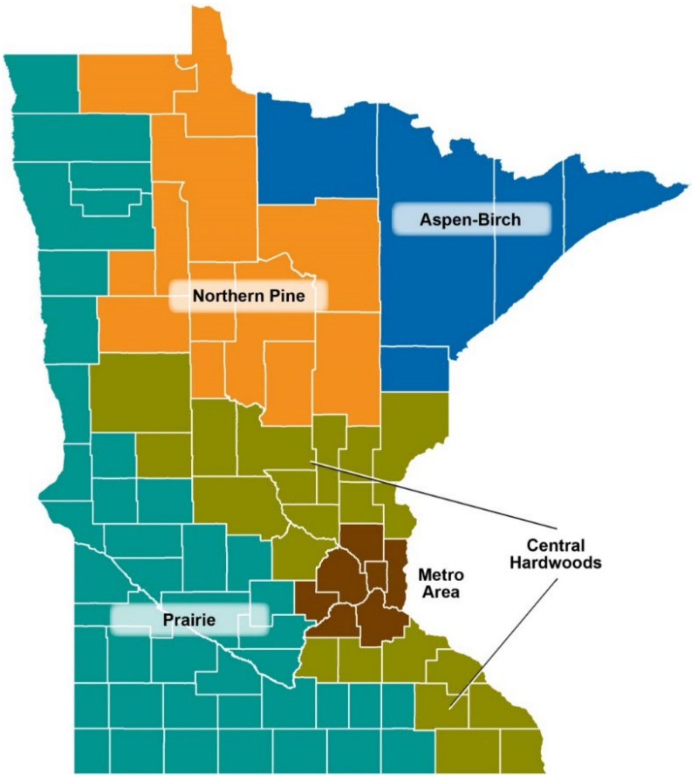
Sample selection

A sample of 7,000 addresses selected at random from valid Minnesota residential addresses, based on a U.S. postal service list of residential addresses, was purchased from Marketing Systems Group (MSG), a company specializing in sampling services. Vacant, seasonal, PO Boxes, and drop points (single addresses that are for multiple residences) were excluded from the sample.

These Minnesota households were included in the sampling frame using a disproportionate stratified sampling design. Households in the Northern Pine and Aspen-Birch regions had a five times greater chance of being invited to take the survey than did those living in the Metro region. Chances for households in the Prairie and Central Hardwoods regions to be surveyed were respectively 1.9 and 1.3 times higher than for the Metro region. Based on the number of households in each region, this resulted in the Metro region being sent about twice as many surveys as each of the other regions. This is consistent with the sampling method used in the 2012, 2015, and 2018 survey design. Figure 2 shows the number of occupied households in and sampled from each survey region. The pre-2012 surveys invited similar numbers of households to take the survey from each region.

Beginning with the 2012 survey, the Metro area was sent twice as many surveys as each of the other regions for several reasons. Because more than half of the households in Minnesota are in the Metro area, residential wood smoke from the relatively dense population in the Metro area has been estimated to result in a larger localized air quality impact due to a denser population than the rest of the state and the Metro region has previously experienced slightly lower response rates.

Figure 26: Survey regions for stratified sample



Changes from previous survey administration

The 2021 research design was changed slightly to try to increase the accuracy of the results. Section F (woodstoves, wood burning fire place inserts, and pellet stoves) was simplified further from 2018 survey.

Wilder pilot tested the web survey by sending it to five individuals who were known to burn wood at their primary and/or secondary residence. All five individuals completed the test survey and were then asked a series of questions to gather their feedback on the length of the survey, any difficult or confusing questions, and any general suggestions. Based on these results, question language and flow were revised to make the survey easier to complete.

Survey administration

On May 6, 2021, all addresses in the sample were mailed an invitation letter with a paper survey packet and an addressed, postage-paid envelope. Approximately one week later, a reminder postcard was sent to the full sample. Addresses for materials returned completed or as undeliverable were then removed from the sample and the remaining addresses were sent a final full survey on June 3, 2021

There were no within-household respondent selection quotas, so any resident of the household could complete the survey. Presumably, the household member who was willing or who knew the most about the household's wood burning practices completed the survey.

Each survey had a unique number printed in the upper right-hand corner that corresponded to an address in the sample. As surveys were completed, the unique survey numbers were checked off a master list. Over 1,500 surveys were returned.

Table 7: Survey mailings and response rates

	Northern Pine	Aspen-Birch	Prairie	Metro	Central Hardwoods	Statewide
Number of occupied housing units	125,315	112,841	315,677	1,187,423	444,347	2,185,603
Number of addresses in sample	1,195	1,168	1,195	2,300	1,142	7,000
Number returned as undeliverable	21	21	0	49	32	168
Number of refusals	1	0	0	0	0	1
Total completed	263	248	233	477	239	1,460
Response rate	23.0%	21.3%	19.5%	20.4%	20.3%	21.4%

Paper survey results were entered into an electronic database so all the data could be compared easily using Excel software. Once all responses were entered and checked for quality, the unique numbers were disassociated from the addresses to maintain privacy of the respondents and prevent associating responses with specific mailing addresses. The data could still be tracked by city, county, zip code, and survey region.

Data analysis methods

Prepare data for analysis

The first step to prepare data for analysis was to import the paper survey responses into the statistical software package (SPSS), review responses for quality, and recode responses into formats appropriate for analysis. To ensure data quality, manually entered data from the paper surveys was rechecked to make any necessary corrections. Additional review of the data set was done to ensure data validity and to discard any unusable surveys. (Discarded surveys included those with duplicate entries and those returned blank). Once the data were checked and quality ensured, the resulting total survey sample was 1,460 responses.

Correct missing, invalid, or contradictory responses

Dealing with missing, invalid, and contradictory responses was a lengthy process that involved a combination of inference, imputation, and common sense. Many of the key assumptions that were made are documented below. Throughout this process any questionable responses were checked with the actual paper surveys to ensure that data were captured correctly. If a questionable response was verified, it was reclassified as invalid and a replacement value for the response was imputed based on the assumptions and methods listed below.

Missing location information

A first step in the data analysis was to determine the location, by survey region, of every reported wood burning activity. Wood burning could occur at three location types: primary residence, secondary residence, or campsite. For respondents who filled out the survey completely and accurately, geographic locations for all of these activities were provided. However, in some instances this information was missing or incomplete. In all cases in which respondents did not provide the location of their primary residence, it was assumed that the primary residence was the address to which the survey was mailed. A total of 30 respondents only mailed in the first page of the survey (all of which indicated that they did not burn wood). The region of their primary residence was imputed using a hot-deck procedure (described below). In most cases where respondents *did* provide the location of their primary residence, it matched our information on where the survey was mailed. In the few cases where there was not a match, the location in the survey response overrode the survey region where the survey was mailed.

When respondents indicated wood burning at a secondary residence but did not provide location information for a secondary residence, its location was inferred based on probabilities for all respondents who did provide secondary residence information (This is known as a random hot deck method). For example, for all Northern Pine residents who provided secondary residence information, data showed the following probabilities for the location of its secondary residence (hypothetical example with made up numbers):

Primary residence:	Northern Pine
Secondary residence:	Northern Pine: 70%
	Aspen-Birch: 10%
	Prairie: 5%
	Metro: 0%
	Central Hardwoods: 15%

Then, for all households with a primary residence in the Northern Pine region that did not provide the location of their secondary residence, their secondary residence location was randomly chosen according to the indicated probabilities.

The final location type for wood burning was campsites. Survey respondents were instructed to select the regions in Minnesota in which they burned wood at campsites. Respondents could select more than one of the five regions. When respondents indicated more than one camping location, the total wood burned while camping was allocated equally to all regions listed. In cases where respondents did not provide campsite locations, the location was inferred based on the modal response of all other responses from households with primary residences in the same region. For example, if among all households with a primary residence in the Metro region, the most common camping location was in the Aspen-Birch region, then all respondents from the Metro region that did not provide campsite locations were assumed to have camped in the Aspen-Birch region.

Missing or invalid wood burning quantities

There were many instances when respondents indicated owning particular wood burning equipment, but they did not enter the quantity of wood burned. Quantities were inferred or imputed in the following ways. In the majority of cases, a missing quantity was inferred to indicate that the respondent did not use the particular wood burning equipment. Only in cases where other responses made it clear that the household did indeed burn wood were missing quantities inferred or imputed. Such responses included indicating the months of the year in which the particular equipment was used. In these cases, simple regression models were used to impute missing quantities based on all those that did provide quantities for that particular equipment. For all households that did provide burning quantities for use of equipment, their reported number of pieces of equipment type and the number of months in which they used equipment were used to estimate the following regression equation:

$$\textit{Quantity burned} = \propto + \beta_1 \textit{ Number of equipment} + \beta_2 \textit{ Number of months equipment used}$$

Thus, using the responses of all other households that did provide burning quantities, the coefficients in the above equation (α, β_1, β_2) were estimated and used to impute the amount of wood burned by any household that did not provide quantities based on the number of pieces of equipment the household reported to have[13] and the number of months[14] for which burning activity was reported. Note that a separate version of the equation above was estimated and applied for each different type of equipment, and separate equations were estimated for primary and secondary residences.

There were two respondents who each listed two pieces of equipment in Q27, though they each omitted wood burning amounts for one of the pieces. It was assumed that they each owned two pieces of equipment but only burned in one of them.

In the case of campfires, when respondents reported having campfires, but did not provide the quantity of wood burned, the median campfire burning amounts for all respondents was assumed.

Other missing information

In several cases, respondents indicated having and using wood burning equipment, but did not give complete information. When respondents failed to indicate how many pieces of a particular type of equipment they had, it was assumed they had only one piece of equipment (which was the modal response for all the equipment types for the households that did provide this information). When respondents did not provide their main purpose for using a piece of equipment, we followed the guidelines from the 2012, 2015, and 2018 studies by replacing missing data with the most typical burning purpose of a particular equipment type —"pleasure" for fireplaces and outdoor wood burning equipment; "secondary heat source" for wood stoves, fireplace inserts, and pellet stoves; and "primary heat source" for wood burning boiler or furnace. For all but wood burning boiler or furnace, the purpose question was changed into a multiple response question. In order to impute the purpose in the analysis, persons who gave more than one response were placed in a "multiple answers" category. For all four of the purpose questions, respondents who said “None” were left as “None”.

For each type of equipment, we determined whether the respondent had the equipment and, if so, whether that equipment was used. Having the equipment was determined from all of the questions in the equipment section of the survey. If the respondent said they had the equipment (for instance, a fire pit), or if any of the follow-up items indicated the equipment existed (for instance, they reported using it for pleasure), then we said that respondent had that type of equipment. Using the equipment was defined as having the equipment and reporting any one of the following: a purpose for burning, months during which there was burning, or amount of wood burned.

[13] *Throughout the survey, if a respondent indicated having a particular type of wood burning equipment, but did not indicate how many pieces of the equipment they had, it was assumed they had one piece, which was the modal response for all equipment types for all households who did indicate the number of equipment pieces.*

[14] *Missing numbers of months were replaced with the median response.*

Other responses revealed clear contradictions that suggested that respondents either did not thoroughly understand the survey or did not know the specific type of equipment that they had. For example, in the section on wood burning furnaces and boilers, some respondents crossed out questions 32 through 36 indicating they did not have a wood boiler or wood furnace but answered questions 42 and 43. In cases of obvious contradictions such as this, corrections were made to most accurately reflect the true behaviors of responding households. In the example above, we corrected the survey to indicate the respondent did not have a wood boiler or furnace.

The type of wood burned and firewood harvesting questions were to be percentages that would sum to 100%. In some cases, that was not true. If a question's percentages summed to less than 100%, the residual was placed in an "unknown" category. Similarly, respondents who harvested wood were asked to list the counties (up to four) from which the wood came and the percentage of wood that came from each county. For some cases, the percentages did not sum to 100%. When that occurred, a fifth, "unknown county" was added, and the residual was placed there. There were also cases where the percentages summed to more than 100%. For those, all percentages were proportionately reduced to make them sum to 100%.

A total of 27 respondents indicated that they used wood stoves, fireplace inserts or pellet stoves, but did not know (or did not provide a response) when their equipment was made. These missing values were imputed using known probabilities from non-missing responses for each type of equipment. It was assumed that if a respondent skips or doesn't know when the equipment was manufactured, they do not have a unit that was made after 2015.

Concurrent to the completion of analysis for this report, the quality-assured data with all the inferences and imputations described above is being transferred into a relational database. It will be publicly available when the transfer is completed.

Aggregate survey responses

Based on locations of primary and secondary residences and provided (or inferred) locations for campsite burning, every burning activity reported in the survey was assigned to one of the five regions. All wood burning quantities were converted into common units of cords. Some survey units (full cords, face cords, and bundles) were converted based on standard conversion factors.[15] Other wood burning units (wax logs, pallets, pounds of pellets) were converted into cord equivalents using the conversion factors listed in Appendix A.

Extrapolate survey sample totals to population-wide estimates

Estimates of the total wood burned, as well as subtotals by equipment type and burning purpose were extrapolated to determine approximate wood burning amounts for the entire population for each region. This extrapolation was based on the number of occupied households in each survey region, according to the 2014-2019 5-year U.S. Census American Community Survey, table DP04. For example, there were 477 survey responses from the Metro region, and there are 1,187,423 households in the region. Thus Metro region totals for the survey sample were scaled up by a factor of $\frac{1,187,423}{477}$ = 2,489[16] to estimate total burning activities for the region. Scaling survey region-wide estimates in this manner corrects for the unequal probability of selection caused by *disproportionate stratified sampling* (i.e., the

15 *Three face cords or 170 bundles equal one full cord.*

16 *This is equivalent to saying that each household responding to the survey from the Metro region represents 2,489 households in the population as a whole.*

fact that the proportion of completed surveys from any individual survey region was unequal to that region's proportion of the total state household population).

Additional technical details

- If secondary residence was not in Minnesota or open-end response indicated that the residence was not actually a residence (e.g., a campground), all responses for secondary residence burning were dropped.
- If information written on a form indicated that wood burning reported for secondary residence was actually for the primary residence (e.g., Q20 to Q23), the responses were moved to primary (Q16 to Q19).
- If respondent failed to answer campfire burning activity or said "No" (Q5) but provided answer for amount of wood burned (Q6) or region(s) in which burning took place (Q7), then the response to Q5 was assumed to be "Yes".
- Missing burning amounts for wood stoves were imputed collectively, without regard to the specific equipment sub-type (convention, non-catalytic, catalytic). This was also done for fireplace inserts.
- If the only burning reported in a survey was of yard waste, all items in the harvesting section (Q50 through Q55) were recoded to not applicable (NA).
- County was not asked if burning = "No"; County came from sample list.
- We assume that respondents with no evidence of a secondary residence and did NOT check the check box next to "I do not have a secondary residence", actually do not have one.
- For wood burning boiler or furnace, if there is evidence of burning and Q32 or Q37 is blank, code Q32 or Q37 = 4 "Yes, unknown device".
- Respondents describe burning throughout the survey. It is necessary to review the entire form to determine where the burning occurred and the volume. We found that some respondents put identical information in multiple sections (for instance, in fireplaces and fireplace inserts). When that happened, we deleted the duplicate.

Appendix A: Sources of secondary calculations of wood fuel volumes

1. Wood slabs. A conversion factor of 1.0368 tons per cord was used for sawmill slabs and edgings, based on: Bell, G. E., & Brooks, E. (1955). *Cord-cubic volume of relationship of slab wood and edgings* [Release No. 232]. American Pulpwood Association. New York, NY.

2. Wood pellets. A conversion factor of 2.752 tons per cord was used for wood pellets, based on information from Jason Berthiaume, Pellet Fuels Institute (PFI). Current standards require a minimum density for PFI-graded pellets of 40lbs/cu ft. Under newly approved standards, implemented in 2009, density for super-premium and premium pellets are 40-46lbs/cu ft, with standard and utility grades at 38-46lbs/cu ft. As super-premium and premium make up the vast majority of residential heating pellets, it makes sense to use the 40-46 range. Mid-range of 43 X 128 cubic feet per cord = 2.752 tons per cord.

3. Wax logs. A conversion factor of 1.0989 tons per cord was used for wax/manufactured fireplace logs, based on: Houck, J. E. (July 2002). OMNI Consulting Services, Inc. Beaverton, Oregon. He determined 444 typical logs make up a cord. The weighted average mass of wax/sawdust fireplace logs is 4.95 lbs. (2.5 lbs., 3.2 lbs., 5 lbs., and 6 lbs. logs are sold). The average mass of densified logs sold is 5 lbs.

4. Wood pallets. A conversion factor of 0.5184 tons per cord was used for wood pallets and crates, based on: WikiAnswers: “How much does a pallet weigh?” and “What is the standard size of a wooden pallet?” It was assumed the Grocery Manufacturers' Association pallet was 48" x 40" and each weighed 45 pounds.

5. 30-gallon bag of branches. A conversion factor of 63 “30-gallon bags of tree branches and wood brush collected from your yard” per cord of wood was used. This is based on a commonly used estimate of 300 pounds per cubic yard of loose yard waste branches from the National Recycling Measurement Standards and Reporting Guidelines, based on information from John Springman, Ramsey County Minnesota Yard Waste Program (2016). This estimate falls within the 250 to 350 pound per cubic yard of loose brush range referenced in Resource Recycling, November 1991.

Calculation of regional and statewide total amounts

Survey results were tallied using the populated relational database and reported as state totals and for the five regions based on the region in which the burning took place. The wood burning equipment and burning activities were grouped into seven categories — outdoor recreational equipment, conventional fireplaces, wood stoves, fireplace inserts, wood pellet stoves, wood boilers (hydronic heaters), and forced-air furnaces. Wood burned in each equipment category was grouped according to the main purpose for which the household reported burning the wood.

Calculation of average annual growth rate

Average annual growth rates in volume of wood burned and population over time were calculated by solving for the compound annual growth rate.

Calculation of the confidence interval for the total wood burned statewide

A confidence interval was calculated for the estimate of the total cords of wood burned statewide. This indicates the range where the true statewide amount burned was expected to be, with a 95% level of confidence. This reflects the inherent variability in how much wood a household burns and the fact that all population-level estimates derived from survey responses have an inherent degree of uncertainty. This uncertainty arises from many causes, including the survey sampling method and size.

Confidence intervals for statewide wood-burning totals were calculated in the following manner. First, a regionally adjusted non-scaling weight was calculated. Out of 1460 total completed surveys, 477 were from respondents with primary residences in the Metro region. Thus, the percentage of surveys in the total survey sample from the Metro region was $\frac{477}{1,460}$ = 33%. The overall number of households in the Metro region is 1,187,423 while there are 2,185,603 households in the state. Thus, the percentage of the state's households in the Metro region is $\frac{1,187,423}{2,185,603}$ = 54.2%. Therefore, Metro region households make up 54% of the state population but only 33% of the survey sample population, so the Metro region was under-represented in the survey sample. Similarly, other regions were either under- or over-represented in the survey sample. As was appropriate for the calculations of the regionally adjusted scaling weights above, because wood-burning behaviors may vary across regions of primary residence, giving equal weight to all surveys regardless of residence location could introduce bias in the total estimates for statewide burning. Weights for surveys from over-represented survey regions were given regionally adjusted non-scaling weights less than one (i.e., the contribution of their wood burning activities to state totals was adjusted down), while under-represented regions were given regionally adjusted non-scaling weights greater than one (their contribution to total estimates was adjusted up). Continuing the Metro region example, responses from this region were given weights of $\frac{54\%\ of\ population}{33\%\ of\ survey\ sample}$ = a weight of 1.66. Weights across the five regions ranged from 0.30 in the most over-represented regions (Aspen-Birch) to 1.66 in the most under-represented region (Metro). Specifically, the regionally adjusted non-scaling weights for the Northern Pine, Aspen-Birch, Prairie, Metro, and Central Hardwoods regions were 0.32, 0.30, 0.91, 1.66 and 1.24, respectively, for respondents living in those regions.

These weights are generally termed "post-stratification weights" and their use is fairly common in survey analysis where response rates are not equivalent across different subgroups within the survey sample or when some subsets of the population are sampled more than others.

A regionally adjusted non-scaling weight was assigned to each of the 1,460 responding households. Next, the mean and standard deviation of the individually reported unweighted total wood burned by the households was calculated for each region. For each household respondent, this calculation used the total number of cords of wood (and wax logs) they burned in all types of equipment anywhere in the state, including zeros for the households who did not report burning any wood or wax logs. The standard deviation of the amounts of wood burned for each region was divided by the square root of the number of surveys in the sample to estimate the standard error (SE) of the sample for each region. (See Table 7) for the sample sizes of each region based on location of primary residences). For 95% confidence intervals, a critical value (t*) was obtained from tables of the t distribution with a significance level (α) of one minus the 95% confidence level, or 0.05. The SE of the sample was multiplied by t* to obtain a margin of error around each region's sample mean. Finally, to correct for the design effect, which entails greater variance in the data and thus greater uncertainty in population-wide wood burning estimates due to the weighting described above, the following correction was made to each region's margin of error. The design effect was calculated as

$$1 + \left(\frac{\sigma}{\mu}\right)^2$$

where σ is the standard deviation of the regionally adjusted non-scaling weight parameters and μ is the mean of the regionally-adjusted non-scaling weight parameters across all 1,460 households in the survey sample. Each region's confidence interval was scaled up by the square root of the design effect, which served to widen the confidence intervals by roughly 17%. Each confidence interval was then multiplied by the total number of households in the respective region to scale the interval to the region. The confidence intervals from all five regions were summed together to apply a confidence interval around the statewide estimate of total cords of wood burned, to obtain overall estimates of a 95% confidence interval for statewide wood burning quantities.

Limitations

There are some important limitations to this study that should be considered when interpreting the results. First, of the 6,877households invited to participate in the survey, 1,460 completed the survey for a response rate of 21.4%. The response rate by region varied from 19.5% to 23%, with the Prairie region having the lowest response rate (see Table 7). Estimated results from this year's survey should still be interpreted with caution, since there are margins of error surrounding the extrapolation of survey results to whole populations.

The survey also relied on retrospective self-reporting of burning and wood harvesting behaviors. These retrospective reports are likely to be strong approximations of actual behaviors, but they should be treated as estimates, as opposed to precise measurements.

It is difficult to confidently compare survey years and examine trends. Each survey administration has involved changes to the survey instrument and collection methods, which may change the results. For example, one change to this year's survey was asking, "In the last year, have you burned any wood?" on the front cover of the survey packet. Respondents could either check a box labeled "Yes" or "No", and were encouraged to return the survey regardless of if they burned wood or not. This change was made in response to a concern that the design of the 2015 survey may have made it more likely for those who did not burn wood to disregard the survey, which may have led to a higher estimated rate of burning in each survey region and amount of wood burned than had actually occurred. Despite survey design changes, some comparisons and trends across survey years were examined in this report, but it should be recalled that all results are estimations, as opposed to precise measurements.

Similarly, because of the design of this year's survey, respondents who indicated they burned no wood immediately ended the survey. Therefore, any wood-burning equipment they may have owned (but did not use) was not accounted for, since they did not continue the survey to indicate what equipment they may or may not have owned. In cases where a respondent reported owning more than one piece of wood-burning equipment but did not use all of them during the survey period, only the used pieces of equipment were coded into the relational database used to analyze results. This report, therefore, unlike past reports, only captures the number of pieces of wood-burning equipment *in use* in the state, as opposed to the number of pieces of equipment owned.

Estimated rates of equipment ownership of wood stoves and outdoor recreational equipment, which are common in all regions, are likely more reliable than estimates for less frequently reported equipment.

The survey did not ask respondents if their conventional fireplaces were wood or gas fueled. It is likely that respondents may have reported a gas-burning conventional fireplace as what would have then been interpreted as a wood-burning fireplace during data analysis. Likewise, the survey did not ask respondents about burning done in any undesignated, impermanent locations, outside of any formal pieces of equipment (say, in an unofficial “spot” in a yard).

Additional weighting by household type, which has been explored in past surveys, was not possible because households that reported no burning activity immediately ended the survey prior to the household type question.

This survey report is limited to residential wood burning. It does not include or discuss commercial or industrial wood burning in Minnesota to any degree.

In spite of these limitations, the survey results contain an abundance of information that can be used by a variety of interested parties.

Appendix B

Sources of secondary calculations of wood fuel volumes

Wood slabs. A conversion factor of 1.0368 tons per cord was used for sawmill slabs and edgings, based on: Bell, G. E., & Brooks, E. (1955). *Cord-cubic volume of relationship of slabwood and edgings* [Release No. 232]. American Pulpwood Association. New York, NY.

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Appendix C

Glossary and definitions for this report

Bundle: A unit measure for wood volume that measures about 16 inches by 9 inches by 9 inches (0.75 cubic feet). One hundred and seventy-one bundles is equivalent to one cord. Note that in prior surveys a bundle was defined as 2 cubic feet or 64 bundles per cord.

Confidence interval: A range of values centered on the sample estimate that is known to contain the true value with a given degree of confidence (usually 95%).

Conventional fireplace: Conventional fireplaces are generally used for aesthetic purposes rather than for heat. They are often open but may have non-sealed glass doors. The survey did not distinguish whether the fireplaces were located inside or outside the residence.

Cord: A unit of measure for a volume of wood. It measures four feet high by four feet wide by eight feet long and has a volume of 128 cubic feet (Figure 1). Cords do not describe how much the wood weighs, so a cord of one species of wood may weigh more than a cord of a less dense wood.

Design effect: An adjustment used in some statistical studies, which inflates the variance of parameter estimates, to allow for the design structure. In this case, it is an adjustment for the population weighting that was done to address the disproportionate stratified sampling and response rates. The weighting of the data increases its variance, and the design effect is used to adjust confidence interval estimates to account for the increased variance.

Differential response rates: These refer to the situation where the response rate was (substantially) different in different subgroups of the population (e.g., in households from different survey regions or from different demographic groups).

Disproportionate stratified sampling: Conducting a survey where the sizes of different groups (in this case, number of surveys sent to each survey region) vary and do not represent the percentage of any particular group within the larger population.

Estimate: The value obtained from a sample, which is used with a known margin of error, as an approximation for a population characteristic.

Face cord: A unit of volume that is four feet high by eight feet long by 16 inches wide, equal to one-third of a cord.

Fireplace insert: An enclosed space-heating device, similar in function to a wood stove that is designed to fit into the opening of an existing fireplace. These are designed to be more energy efficient than most conventional fireplaces.

Household: The person or persons occupying a housing unit.

Margin of error: The statistic, which describes the amount of random sampling error in a survey's results. When the margin of error is great, there is less confidence that the results of the survey correctly represent what would have been found by surveying the entire population.

Methodology: A description of the way in which data are collected and analyzed in a research project.

Outdoor recreational burning: In this study, outdoor recreational burning includes burning in outdoor fire pits, chimineas, or fire rings. They may be used for recreational backyard burning or at campgrounds.

Outlier: An extremely small or extremely large value in a set, compared with the mean of all values in the set.

Primary residence: The dwelling where a person or persons usually live, typically a house or an apartment. The survey questionnaire defined the primary residence as "your main home."

Response bias: Inaccuracy of data collected caused by participant error. This could be caused by misunderstanding or misinterpreting survey questions or in some cases could be deliberate misrepresentation of one's actions.

Response rate: The number of completed surveys divided by the number of eligible units (i.e., households) in a sample. In other words, this is the number of completed surveys returned divided by the number of surveys sent that successfully reached the households. The surveys sent out that were returned by the post office are not included.

Sample: A subset of the population from which data are collected to be used in estimating actions or behaviors of the total population. In this case, the "survey sample" is all the households who completed and submitted a survey.

Secondary residence: This includes all dwellings that are not the primary place where a person or persons live. In this study, it includes second homes, cabins, trailers, or other vacation properties. Camping locations were not included.

Selection bias: A type of non-sampling error that occurs when participants who chose to participate in some research (i.e., who choose to fill out and submit a survey) are systematically different than the intended sample. This type of bias is caused by certain types of participants replying to a survey invitation more than others or when participants put themselves into groups to which they aspire but do not currently belong. For this study, a potential source of selection bias could be that households who burn wood are more likely to answer a survey about residential wood burning than households who do not burn wood. As a result, the survey analysis could overestimate wood burning activity in the overall population. Similar to "non-response error," which is error caused by some sub-groups of the sample responding less often than the rest of the sample.

Slab: Rounded edges of wood typically sawn from a log face when squaring a log.

Statistical significance: Refers to whether some research results genuinely reflect a population of interest in some way or whether the results could occur by chance. Statistical significance is determined by comparing the research results with the values defined by the confidence interval.

Survey regions: The key geographic unit for this analysis. The five survey sampling regions have been used in past Minnesota residential wood fuel use surveys. Minnesota is comprised of five regions that roughly correspond to the state's ecoregions. An ecoregion is an area of land with similar ecological characteristics. The five survey regions of Minnesota—Northern Pine, Aspen-Birch, Prairie, Metro Area, and Central Hardwoods — were delineated based on forest cover and predominant tree types.

Wood boiler: A wood burning central heating device that heats a liquid (generally water or glycol) as the medium to transfer the heat to where it is needed. Hydronic heater is the more technical term for this equipment as they do not actually boil the water. Wood boilers are generally, though not exclusively, located outside the main building. The heated liquid may provide space heat through radiators, in-floor heating, or to the air by the use of a heat exchanger. In residential settings, they may also be used to heat multiple buildings, the domestic water supply swimming pools, etc. Because some wood “boilers” (hydronic heaters) are called “outdoor wood furnaces”, this survey distinguished the boilers from the forced-air furnaces using descriptive characteristics including brand or model information and whether it used water to transfer the heat.

Wood furnace: A wood burning central heating device in which the heat in the combustion chamber directly heats air that is transferred through ducts to provide space heat to the home or building. In this survey, the term “furnace” was specifically used for the forced-air furnaces that heat air, not those that use water as the heat transfer medium.

Wood pellet stove: A room heating device similar to a wood stove, designed to burn wood pellets.

Wood stove: An enclosed free-standing heating appliance capable of burning wood fuel generally connected by ventilating stove pipes to a suitable chimney or flue. A wood stove can generally be used to burn wood, or wood-derived biomass fuel, such as wood pellets. It is generally designed to heat the air in a few rooms or a smaller home.

Appendix D

Start Here ▶ **In the last year, have you burned wood at your primary or secondary residence in Minnesota (indoors or outdoors) or at a campground?**

☐ **NO.** Please return the survey with this box checked.
You do not need to answer any other questions.

☐ **YES.** Please continue.

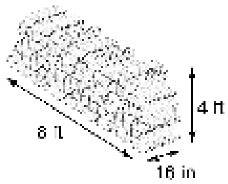
Residential Wood Fuel Survey

MINNESOTA

Conducted by the Minnesota Pollution Control Agency in partnership with the Department of Natural Resourses and the US Forest Serives

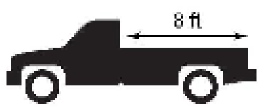
Section A: Key

A full cord of wood measures 4 feet high by 4 feet wide by 8 feet long (4' x 4' x 8') and has a volume of 128 cubic feet.



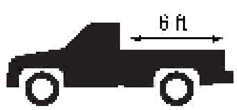
A face cord

A face cord of wood is 4 feet high by 8 feet long and is as wide as the individual firewood pieces, but averages 16 inches wide. A 16-inch wide face cord (sometimes called **a fireplace cord**) is equal to one-third of a full cord.



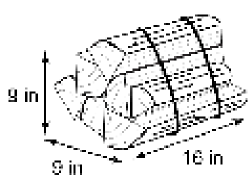
x2

Two full-size pick-up truck loads (8 foot box) equals **one full cord**, whether the wood is stacked carefully so it is about level with the truck box sides, or is thrown into the truck box with the top of the pile about as high as the cab.



x4

Four compact pick-up truckloads (6 foot box) equals **one full cord**, whether the wood is stacked carefully so it is about level with the truck box sides, or is thrown into the truck box with the top of the pile about as high as the cab.



X170

Bundles of wood sold at gas stations, hardware stores and state parks are often 0.75 cubic feet. They often measure about 16 inches x 9 inches x 9 inches. 170 bundles equals **one full cord**.

Section B: Residence

The survey asks about the **wood-burning equipment** you use. **Wood-burning equipment** includes wood-burning fireplaces, fireplace inserts, wood stoves, wood furnaces, wood boilers, outdoor fire pits, chimeneas, etc.

The survey also asks about how much you burn at your primary and secondary residence in Minnesota. We are using the following definitions for these residences:

- **Primary residence** includes your main home, including garages and outbuildings.
- **Secondary residence** includes your or your family's second home, cabin, trailer, rented cabin, or other residential property. If you have more than one secondary residence, please consider only the most frequently used secondary residence.

1. Where is your **primary** residence located? (Your main home, including garages and other outbuildings.)

   Primary residence location:

   County: ______________________________

   City/Township: ______________________________

   Zip Code: ______________________________

2. Which of the following best describes your ***primary*** residence?

   ☐[1] Single-family house (detached)
   ☐[2] Townhouse or twinhome (attached)
   ☐[3] Multi-family building (such as condominiums, apartments, or cooperatives)
   ☐[4] Mobile home or trailer

☐ **I do not have a secondary residence in Minnesota.**

If you do not have a secondary residence in Minnesota skip all questions about secondary residence.

3. If you have a **secondary** residence, where is it located? (A second home, cabin, trailer, rented cabin, or other residential property that is located in Minnesota. If your secondary residence is not in Minnesota do not include it.)

   Secondary residence location:

   County: ______________________________

   City/Township: ______________________________

   ZIP: ______________________________

4. Which of the following best describes your ***secondary*** residence, cabin, trailer, rented cabin, or vacation property?

   ☐[1] Single-family house (detached)
   ☐[2] Townhouse or twinhome (attached)
   ☐[3] Multi-family building (such as condominiums, apartments, or cooperatives)
   ☐[4] Mobile home or trailer
   ☐[5] Cabin

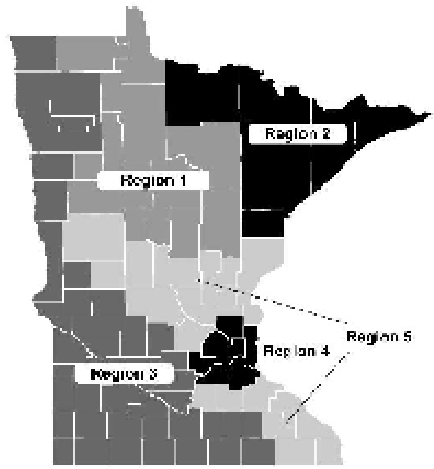
Section C: Campsites and campgrounds

5. Did you burn firewood at a campsite or campground in Minnesota between May 2020 and April 2021?
   - ☐ 1 No. **Skip to Q8.**
   - ☐ 2 Yes. Please continue.

6. If you burned firewood at a campsite between May 2020 and April 2021, please estimate the total amount of wood burned.

   ____________ Estimated total amount (in bundles) of wood burned at all campsites

7. Please check all of the regions in which you burned wood at a campsite between May 2020 and April 2021, based on the following map.
   - ☐ 1 Region 1
   - ☐ 2 Region 2
   - ☐ 3 Region 3
   - ☐ 4 Region 4
   - ☐ 5 Region 5



Section D: Outdoor wood burning fire pits, chimeneas or fire rings

Chimenea

Fire pit

Chimeneas, fire pits, fire rings, etc.

- Can be above the ground or dug into the ground
- Are located outside the house
- May be a designated "spot" used to burn wood on the property
- **Please answer only for those that burn wood rather than propane**

PRIMARY RESIDENCE

8. Do you have a fire ring, fire pit, chimenea or similar type of equipment/area at your primary residence?
   - ☐1 No. **Go to Q12.**
   - ☐2 Yes.

9. In the past 12 months, did you use this equipment ***mainly*** for:
   - ☐1 Pleasure
   - ☐2 Disposal by burning of woody yard materials (e.g. fallen branches, trees and twigs, brush/trees collected from property)
   - ☐3 None. Please check if you did not burn wood in this equipment during the last year and **Go to Q12.**

10. Please check which months you used this wood-burning equipment at your home over the last year.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

11. Please indicate how much wood or wax logs you burned in the past 12 months in your fire ring, fire pit, chimenea or any similar type of equipment. (Respond to as many as you need to collectively best describe how much wood was burned.)
   - 1 _______ Bundles of wood .75 cubic feet each
   - 2 _______ Bags of tree branches and woody brush collected from your yard (Estimate how many 30 gallon bags – typical size of yard waste bags sold)
   - 3 _______ Full cords of firewood (answer to the nearest tenth of a cord)
   - 4 _______ Face cords of firewood (answer to the nearest tenth of a face cord)
   - 5 _______ Number of wax logs (such as Duraflame, Emuiro Log, Pine Mountain, etc.)
   - 6 _______ Number of wood pallets

If you do not have a secondary residence in Minnesota skip all questions about secondary residence.

SECONDARY RESIDENCE

12. Do you have a fire ring, fire pit, chimenea or similar type of equipment/area at your secondary residence?
   - ☐1 No. **Go to Q16.**
   - ☐2 Yes.

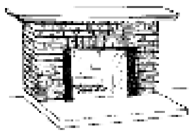
13. In the past 12 months, did you use this equipment ***mainly*** for:
   - ☐1 Pleasure
   - ☐2 Disposal by burning of woody yard materials (e.g. fallen branches, trees and twigs, brush/trees collected from property)
   - ☐3 None. Please check if you did not burn wood in this equipment during the last year and **Go to Q16.**

14. Please check which months you used this wood-burning equipment at your home over the last year.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

15. Please indicate how much wood or wax logs you burned in the past 12 months in your fire ring, fire pit, chimenea or any similar type of equipment. (Respond to as many as you need to collectively best describe how much wood was burned.)
   - 1 _______ Bundles of wood (0.75 cubic feet each)
   - 2 _______ Bags of tree branches and woody brush collected from your yard (Estimate how many 30 gallon bags – typical size of yard waste bags sold)
   - 3 _______ Full cords of firewood (answer to the nearest tenth of a cord)
   - 4 _______ Face cords of firewood (answer to the nearest tenth of a face cord)
   - 5 _______ Number of wax logs (such as Duraflame, Emuiro Log, Pine Mountain, etc.)
   - 6 _______ Number of wood pallets

Section E: Conventional wood burning fireplaces



DEFINITION: A CONVENTIONAL FIREPLACE

- Often for aesthetic use rather than primarily for heating
- May have hot air grilles
- May either have no doors or glass doors without gaskets (not airtight)
- Doors can be double or bifold doors
- Includes fireplaces known as "heatilators" and fireplaces with tubular grates or other devices intended to increase heat flow
- Includes freestanding fireplaces
- Does not have an insert (if your fireplace has an insert **go to Section F, page 6**)
- Please answer only for those that burn wood rather than propane or natural gas

PRIMARY RESIDENCE

16. Do you have a conventional wood burning fireplace at your primary residence (including outbuildings such as pole barns or garages)?
    - ☐1 No. **Go to Q20.**
    - ☐2 Yes → How many? _______

17. During the past 12 months, did you use this equipment ***mainly*** for:
    - ☐1 Pleasure
    - ☐2 Primary heat source for my residence
    - ☐3 Supplemental heating for my residence
    - ☐4 None. Please check if you did not burn wood in your fireplace and **Go to Q20.**

18. Please check which months you used this wood-burning equipment in your home.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

19. If you used your fireplace please indicate how much wood or wax logs you burned in your fireplace(s) in the past 12 months.
    - 1 _______ Full cords of wood (If necessary, you can answer in fractions of full cords, such as 1/2, 1.5)
    - 2 _______ Face cords of wood
    - 3 _______ Bundles of wood (0.75 cubic feet each)
    - 4 _______ Number of wax logs (such as Duraflame, Emuiro Log, Pine Mountain, etc.)

If you do not have a secondary residence in Minnesota skip all questions about secondary residence.

SECONDARY RESIDENCE

20. Do you have a conventional wood burning fireplace at your secondary residence (including outbuildings such as pole barns or garages)?
    - ☐1 No. **Go to Q24.**
    - ☐2 Yes → How many? _______

21. During the past 12 months, did you use this equipment ***mainly*** for:
    - ☐1 Pleasure
    - ☐2 Primary heat source for my residence
    - ☐3 Supplemental heating for my residence
    - ☐4 None. Please check if you did not burn wood in your fireplace and **Go to Q24.**

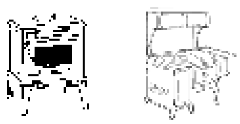
22. Please check which months you used this wood-burning equipment in your home.

2017								2018			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

23. If you used your fireplace please indicate how much wood or wax logs you burned in your fireplace(s) in the past 12 months.
    - 1 _______ Full cords of wood (If necessary, you can answer in fractions of full cords, such as 1/2, 1.5)
    - 2 _______ Face cords of wood
    - 3 _______ Bundles of wood (0.75 cubic feet each)
    - 4 _______ Number of wax logs (such as Duraflame, Emuiro Log, Pine Mountain, etc.)

Section F: Wood stoves, wood burning fireplace inserts, and pellet stoves

Wood stoves



Wood stoves are freestanding space heaters often used to heat a small house or zone of the house.

Wood burning fireplace inserts

Wood burning fireplace inserts are space heaters designed to fit into an existing fireplace opening.

Wood pellet stoves

Wood pellet stoves burn small compressed wood pellets. A pellet-burning appliance has a hopper to hold the fuel.

PRIMARY RESIDENCE

24. Do you have this equipment in your primary residence (including outbuildings such as pole barns or garages)?
    - ☐1 No. **Go to Q28**
    - ☐2 Yes. → If yes, how many pieces of equipment do you use? _______

25. In the past 12 months, did you use this equipment ***mainly*** for:
    - ☐1 Pleasure
    - ☐2 Primary heat source for my residence
    - ☐3 Supplemental heating for my residence
    - ☐4 None. Please check if you did not burn wood in your wood stove, fireplace insert, or wood pellet stove, and **Go to Q28**.

26. Check the months in which you used this wood-burning equipment in your home over the last year.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

Beginning in 1989, wood stoves and fireplace inserts sold were required to have EPA-certified pollution control technology. Some EPA-certified woodstoves and fireplace inserts have a ceramic or metal honeycomb catalyst as one such control device.

27. Fill in the grid below for each piece of equipment you have at your primary residence.

EQUIPMENT				TOTAL AMOUNT OF WOOD BURNED IN UNIT between May 2020 and April 2021				
Equipment number	Type	When was it made?	Does it have a catalyst?	# Full cords	# Face cords	# Wood bundles	# Wax logs	Pounds of wood pellets
1	☐1 Wood stove	☐1 Before 1989	☐1 Yes					
	☐2 Wood-burning fireplace	☐2 1989 - 2015	☐2 No					
	☐3 Pellet stove	☐3 After 2015	☐-8 Don't know	____	____	____	____	____
		☐-8 Don't know						
2	☐1 Wood stove	☐1 Before 1989	☐1 Yes					
	☐2 Wood-burning fireplace	☐2 1989 - 2015	☐2 No					
	☐3 Pellet stove	☐3 After 2015	☐-8 Don't know	____	____	____	____	____
		☐-8 Don't know						
3	☐1 Wood stove	☐1 Before 1989	☐1 Yes					
	☐2 Wood-burning fireplace	☐2 1989 - 2015	☐2 No					
	☐3 Pellet stove	☐3 After 2015	☐-8 Don't know	____	____	____	____	____
		☐-8 Don't know						
4	☐1 Wood stove	☐1 Before 1989	☐1 Yes					
	☐2 Wood-burning fireplace	☐2 1989 - 2015	☐2 No					
	☐3 Pellet stove	☐3 After 2015	☐-8 Don't know	____	____	____	____	____
		☐-8 Don't know						

Section F: Wood stoves, wood burning fireplace inserts, and pellet stoves

If you do not have a secondary residence in Minnesota skip all questions about secondary residence.

SECONDARY RESIDENCE

28. Do you have this equipment in your secondary residence (including outbuildings such as pole barns or garages)?

☐1 No. **Go to Q32.**

☐2 Yes → If yes, how many pieces of equipment do you use? ______

29. In the past 12 months, did you use this equipment ***mainly*** for:

☐1 Pleasure

☐2 Primary heat source for my residence

☐3 Supplemental heating for my residence

☐4 None. Please check if you did not burn wood in your wood stove, fireplace insert, or wood pellet stove, and **Go to Q32.**

30. Check the months in which you used this wood-burning equipment in your home over the last year.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

31. Fill in the grid below for each piece of equipment you have at your secondary residence.

EQUIPMENT				TOTAL AMOUNT OF WOOD BURNED IN UNIT between May 2020 and April 2021				
Equipment number	Type	When was it made?	Does it have a catalyst?	# Full cords	# Face cords	# Wood bundles	# Wax logs	Pounds of wood pellets
1	☐1 Wood stove ☐2 Wood-burning fireplace ☐3 Pellet stove	☐1 Before 1989 ☐2 1989 - 2015 ☐3 After 2015 ☐-8 Don't know	☐1 Yes ☐2 No ☐-8 Don't know	____	____	____	____	____
2	☐1 Wood stove ☐2 Wood-burning fireplace ☐3 Pellet stove	☐1 Before 1989 ☐2 1989 - 2015 ☐3 After 2015 ☐-8 Don't know	☐1 Yes ☐2 No ☐-8 Don't know	____	____	____	____	____
3	☐1 Wood stove ☐2 Wood-burning fireplace ☐3 Pellet stove	☐1 Before 1989 ☐2 1989 - 2015 ☐3 After 2015 ☐-8 Don't know	☐1 Yes ☐2 No ☐-8 Don't know	____	____	____	____	____
4	☐1 Wood stove ☐2 Wood-burning fireplace ☐3 Pellet stove	☐1 Before 1989 ☐2 1989 - 2015 ☐3 After 2015 ☐-8 Don't know	☐1 Yes ☐2 No ☐-8 Don't know	____	____	____	____	____

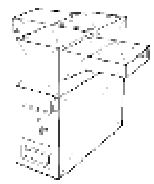
Section G: Wood burning boiler or furnace

DEFINITION: WOOD BURNING BOILER OR FURNACE

Outdoor wood boiler

Wood boilers
- Wood boilers are usually installed outside and may look like a small shed
- Wood boilers heat water that moves in pipes to where the heat is used

Indoor wood furnace



Wood furnaces
- Wood furnaces are usually installed in basement or utility rooms
- Wood furnaces heat air directly and are connected to ducts that move the hot air around the building

If you do not have a wood boiler or furnace at your primary or secondary residence Go to Q46.

PRIMARY RESIDENCE

32. Do you have any of this equipment at your primary residence (including outbuildings such as pole barns or garages)?
   - ☐1 No. **Go to Q37.**
   - ☐2 Yes a forced air furnace
   - ☐3 Yes a wood boiler

33. Brand and model (if known)

   ____

34. Is the equipment inside or outside the house?
   - ☐1 Inside
   - ☐2 Outside

35. When was the boiler made?
   - ☐1 2014 or before
   - ☐2 2015 to 2019
   - ☐3 2020 or after
   - ☐4 Don't know

36. In the past 12 months did you use this equipment ***mainly*** for:
   - ☐1 Primary heat source at my residence
   - ☐2 Supplemental heating at my residence
   - ☐3 None. Please check if you did not burn any wood in your heater or boiler, then **Go to Q37.**

SECONDARY RESIDENCE

37. Do you have any of this equipment at your secondary residence (including outbuildings such as pole barns or garages)?
   - ☐1 No. **Go to Q42.**
   - ☐2 Yes a forced air furnace
   - ☐3 Yes a wood boiler

38. Brand and model (if known)

   ____

39. Is the equipment inside or outside the house?
   - ☐1 Inside
   - ☐2 Outside

40. When was the boiler made?
   - ☐1 2014 or before
   - ☐2 2015 to 2019
   - ☐3 2020 or after
   - ☐4 Don't know

41. In the past 12 months did you use this equipment ***mainly*** for:
   - ☐1 Primary heat source at my residence
   - ☐2 Supplemental heating at my residence
   - ☐3 None. Please check if you did not burn any wood in your heater or boiler, then **Go to Q42.**

Section G: Wood burning boiler or furnace

If you do not have a wood boiler or furnace at your primary or secondary residence Go to Q46.

PRIMARY RESIDENCE

42. Please check which months you used your wood burning boiler or furnace in your home.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

43. If you used your boiler or furnace, please indicate how much wood you burned in your furnace or boiler in the past 12 months (If necessary, you can answer in fractions of full cords, such as 1/2, 1.5).
    1 _______ Full cords of wood
    2 _______ Full cords of slabs (the round parts of a log cut off to make milled wood)
    3 _______ Face cords of wood
    4 _______ Number of wooden pallets

SECONDARY RESIDENCE

44. Please check which months you used your wood burning boiler or furnace in your home.

2020								2021			
MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
☐1	☐2	☐3	☐4	☐5	☐6	☐7	☐8	☐9	☐10	☐11	☐12

45. If you used your boiler or furnace, please indicate how much wood you burned in your furnace or boiler in the past 12 months (If necessary, you can answer in fractions of full cords, such as 1/2, 1.5).
    1 _______ Full cords of wood
    2 _______ Full cords of slabs (the round parts of a log cut off to make milled wood)
    3 _______ Face cords of wood
    4 _______ Number of wooden pallets

Section H: Types of wood, storage and how obtained (burned in the past 12 months)

46. Of all the firewood you **burned** at your ***primary*** residence how much wood is stored in a way that is protected from the elements, such as rain?
    ☐1 All
    ☐2 Some
    ☐3 None

47. Of all the firewood you **burned** at your ***secondary*** residence how much wood is stored in a way that is protected from the elements, such as rain?
    ☐1 All
    ☐2 Some
    ☐3 None

48. Of all the firewood you **burned** at your ***primary*** residence in the past 12 months, what percent was burned of each type (if known)? (Percentages should add up to 100%.)

Oak	Birch	Ash	Elm	Maple	Aspen	Basswood	Pine	Unknown	
____%	____%	____%	____%	____%	____%	____%	____%	____%	= 100%

49. Of all the firewood you **burned** at your ***secondary*** residence in the past 12 months, what percent was burned of each type (if known)? (Percentages should add up to 100%)

Oak	Birch	Ash	Elm	Maple	Aspen	Basswood	Pine	Unknown	
____%	____%	____%	____%	____%	____%	____%	____%	____%	= 100%

50. Of all the wood your household burned between May 2020 and April 2021, indicate the percent(s) you harvested or obtained from the following sources (Percentages should add up to 100%):
   - 1 _______ % Purchased or free slabs from sawmills
   - 2 _______ % Purchased from a firewood dealer or logger
   - 3 _______ % Purchased from a store or campground
   - 4 _______ % Free or purchased from other sources
   - 5 _______ % Harvested by you or an immediate family member (**Harvested** includes all live or dead whole trees harvested primarily for the purpose of firewood anywhere in Minnesota, excluding yard waste.)

IF YOU HARVESTED IN MINNESOTA, PLEASE GO TO THE NEXT SECTION.

IF 0% HARVESTED IN MINNESOTA, THANK YOU FOR YOUR TIME. YOU HAVE COMPLETED THE SURVEY.

Section I: Complete this section if you harvested wood in Minnesota (burned in the past 12 months)

IF YOU OR AN IMMEDIATE FAMILY MEMBER DID NOT HARVEST WOOD IN MINNESOTA IN THE PAST 12 MONTHS, PLEASE SKIP ALL REMAINING QUESTIONS AND RETURN THE SURVEY.

For the following questions, please use the following definitions:

- **Harvested** includes all live or dead whole trees harvested primarily for the purpose of firewood anywhere in Minnesota.
- Harvested wood <u>excludes</u> **yard waste**, which is wood produced from the care and maintenance of landscaped areas, gardens, and lawns. Yard waste includes material such as: pruned branches and stems, brush, Christmas trees, mulch, stumps and roots. Wood yard waste also includes the removal of unwanted live trees and dead or diseased trees or any wood cleared for construction in a maintained area.

51. Indicate the total amount of firewood that was ***harvested*** in Minnesota by you or a member of your immediate family between May 2020 and April 2021: (If necessary, you can answer in fractions of full cords, such as 1/2, 1.5. If none enter "0")

    _______ Full cords

52. What percent of that ***harvested wood*** came from the following locations: (Percentages should add up to 100%)
   - 1 _______ % Private land
   - 2 _______ % State land
   - 3 _______ % County land
   - 4 _______ % Municipal land
   - 5 _______ % National forestland
   - 6 _______ % Unknown location

53. What percent of that ***harvested wood*** came from the following sources? (Percentages should add up to 100%)
   - 1 _______ % Live trees from forest land
   - 2 _______ % Dead trees from forest land
   - 3 _______ % Cut trees and/or tops and branches after a timber harvest
   - 4 _______ % Live or dead trees from pasture land and/or cropland
   - 5 _______ % Live or dead trees from yards, inside city limits, or other non-forest land
   - 6 _______ % Unknown location

Section I: Complete this section if you harvested wood in Minnesota (burned in the past 12 months)

54. What percent of that ***harvested wood*** came from the following types: (Percentages should add up to 100%)

Oak	Birch	Ash	Elm	Maple	Aspen	Basswood	Pine	Unknown species	
____%	____%	____%	____%	____%	____%	____%	____%	____%	= 100%

55. What counties did that ***harvested wood*** come from and the percent from each county (Percentages should add up to 100%.):

County name: 1. ______________________________ Percent: ______ %

2. ______________________________ ______ %

3. ______________________________ ______ %

4. ______________________________ ______ %

☐[1] I do not know

Thank you for completing this survey.
Please place the survey in the postage paid envelope provided and mail it promptly.

Survey sponsored by
Minnesota Department of Natural Resources
Minnesota Pollution Control Agency
U.S. Forest Service

Thanks to John Gulland of Gulland and Associates, Killaloe, CA, for allowing the use of parts of his survey.

Appendix E

USDA FOREST SERVICE RECREATIONAL FIREPIT EMISSIONS TESTING

Final Report to the Minnesota Pollution Control Agency

November 20, 2021

Shawn Urbanski, PhD
USDA Forest Service, Rocky Mountain Research Station
Missoula Fire Sciences Laboratory
5775 US Highway 10 W
Missoula, MT 59808

1. Introduction

This report presents the methods and results of recreational outdoor firepit emissions testing conducted by the USDA Forest Service Fire Sciences Laboratory (FSL) in collaboration with the Minnesota Pollution Control Agency (MPCA). This project quantified fine particulate matter (PM) emissions from two commercially available outdoor firepits designed to burn wood logs with minimal smoke production (low smoke) and from a traditional outdoor firepit. This report provides PM emission rates and emission factors for each firepit based on emissions measured during burn-cycles designed to represent typical recreational use.

Three rounds of testing burned firewood of different moisture content (MC) levels: low (MC < 10%), moderate (10% ≤ MC < 20%), and high (MC ≥ 21%). A total of 32 burns were conducted, 12 for each low smoke firepit and 8 for the traditional firepit. The experiments measured emissions of $PM_{2.5}$ and PM_1 (PM with an aerodynamic diameter < 2.5 µm and < 1.0 µm, respectively) and carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4). Measurements of CO_2 and CO were used to determine modified combustion efficiency (MCE) and emission factors (EF) for PM. (Hereafter we will use PM to refer to $PM_{2.5}$ and PM_1 for reason discussed in the methods section.) In the last round of testing (high MC), emissions of organic carbon (OC) and elemental carbon (EC) PM were also measured. Radiant heat flux (RF) produced by the fires was also measured to normalize emissions across firepits. The RF normalized emissions could be used to model emissions based on different firepit activity scenarios which are linked to operator behavior. The premise being is that from the perspective of a firepit user, the warmth provided by the fire is probably the best metric for to standardizing wood input and emission rates.

2. Methods

2.1 Combustion facility

The firepit testing was conducted in the FSL combustion chamber which is depicted in Figure 1. The combustion chamber measures 12.5 m × 12.5 m × 22 m high. An exhaust stack with an inverted funnel at its entrance extends from 2 m above the floor to the top of the chamber. A sampling platform surrounds the stack 17 m above the chamber floor. The funnel opening of the exhaust stack is 3.5 m diameter and the exhaust stack is 1.6 m diameter. Air is drawn through the stack and entrains emissions from fires burning directly beneath the funnel. Within the exhaust stack, a few meters from the funnel opening, is a diffuser ring (0.8 m inside diameter) which mixes the air and entrained emissions. At the height of the sampling platform temperature and mixing ratio are uniform across the width of the stack (Christian et al., 2003, 2004). During our testing the gas and particle measurement equipment was positioned on the platform and the emissions were drawn through sample lines constructed of stainless steel, Teflon, or conductive tubing as described in Section 2.4.

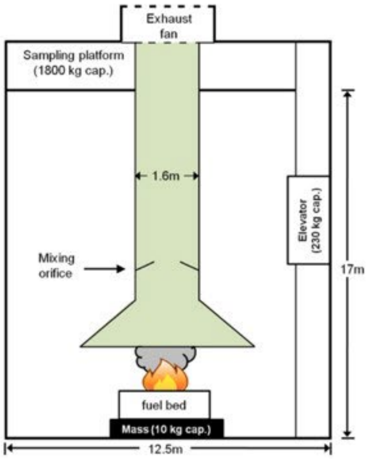


Figure 1. *Top left.* Schematic of combustion chamber at the Missoula Fire Sciences Laboratory (from Burling et al., 2010)

Top right. Firepits post testing, top row: Solo Yukon Stove, middle Row: Breeo, bottom row: Pilot Rock (traditional campground fire pit)

Bottom right. Typical pieces of split firewood (left) and firewood conditioning the environmental chamber at the Missoula Fire Sciences Laboratory (right).

2.2 Firepits

Two commercially available outdoor firepits designed to burn wood logs with minimal smoke production (low smoke), the Solo Yukon Stove (Solo) and the Breeo (Breeo), and a traditional outdoor firepit (Pilot Rock) were tested. Photos of the firepits are provided in Figure 1. All three firepits had diameters of roughly 27 inches. The Solo and Breeo firepits included instructions for wood log loading which were followed as closely as possible during the testing. Both the Solo and Breeo firepits instructed that wood logs be kept below the interior ventilation holes (Figure 1) which was done throughout the testing. Instructions included with the Solo and Breeo firepits and online instructions (including video guides) were used to ensure the firepits were operated as intended by the manufacturer.

2.3 Fuels

Pallets of split firewood, a mix of red oak, maple, and birch from Minnesota was used for the firepit testing. The split firewood had typical dimensions of 15 inches in length and maximum cross section of 3 inches (Figure 1). Firewood used in the first two rounds of testing (moderate and low MC) was delivered to the FSL in April of 2019. Half of this firewood load was conditioned at ambient conditions prior to tests in May 2019. The remaining firewood was cured in Missoula for nine months (April – December) at ambient conditions for tests in December 2019. A third round of tests used uncured firewood delivered to the FSL a few weeks before June 2021 tests. During the firepit testing the burn average MC for each round was 10 – 27% (May 2019), 6 – 9% (December 2019) and 14 – 35% (June 2021). MPCA recommends only burning wood with a moisture content of less than 20%.

2.4 Laboratory setup

The experimental setup is shown in Figure 2. The firepit being tested was placed directly under the center of the exhaust stack. Two radiant heat sensors were placed a horizontal distance of 27 inches from the firepit center and vertically positioned approximately 4 inches above the firepit rim. The inlet of a NDIR CO_2 gas analyzer (LI-COR LI-7000), which was used to monitor the background CO_2 concentration, was placed 52 inches from the firepit center at a height of 3 feet above the chamber floor. A Cavity Ring-Down Spectroscopy (CRDS) gas analyzer was positioned on the platform and sampled emissions from the exhaust stack through lines constructed of Teflon. Two particulate matter filter sampling units and a three wavelength nephelometer (testing rounds 1 and 2) were positioned on the platform and the emissions were drawn from the exhaust stack through sample lines constructed of stainless steel and conductive tubing. During the final 5 burns of round 3 testing, the NDIR CO_2 gas analyzer was repositioned to the sampling platform as a backup measurement for the CRDS analyzer which began having computer hardware issues that resulted in periodic failure to log data. The sampling floor CO_2 measurements obtained in the previous 27 burns showed that fluctuations in the background CO_2 over the duration of a burn were negligible.

2.5 Burn procedure

The test burns involved three phases: burnup, steady burn, and burndown. The steady burn phase is intended to represent the standard mode of recreational use—maintenance of a robust fire through periodic additions of split logs. The purpose of the burnup phase was to initiate a robust, steady fire. In the burnup phase, the ignition fuel bed was a small amount of excelsior shavings (< 4 oz), several pieces of kindling spliced from split logs, and one or two split logs. A typical ignition fuel bed is shown in Figure 3a. Following ignition, logs were added to the fire, at irregular intervals, over a period of 20-30 minutes. The steady burn phase began after a regular, consistent fire was achieved. During the steady burn phase logs were added at a regular interval of 10 minutes over a period of 45-60 minutes. Each log addition during the steady burn phase was 1 to 3 logs, with number added varied to maintain a robust fire. The burndown phase was a 20 to 30-minute period beginning 10 minutes after the final steady phase log addition. At the end of the burndown phase the fire was extinguished with water to preserve charcoal and unburnt fuel to determine fuel consumption. The mass and log count for all fuel additions were recorded. Photos of typical fire behavior during the burn phases are provided Figure 3b-e.

2.6 Instrumentation

Particulate matter

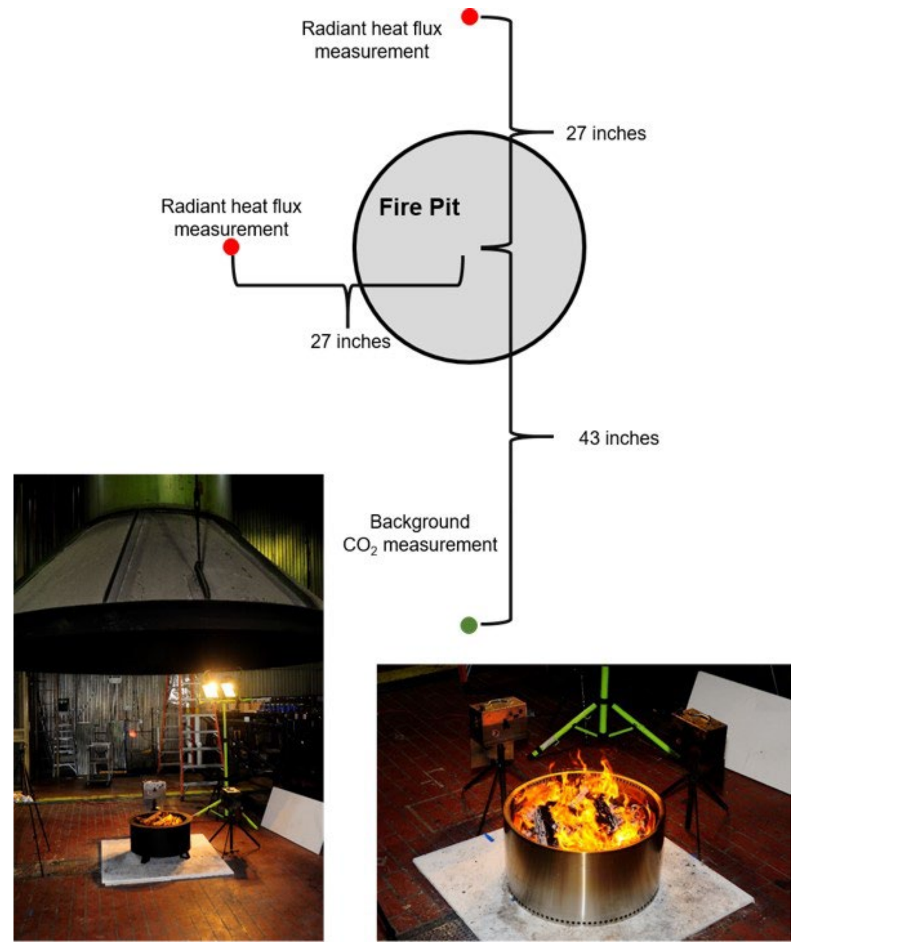


Figure 2. Schematic of experimental setup on the combustion chamber floor. The inset photo shows the position of the fire behavior packages containing the radiant heat flux sensors.

In rounds 2 and 3, PM emissions ($PM_{2.5}$) were measured using an ARA Instruments Low Flow Research Sampler (LFR-6) configured for stack sampling. The performance of the ARA sampler for measuring biomass burning smoke was evaluated against a Tisch Federal Reference Method (FRM) monitor in conjunction with the Environmental Protection Agency in a series of static chamber burn at the FSL in April 2019 (Krug et al. 2021). The sampler pulled emissions through stainless steel tubing inserted 60 cm into the exhaust stack. The sampler drew emissions at 6 slpm (standard liters per minute) from the exhaust stack through a Federal Reference Method style impactor with a cutoff of ≤ 2.5 μm aerodynamic diameter and onto a 47 mm Teflon filter. During round 1 testing, PM emissions collected by pulling emissions from the exhaust stack through a conductive tubing sample line connected to a copper tube inserted 60 cm into the exhaust stack at 14 slpm through a cyclone with a cutoff of ≤ 1.0 µm aerodynamic diameter (URG-2000-30EC, URG Corp., USA) and onto a 37 mm Teflon filter. The literature on biomass burning PM indicates the majority of fine particulate matter mass ($PM_{2.5}$) in fresh smoke is contained in submicron particles (PM_1) (Hosseini et al., 2010; Reid et al., 2005), however the PM_1 emission measurements reported in round 1 testing may slightly underestimate of $PM_{2.5}$. Particle size distribution measurements taken for five burns during round 3 testing confirmed that particles counts and mass was negligible for particle diameter > 1µm as described below.

The 37 mm and 47 mm Teflon filters used in the PM determination were conditioned and weighed in a controlled- environment room at 68 F and 50% relative humidity. Prior to weighing, the filters are conditioned for at least 24 hours. Each filter is weighed three times on a Mettler M4 microbalance with a precision of one microgram. The balance is linked to a software program that collects and stores the weights and room condition. The balance is tared (zeroed) before each weighing. A calibration weight is used once every five filters to verify the accuracy and calibration of the microbalance. Filters whose weights are not reproducible to within 5 µg are withheld from analysis. Control filters are used to correct for environmental and handling variability in the filter weights. The control filters are handled in the same way at the treatment filters. Each filter is pre-weighed prior to sample collection using this procedure, and then again after field collection. They are again conditioned at least 24 hours to stabilize the particulate matter weights and to reduce the effects of static electricity on the weighing process. The PM concentrations are calculated based on the final particulate matter weights (post-weight minus pre-weight), control filter results, and the volume of air drawn through the filter during the emission sampling. During firepit testing, at the end of each day the filters with samples were placed in a freezer to preserve semi-volatiles that may evaporate over time. The filters were analyzed using the methods described above, one week after completion of the firepit testing.

An additional emission measurement for quantifying OC and EC PM was included in round 3 testing. Emissions were collected by pulling smoke from the exhaust stack through a conductive tubing sample line connected to a copper tube inserted 60 cm into the exhaust stack at 16.7 slpm through a cyclone with a cutoff of ≤ 2.5 µm aerodynamic diameter and onto a 37 mm quartz filter. Pre-fired quartz filters are supplied by Sunset Laboratory in Tigard, OR. The filters are stored in laboratory freezer except for packaging transfers and sampling. Filters arrive from Sunset Lab in a petri dish and are transferred to cassettes for sample collection. Post sampling the filters are transferred back to petri dishes and sent to Sunset Laboratory for analysis using the NIOSH Method 5040.

During the round3 testing, visiting researchers from the University of Wyoming measured particle size distributions for five burns. Particles were sampled from the center of the burn chamber chimney at a rate of 2.7 SLPM using a rotary vane vacuum pump and 1/4" Teflon tubing. The aerosol stream was then diluted with 4.0 SLPM of dry air and the diluted mixture was drawn at a total rate of 6.7 SLPM through a bypass (BP) or thermodenuder (TD3 by Dekati) before entering an electrical low-pressure impactor (ELPI by Dekati) for real-time aerosol number and size measurement. The ELPI has 14 detection stages and can sense from 10 nm to 10 µm. The bypass and thermodenuder (TD) lines were utilized to determine aerosol volatility. The measurements consistently showed minimal particle count and mass for particle diameter > 1 µm. Appendix Figure A1 shows representatives results for these particle size distribution measurements.

CO_2, CO, and CH_4

Continuous measurements (data acquisition rate of 2 s) of CO_2, CO, CH_4, and H_2O were obtained using a CRDS trace gas analyzer (G2401-m, Picarro Inc., USA). Details of the CRDS method and this specific instrument may be found elsewhere (Urbanski, 2013). Air was sampled by the CRDS through Teflon tubing connected to stainless steel tubing inserted in the exhaust stack with its orifice near the stack's center. A three-point calibration was run periodically to verify the accuracy of the CRDS measurements. Gas mixtures of CO_2, CO and CH_4 in Ultrapure air served as calibration standards. The CRDS response varied little from day to day and study average calibration factors were applied to the data offline. The NDIR CO_2 analyzer used to monitor the background CO_2 (Figure 2) was cross calibrated versus the CRDS analyzer.

Nephelometry

A TSI three wavelength nephelometer was used in testing rounds 1 and 2 to measure total light scattering by PM at 700 nm (red), 550 nm (green), and 450 nm (blue) at a data acquisition rate of 0.5 Hz. Total light scattering at these wavelengths responds strongly to PM concentration, particle size distribution, and particle chemical properties. The nephelometer measurements at 700 nm may be used to estimate the temporal PM concentration profile based on the integrated PM measurements obtained with the filter sampling system.

Radiant Heat

Radiant energy flux was measured using Medtherm Dual Sensor Heat Flux sensors (Model 64-20T) contained in Fire Behavior Packages (FBP). These FBP have been widely used in field research projects conducted by the Fire Lab's fire behavior research group and details may be founds in Jimenez et al. (2007; https://www.fs.usda.gov/treesearch/pubs/28594). The heat flux sensors were calibrated in a black body over a range of 0 to 200kW m^{-2} and fit a power law curve to the calibration data resulting in a calibration error of less than 3% of reading over the range.

2.7 Emission Calculations

Emissions of a given species X were quantified using burn phase average excess mass mixing ratios ΔX ($\Delta X = X_{fire} - X_{background}$). Phase average emission factors for each species X, EF_X, were calculated using the carbon mass balance method (Yokelson et al., 1999) implemented with Eq. (1). In Eq. (1), ΔC_i are the excess mass mixing ratios of carbon in species X, and F_c is the mass fraction of carbon in the dry fuel which was taken as 0.50 for all wood used in this study.

Eq. 1 $$EF_x = F_c \times 1000\ (g\ kg^{-1}) \times \frac{\Delta X}{\Delta C_{CO_2} + \Delta C_{CO} + \Delta C_{CH_4} + \Delta C_{PM}}$$

The carbon mass balance method assumes that all the fuel carbon volatilized as gases or PM is measured. However, since the majority of carbon mass (> 95%) in fresh biomass smoke from efficient fires is contained in CO_2, CO, and CH_4 (Urbanski, 2014), neglecting other carbon containing gases in the carbon mass balance method introduces only a minor bias of < +5%. The steady burn phase of the testing was highly efficient, the fraction of measured carbon in species other than CO_2 was quite small, and EFPM calculated using only ΔCO_2 in the denominator of Eq. 1 resulted in < 5% underestimate compared to EFPM calculated using all four species. We assumed a PM carbon content of 75% (Reid et al., 2005) in our EF calculations. The difference in the denominator between assumed PM carbon content of 0% and 100% was < 1.0%. Combustion efficiency (CE) is the fraction of carbon evolved in gases and PM that is emitted as CO_2. Given most carbon is contained in CO_2, CO, and CH_4, we estimate CE as $\Delta CO_2/(\Delta CO_2 + \Delta CO + \Delta CH_4)$. In biomass burning, modified combustion efficiency (MCE; MCE = $\Delta CO_2/(\Delta CO_2 + \Delta CO)$) is used to characterize the relative amount of flaming and smoldering combustion (Akagi et al., 2011). MCE approaches 0.99 for "pure" flaming combustion (Yokelson et al., 1996).

Emissions of species X by fire phase were calculated using Eq. 2.

Eq. 2 $$E_i X = EF_i X \times FCON \times \frac{\Delta C_i \times \Delta t_i}{\sum \Delta C_i \times \Delta t_i}$$

In Eq. 2 the index i is the fire phase (burn-up, steady burn, burn-down), FCON is the total dry mass of fuel consumed in the fire (g), EF_iX is the EF for species X (Eq 1) for phase i, ΔC_i is average mass mixing ratio of carbon emitted during phase i (denominator of Eq. 1), and Δt_i is the sampling duration of phase I, and E_iX is in units of g of X. The emission rates for species X by fire phase were calculated using Eq. 3

Eq. 3 $$ER_i X = \frac{E_i X}{\Delta t_i}$$

Where E_iX is the amount of X emitted in phase i (Eq. 2) and Δt_i is the sampling duration of phase i, and ER_iX is in units of g of X per minute. Emissions of species X for phase I, normalized to radiant heat flux is given by Eq; 4:

Eq. 4 $$NE_i X = \frac{E_i X}{RF_i}$$

where E_iX is the amount of X emitted in phase i (Eq. 2) and RF_i is average radiant heat flux during of phase i, and NE_iX is in units of g m^2 kW^{-1}.

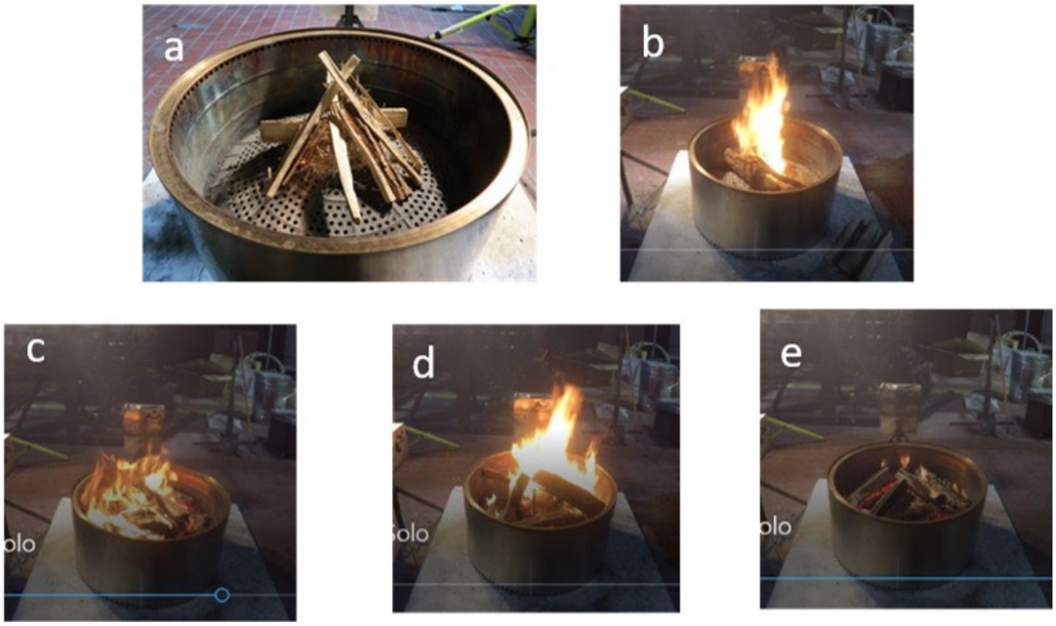


Figure 3. Burn phases of firepit testing a) ignition fuel bed, b) ignition, c) burn-up phase, d) steady burn phase, and e) burn-down phase.

3. Results

A total of 32 burns were conducted as summarized in Table 1. The course of a typical burn is illustrated by Figure 4 which shows time series of gaseous emissions, combustion efficiency (CE), radiant heat flux (RF), and fuel input for low MC firewood burned in the Breeo firepit (burn id 2019121002). Following ignition and during the first few rounds of firewood addition, RF remains low (< 100 W m^{-2}) and gaseous carbon emissions (ΔC) are less than half the average value of the steady burn phase (Fig. 4, top). By the end of the burn-up phase ΔC has peaked and RF has neared the average value measured over the steady burn phase. During the later stages of the burn-up and throughout the steady burn, inputs of firewood produced a large spike in ΔC, while RF spikes upon firewood addition do not occur consistently. During the burn-down phase CE decreases rapidly (Fig. 4, bottom) due to shift in production from CO_2 to CO. The increase in CO production during the burn-down phase is due to glowing combustion of char (Yokelson et al., 1996). Glowing combustion of char is characterized by low MCE, relatively high EFCO, and low PM production.

Table 1. Summary of test burns. Moisture content (MC) is percent of dry mass. Mass of wood fuel and wood consumed is dry mass. Ash includes charcoal.

Burn ID	Burn No.	Date	Firepit	Wood MC (%)	Wood fuel (lb)	Charcoal and ash (lb)	Wood consumed (lb)	Percent consumed (%)
Round 1 Testing								
2019050702	2	20190507	Solo	14	69.3	6.3	63.1	91
2019050803	3	20190508	Solo	27	52.3	2.8	49.5	95
2019050804	2	20190508	Breeo	21	50.0	7.6	42.4	85
2019050905	5	20190509	Breeo	24	50.5	9.0	41.5	82
2019050906	6	20190509	Solo	11	59.7	4.6	55.1	92
2019051007	7	20190510	Breeo	13	48.4	7.4	41.1	85
2019051008	8	20190510	Solo	14	65.3	7.2	58.1	89
2019051309	9	20190513	Breeo	10	48.4	6.4	42.0	87
2019051310	10	20190513	Pilot Rock	18	43.4	7.3	36.1	83
2019051411	11	20190514	Pilot Rock	14	49.0	9.6	39.4	80
Round 2 testing								
2019120901	1	20191209	Breeo	9	59.1	8.1	51.0	79
2019121002	2	20191210	Breeo	9	62.0	9.9	52.1	77
2019121003	3	20191210	Solo	7	66.4	5.0	61.4	86
2019121104	4	20191211	Solo	6	74.5	4.9	69.7	88
2019121205	5	20191212	Solo	8	76.0	7.7	68.4	83
2019121306	6	20191213	Breeo	8	55.5	10.1	45.5	76
2019121607	7	20191216	Pilot Rock	8	56.3	8.3	48.0	79
2019121708	8	20191217	Pilot Rock	8	61.4	NA	42.5[1]	64
2019121809	9	20191218	Solo	9	59.6	4.9	54.7	84
2019121910	10	20191219	Breeo	8	58.3	11.0	47.3	75
Round 3 Testing								
2021060701	1	20210607	Breeo	28	53.6	16.8	36.8	69

2021060802	2	20210608	Breeo	35	50.9	23.3	27.5	54
2021060903	3	20210609	Solo	24	56.2	15.6	40.6	72
2021061004	4	20210610	Solo	25	54.0	16.4	37.6	70
2021061105	5	20210611	Solo	14	60.0	14.9	45.0	75
2021061506	6	20210615	Breeo	21	57.1	15.6	41.4	73
2021061507	7	20210615	Solo	30	52.8	12.4	40.4	77
2021061708	8	20210617	Breeo	27	54.6	15.3	39.3	72
2021062109	9	20210621	Pilot Rock	19	58.6	13.0	45.6	78
2021062110	10	20210621	Pilot Rock	17	61.5	16.8	44.7	73
2021062211	11	20210622	Pilot Rock	23	58.6	34.8	23.8	41
2021062312	12	20210623	Pilot Rock	26	56.6	30.5	26.1	46

[1]The ash pit, which was left to cool overnight, was not fully extinguished and smoldered overnight preventing an accurate measurement of post burn ash. It was assumed the percent consumption for this burn was the same as that for the other Pilot Rock burn for this round of testing (77%).

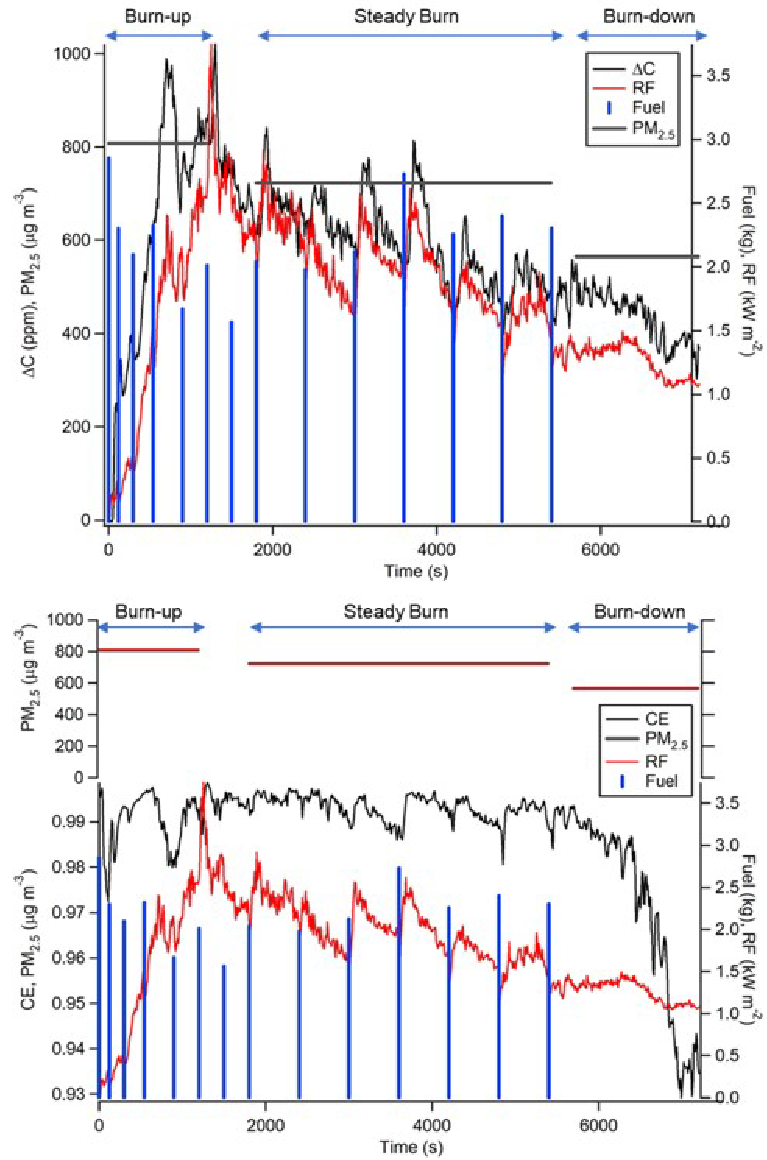


Figure 4. Top: Emissions of gaseous carbon (ΔC) in CO_2, CO, and CH_4 and radiant heat flux averaged to 10 s, fuel additions (dry mass), and average $PM_{2.5}$ concentration from filter measurements. Bottom: Same as top, except plot of combustion efficiency (CE) instead of ΔC.

Table 2. Steady burn phase results by firewood moisture level. Average values of modified combustion efficiency (MCE), PM, CO_2, CO, CH_4 emission factors (EF), PM emission rates (ER), PM emitted normalized to radiant heat flux (RF), fuel consumption (FC). FC is dry mass and MC percent of dry mass. Numbers in parathesis are standard deviation. Data for individual burns is provided in Appendix Table A1.

Firepit	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^2 Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	$EFCO_2$ (lb ton^{-1})	EFCO (lb ton^{-1})	$EFCH_4$ (lb ton^{-1})
Low moisture, MC < 10%									
Solo	98.7(0.4)	6.18(0.54)	1.99(0.21)	12.82(2.11)	42.8(5.8)	0.167(0.025)	3619(20)	30(10)	0.5(0.4)
Breeo	99.4(0.2)	2.34(0.56)	0.52(0.04)	6.02(1.87)	31.2(3.3)	0.085(0.020)	3643(6)	14(4)	0.6(0.1)
Pilot Rock[1]	99.0(0.0)	2.69(0.10)	0.69(0.08)	4.94(0.46)	28.2(2.3)	0.122(0.003)	3625(1)	24(1)	1.3(0.2)
Moderate moisture, 10% ≤ MC < 20%									
Solo	97.9(1.4)	2.68(0.40)	0.73(0.20)	21.84(18.78)	35.7(2.3)	0.053(0.022)	3579(52)	49(32)	1.4(0.7)
Breeo[1]	96.4(0.7)	3.53(3.63)	0.71(0.73)	28.91(33.30)	28.0(3.3)	0.033(0.006)	3510(40)	83(16)	6.0(1.7)
Pilot Rock	96.0(1.2)	5.29(0.91)	1.21(0.57)	35.36(32.26)	27.6(6.7)	0.024(0.008)	3497(54)	93(28)	6.3(1.6)
High moisture, MC >= 20%									
Solo	98.4(0.6)	3.73(0.95)	0.96(0.22)	56.43(34.68)	32(4)	0.024(0.017)	3595(25)	38(14)	2.0(0.4)
Breeo	96.1(1.4)	5.70(3.12)	1.64(1.06)	87.69(74.42)	27(4)	0.018(0.009)	3495(60)	90(31)	6.4(2.3)
Pilot Rock[1]	96.4(0.1)	5.31(0.04)	0.83(0.09)	59.44(0.71)	18(2)	0.013(0.001)	3522(6)	84(3)	5.8(0.8)

[1]Only 2 burns at this moisture level

3.1 Steady burn phase

The steady burn phase is designed to represent typical recreational firepit use and is expected to typify the activity responsible for the majority of firewood burned in firepits. The combustion of dead wood and other biomass is sensitive to the moisture content of the fuel. As moisture content increases, combustion efficiency decreases and the portion of volatilized biomass carbon emitted as PM, CO, CH_4 and other incomplete combustion products increases, while CO_2 decreases (Urbanski 2014; Peterson et al. 2021). Therefore, we anticipated observing an increase in EFPM, EFCO, and $EFCH_4$ (and a decrease in MCE) with increasing firewood moisture content. PM emissions, MCE, RF, and fuel consumption (FC) for the steady burn phase are summarized by firewood moisture level in Table 2. Steady phase PM emission metrics by MC level are plotted in Figure 5 and results for each burn are given in Appendix Table A1.

Emissions response to MC

The MPCA recommends only burning firewood with an MC < 20%; considering these guidelines we focus on comparing results for well-seasoned (MC < 10%; low MC) and moist (MC > 20%; high MC) firewood. PM emission metrics were lowest for both the Breeo and Pilot Rock firepits for low MC (< 10%) as expected. In going from low to high MC, EFPM increases from 2.34 to 5.70 lb ton^{-1} for the Breeo firepit and from 2.69 to 5.31 lb ton^{-1} for the Pilot Rock firepit (Table 2). PM emissions normalized to radiant heat flux (NE) showed a more dramatic rise, increasing by factors of 14.7 and 12.1 for the Breeo and Pilot Rock firepits, respectively (Table 2).

Surprisingly, the Solo firepit EFPM for low MC was nearly double that for high MC, 6.18 versus 3.73 lb ton^{-1}. The increase is not attributable to outlier values or high burn-to-burn variability (see Appendix Table A1). This behavior as MC decreased contravenes that observed for MCE (increase) and EFCO

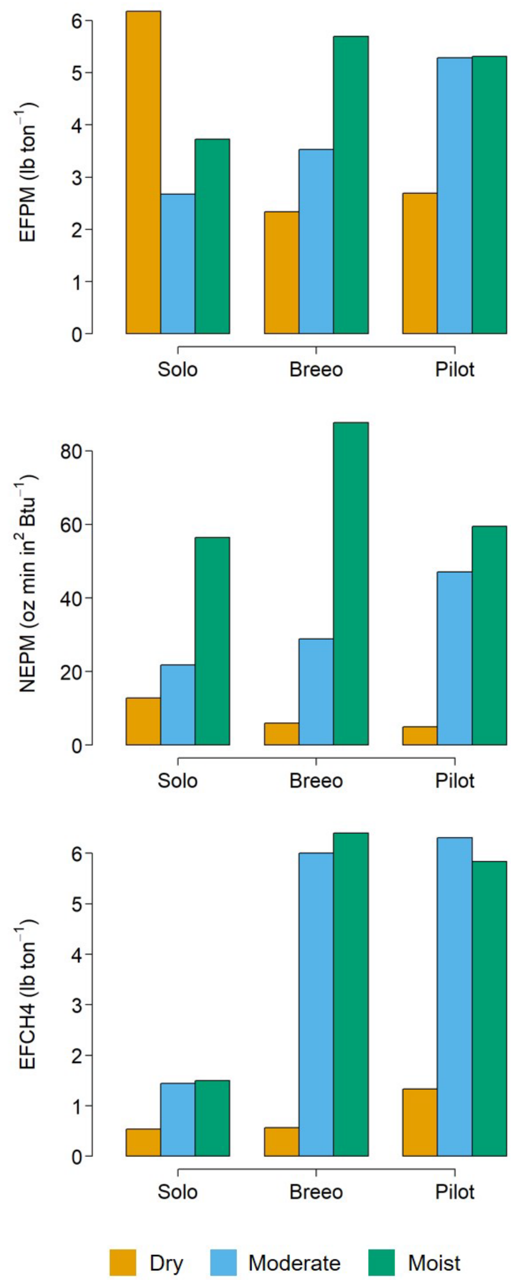


Figure 5. Average EFPM (top), PM emissions normalized to radiant heat flux (NE) (middle) and $EFCH_4$ (bottom) by firewood moisture content for steady burn phase.

and $EFCH_4$ (decrease) which demonstrate a more efficient combustion process at low MC (Table 2 and Figure 5). For NE, the higher EFPM of the low MC burns *versus* high MC burns was more than offset by the greater realized radiant heat flux relative to fuel consumed. As with the Breeo and Pilot Rock firepits, the Solo firepit NE value at high MC was considerably higher (by a factor of 4.4) than that at low MC (Figure 5).

"Low smoke" versus traditional

Here we compare PM emissions of the "low smoke" firepits with those of the traditional design (Pilot Rock), beginning with the low MC firewood tests. Compared with the traditional firepit, Solo EFPM and NE were ~ 2.5 times greater, while the Breeo EFPM and NE were roughly the same (Table 2). When burning moderate MC firewood, Solo firepit emissions were 60% that of the traditional firepit (Table 2). The Breeo had only two burns with firewood MC in the intermediate range and EFPM and NE varied greatly (see Appendix Table A1) and their average values fell between those of the Solo and traditional firepit. For the high MC tests the Solo firepit had a lower EFPM (3.73 lb ton^{-1}) than either the Breeo or Pilot Rock which were comparable to one another (5.70 and 5.31 lb ton^{-1}, respectively). When burning moist firewood, the Breeo firepit NE had high burn-to-burn variability (Appendix Table A1) and an average ~ 50% higher than the Solo and Pilot Rock.

3.2 Burndown phase

In the burndown phase no firewood is added and the fire is allowed to transition from flaming to smoldering. During real world use, total fuel consumption and emissions of the burndown phase will be small relative to the steady burn phase. In general, smoldering biomass has larger EF for PM, CO, CH_4, and other incomplete combustion products. However, once volatiles are depleted from the wood the process may transition to glowing combustion which does not produce visible smoke and has very low EFPM, but high EFCO and $EFCH_4$ compared with flaming combustion.

Emission metrics for the burndown phase are summarized in Table 3 and Figure 6 by firewood moisture level. Appendix Table A2 provides results for all burns. In general, EFPM for the burndown phase were lower or roughly comparable to the steady burn phase while EFCO and $EFCH_4$ are significantly higher. These results are consistent with the burndown phase including both smoldering and glowing combustion. The only metrics which clearly varies with firewood MC is RF which was much higher for the low MC burns compared with moderate and high MC burns (Table 3). As a result of higher RF at low MC, NE is lowest for these burns, however the results are highly variable across the range of MC (Figure 6).

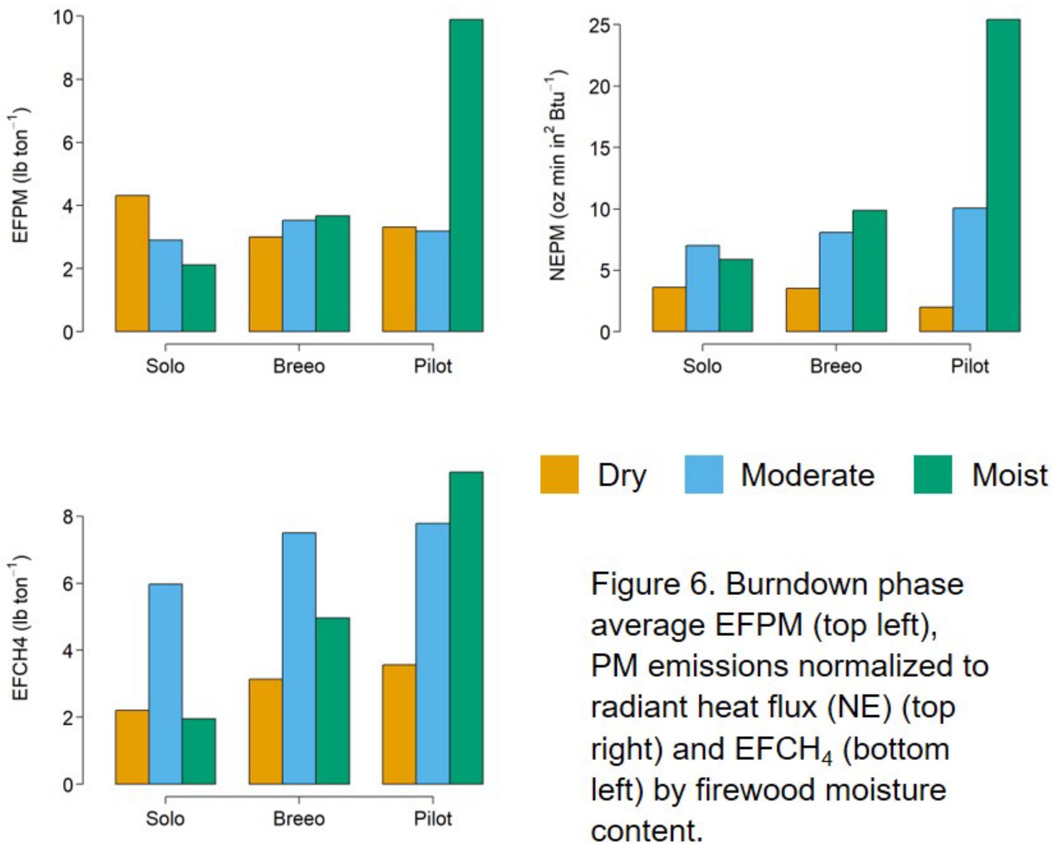


Figure 6. Burndown phase average EFPM (top left), PM emissions normalized to radiant heat flux (NE) (top right) and $EFCH_4$ (bottom left) by firewood moisture content.

Table 3. Burndown phase results by firewood moisture level. Average values of modified combustion efficiency (MCE), PM, CO, CH_4 emission factors (EF), PM emission rates (ER), PM emitted normalized to radiant heat flux (RF), fuel consumption (FC). FC is dry mass and MC percent of dry mass. Numbers in parathesis are standard deviation. Data for individual burns is provided in Appendix Table A2.

Firepit	MCE (%)	EFPM ($lb\ ton^{-1}$)	ER PM ($oz\ hr^{-1}$)	NE PM ($oz\ min\ in^2\ Btu^{-1}$)	FC (lb)	RF ($Btu\ min^{-1}\ in^{-2}$)	$EFCO_2$ ($lb\ ton^{-1}$)	EFCO ($lb\ ton^{-1}$)	$EFCH_4$ ($lb\ ton^{-1}$)
Low moisture, MC < 10%									
Solo	89.3(3.4)	4.32(0.86)	0.79(0.27)	3.60(0.95)	8.3(1.2)	0.080(0.012)	3270(124)	249(79)	2.2(0.8)
Breeo	94.8(1.8)	3.00(0.59)	0.39(0.02)	3.52(0.88)	7.7(1.1)	0.050(0.013)	3466(67)	122(41)	3.1(1.0)
Pilot Rock[1]	94.6(2.8)	3.31(0.35)	0.52(0.06)	2.01(0.21)	8.2(0.01	0.109(0.002)	3459(103)	126(65)	3.6(0.06)
Moderate moisture, 10% ≤ MC < 20%									
Solo	91.9(3.5)	2.91(0.72)	0.37(0.15)	7.02(2.05)	6.3(0.8)	0.022(0.010)	3347(135)	189(81)	6.0(3.7)
Breeo[1]	91.1(0.4)	3.53(1.32)	0.42(0.15)	8.07(2.35)	5.7(0.6)	0.020(0.004)	3313(13)	206(8)	7.5(1.8)
Pilot Rock	93.1(4.3)	3.18(0.49)	0.32(0.12)	10.06(8.05)	4.8(1.5)	0.019(0.010)	3394(172)	159(98)	7.8(3.9)
High moisture, MC >= 20%									
Solo	95.9(3.4)	2.12(0.44)	0.22(0.08)	5.88(3.96)	5.5(2.1)	0.017(0.005)	3507(127)	95(79)	2.6(1.4)
Breeo	95.5(2.7)	3.67(0.96)	0.30(0.18)	9.86(4.47)	4.7(1.1)	0.015(0.005)	3482(104)	104(63)	5.0(2.0)
Pilot Rock[1]	94.2(0.1)	9.89(0.69)	0.44(0.00)	25.41(0.58)	2.3(0.2)	0.007(0.000)	3431(4)	134(3)	9.3(0.2)

[1]Only 2 burns at this moisture level

3.3 Burnup phase

Results for the burnup phase are summarized in Table 4 by firewood moisture level and given for individual burns in Appendix Table A3. Emission metrics are plotted by MC level in Figure 7. The burnup phase had the largest and most variable EFPM of the three fire phases. The burns with dry firewood consistently had the highest MCE, and lowest EF for PM, CO, and CH_4 (Figure 7 and Table 4). The moderate and high MC burns had highly variable EF and no noticeable trend with respect to MC (Table 4 and Appendix Table A3). As with the steady burn and burndown phases, RF decreased with increasing MC resulting in a noticeable upward trend in NE with MC (Figure 7), despite the high variability in EFPM.

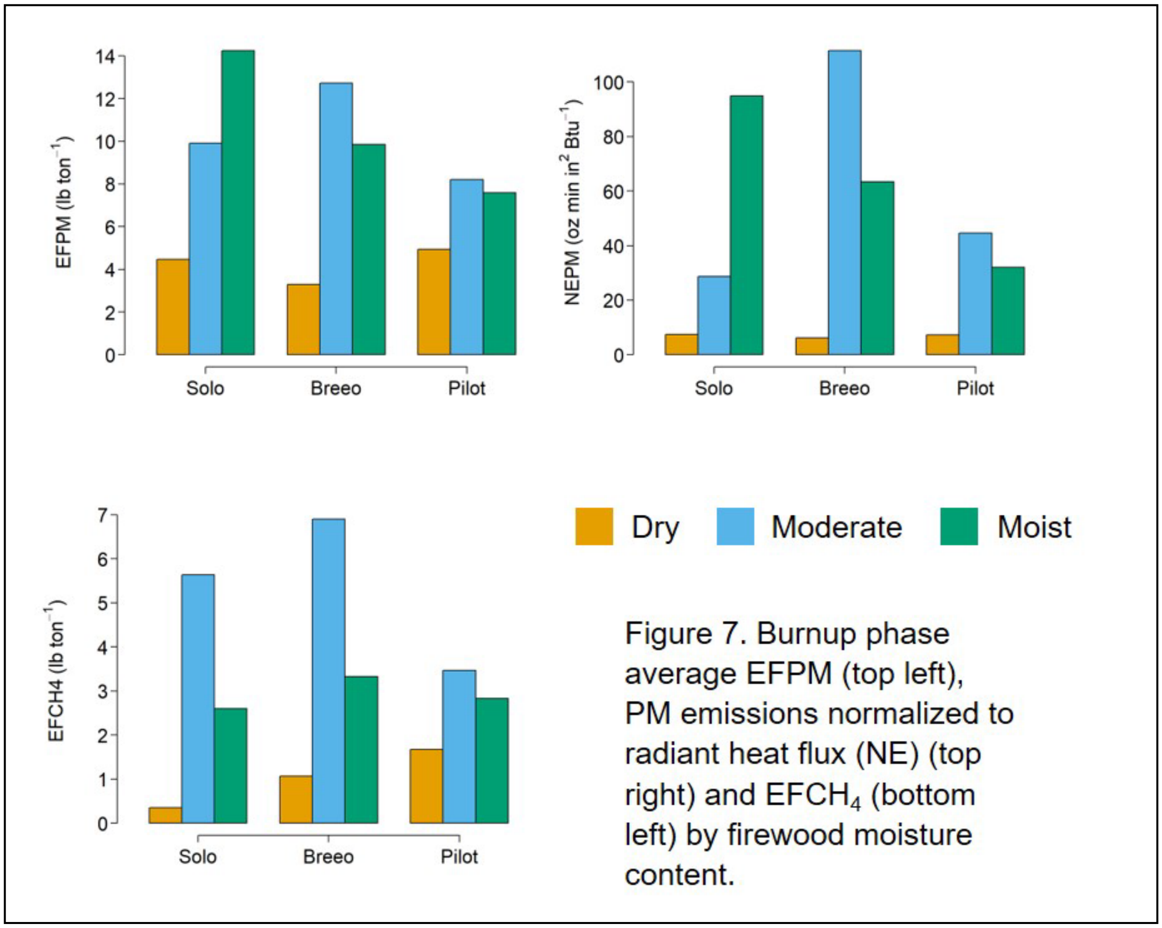


Figure 7. Burnup phase average EFPM (top left), PM emissions normalized to radiant heat flux (NE) (top right) and $EFCH_4$ (bottom left) by firewood moisture content.

Table 4. Burnup phase results by firewood moisture level. Average values of modified combustion efficiency (MCE), PM, CO, CH_4 emission factors (EF), PM emission rates (ER), PM emitted normalized to radiant heat flux (RF), fuel consumption (FC). FC is dry mass and MC percent of dry mass. Numbers in parathesis are standard deviation. Data for individual burns is provided in Appendix Table A3.

Firepit	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^2 Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	$EFCO_2$ (lb ton^{-1})	EFCO (lb ton^{-1})	$EFCH_4$ (lb ton^{-1})
Low moisture, MC < 10%									
Solo	99.5(0.1)	4.46(0.85)	1.02(0.20)	7.52(2.45)	12.5(1.4)	0.064(0.028)	3645(3)	13(2)	0.4(0.1)
Breeo	99.0(0.2)	3.30(0.55)	0.69(0.10)	6.19(1.76)	10.2(1.6)	0.045(0.008)	3626(7)	25(4)	1.1(0.2)
Pilot Rock[1]	98.4(0.1)	4.93(0.13)	0.92(0.15)	7.29(0.04)	8.8(1.7)	0.047(0.008)	3603(7)	38(4)	1.7(0.1)
Moderate moisture, 10% ≤ MC < 20%									
Solo	96.1(4.9)	9.91(9.66)	0.75(0.26)	29.71(33.74)	10.3(6.5)	0.025(0.029)	3484(223)	90(110)	5.6(8.5)
Breeo[1]	95.1(1.0)	12.72(8.57)	1.39(0.49)	111.49(115.57)	7.8(3.2)	0.011(0.010)	3434(59)	113(21)	6.9(0.7)
Pilot Rock	97.3(0.4)	8.21(3.11)	1.10(0.23)	33.45(34.63)	8.4(2.6)	0.014(0.007)	3542(15)	63(8)	3.5(0.4)
High moisture, MC >= 20%									
Solo	96.6(0.7)	14.25(4.71)	0.84(0.07)	94.96(40.56)	3.5(1.7)	0.005(0.004)	3502(35)	78(16)	3.5(1.1)
Breeo	97.0(1.0)	9.84(3.69)	0.74(0.32)	63.48(31.57)	5.4(2.3)	0.007(0.004)	3525(51)	69(23)	3.3(1.2)
Pilot Rock[1]	97.9(0.6)	7.59(0.24)	0.51(0.06)	32.00(1.81)	3.4(0.3)	0.007(0.000)	3563(21)	55(13)	2.8(1.1)

[1]Only 2 burns at this moisture level

3.4 Possible Solo firepit high EFPM – EC linkage

In preliminary firepit testing conducted in May 2019 using firewood with moderate to high MC (Table 1), steady burn phase EFPM for the Breeo and Solo firepits were 3.7±2.2 lb ton^{-1} (n=4) and 2.7±0.4 lb ton^{-1} (n=4), respectively. The second round of testing used well-seasoned firewood (MC < 10%) resulted in steady burn phase EFPM of 2.3±0.6 lb ton^{-1} (n=4) for the Breeo firepit and 6.2±0.5 lb ton^{-1} (n=4) for the Solo firepit. The low MC firewood used in the second round of testing burned with a greater combustion efficiency, having higher MCE (≥ 0.98) and lower EFCO and $EFCH_4$, than the first round of burns using moderate MC firewood. These results indicate the use of well cured firewood reduced EFPM (and EFCO and $EFCH_4$) for the Breeo firepit, as expected (Tables 2 and Appendix A1, Figure 5). This finding is consistent with both the expectation that dry firewood burns more efficiently and with published studies of open biomass burning emissions showing EFPM, EFCO, and $EFCH_4$ decrease with increasing MCE (e.g., Burling et al. 2010; McMeeking et al. 2009; Yokelson et al. 2013; Jen et al. 2019).

In contrast to the Breeo firepit, we observed a large increase in EFPM for the Solo firepit when burning low MC firewood despite slightly higher average MCE and significantly lower EFCO and $EFCH_4$ (Tables 2 and Appendix A1, Figure 5). This observed increase in EFPM coinciding with increased combustion efficiency is contrary to expectations. One possible explanation for this result is that the relationship between combustion efficiency and OA and black carbon aerosol (BC, also referred to as soot or elemental carbon (EC)) production is different. Particulate matter produced by the open burning of forest surface fuels (litter and dead wood) is primarily carbonaceous, being either OA or EC, with ionic aerosols— sulfate, nitrate, ammonium, and chloride— generally comprise < 10% of aerosol mass generated by the combustion of forest fuels (McMeeking et al. 2009; Hosseini et al. 2013; May et al. 2014). Laboratory studies of emissions from burning wildland fuels have generally found a strong negative correlation of EFOA, EFOC (the carbon fraction of OA, typically ~70% by mass (Reid et al. 2008; McMeeking

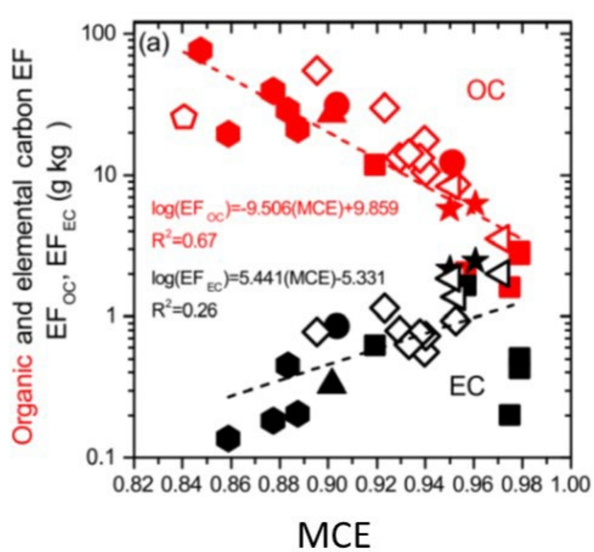


Figure 8. EFOC and EFEC plotted versus MCE for burning of western US wildland fuels at Missoula Fire Sciences Laboratory during FIREX laboratory intensive. Figure is reproduced from Jen et al. (2019), Figure 1.

et al. 2009)), and EFPM (PM = total particulate mass) with MCE (e.g., McMeeking et al. 2009; Jen et al. 2019). The response of EFPM generally follows that of EFOA and EFOC because PM created by burning wildland fuels is mostly OA (McMeeking et al. 2009; Jen et al. 2019). Thus, one would expect the EFPM for the Solo firepit from the low MC firewood tests be similar or lower than that measured in the round 1 tests burning firewood with moderate MC.

However, if a sizeable fraction of the PM generated by the firepits is BC, the observed increase of EFPM for the Solo firepit would be consistent with current knowledge of biomass burning emissions. BC is associated with flaming combustion, and previous emissions studies show that EFBC increases with increasing MCE, as shown in Figure 8, which reproduces a figure

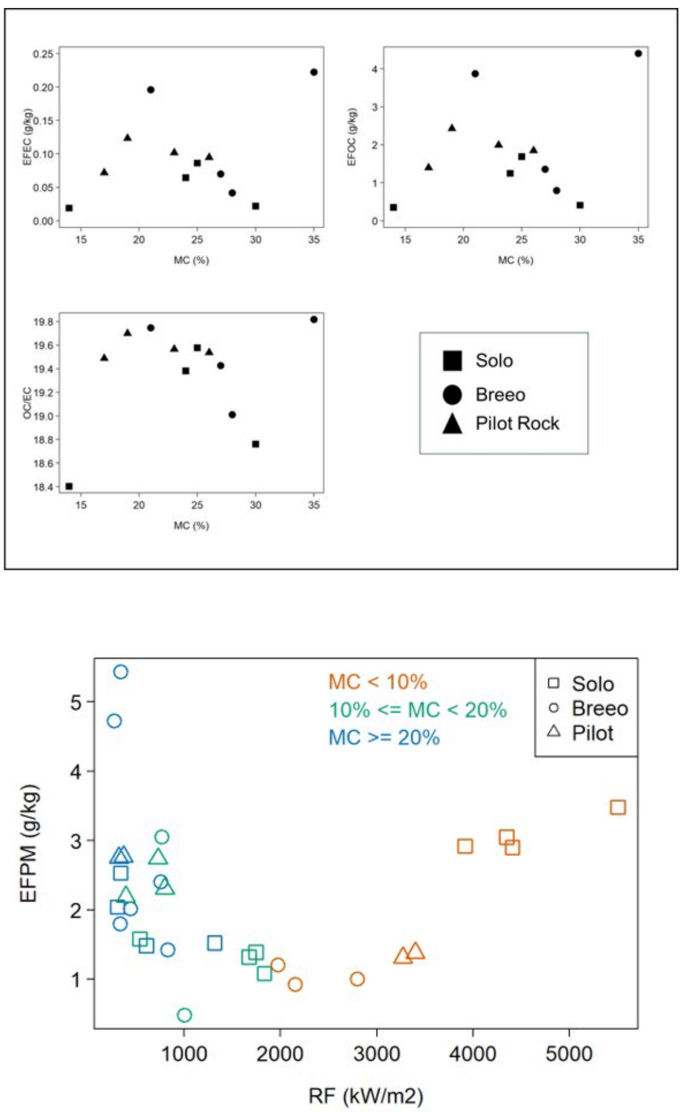


Figure 9. Top: Steady burn phase EFEC, EFOC, and OC/EC ratio plotted versus MC. Bottom: Steady burn phase EFPM plotted versus radiant heat flux.

from Jen et al. (2019). This may explain the relatively high EFPM measured for the Solo firepit burning low MC firewood. In the low MC firewood burns the average RF produced by the Solo firepit was nearly twice that of the Breeo firepit (0.167 Btu min^{-1} in^{-2} vs 0.085 Btu min^{-1} in^{-2}, Table 2), indicating far more intense flaming combustion. The comparatively high intensity fires produced by the Solo firepit may have resulted in increased BC production and hence increased EFPM relative to the round 1 testing using moderate to high MC firewood. In contrast, the fires produced by the Breeo firepit may not have been sufficiently intense to produce additional BC, or enough additional BC to offset a decrease in OA associated with the increased combustion efficiency.

To test this hypothesis, measurements of EFOC and EFEC were included during round three of firepit evaluation. While the primary objective of round three testing was to characterize emissions for high MC firewood, we planned to burn moderate to low MC firewood as well, to determine if EFEC increased at low MC and high HF. Figure 9 (top) plots EFOC, EFEC, and OC/EC *versus* MC for the round three tests. EFEC, EFOC, and OC/EC showed no obvious response to MC over the range tested. Unfortunately, while we were able to measure emissions at high MC (Table 2) limits on the number of tests that could be conducted prevented replication of the low MC (< 10%) firewood burns. None of the round three burns replicated the combustion conditions of the previous Solo firepit tests with low MC firewood: round 2 RF ranged from 0.114 – 0.202 Btu min^{-1} in^{-2}, while RF $\leq$ 0.067 Btu min^{-1} in^{-2} for all other Solo tests (Table 3). For context, Figure 9 (bottom)_ shows steady burn phase EFPM *versus* RF for all 32 burns. With the exception of the round 2 Solo burns, the highest EFPM occur for RF < 0.037 Btu min^{-1} in^{-2} (1.0 kW m^{-2}). The inability to replicate the round 2 combustion conditions of the Solo firepit during the round 3 testing when OC and EC measurements were obtained prevents us from evaluating our hypothesis regarding the Solo firepit's high EFPM when burning low MC firewood.

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Appendix

Table A1. Steady phase results all burns sorted by firepit and firewood moisture level. Modified combustion efficiency (MCE), PM, CO_2, CO, CH_4 emission factors (EF), PM emission rates (ER), PM emitted normalized to radiant heat flux (RF), fuel consumption (FC). FC is dry mass and MC percent of dry mass.

Burn ID	Burn	MC (%)	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^{2} Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	EFCO2 (lb ton^{-1})	EFCO (lb ton^{-1})	EFCH_4 (lb ton^{-1})
Solo											
2019120404	4	6	86.6	4.88	0.92	4.98	9.8	0.077	3174	311	1.4
2019120303	3	7	89.7	3.10	0.50	3.12	8.4	0.067	3284	240	1.8
2019120505	5	8	94.0	4.98	1.11	2.86	6.9	0.097	3440	140	2.4
2019120909	9	9	87.0	4.32	0.65	3.44	7.8	0.078	3180	304	3.3
2019050906	6	11	89.5	3.60	0.55	5.87	6.7	0.033	3258	244	5.6
2019050702	2	14	NA	NA	NA	NA	NA	NA	NA	NA	NA
2019051008	8	14	90.2	2.16	0.28	5.81	6.6	0.020	3280	226	9.8
2021061105	5	14	95.9	2.96	0.30	9.38	5.4	0.014	3502	96	2.5
2021060903	3	24	96.3	2.52	0.32	11.59	7.7	0.013	3518	86	2.6
2021061004	4	25	98.6	1.86	0.19	5.49	5.2	0.014	3608	32	1.2
2019050803	3	27	91.0	1.64	0.25	3.49	6.4	0.024	3324	208	4.0
2021061507	7	30	97.7	2.46	0.13	2.96	2.6	0.017	3576	54	NA
Breeo											
2019120606	6	8	94.4	2.74	0.38	4.00	7.2	0.039	3454	130	3.4
2019121010	10	8	94.5	2.86	0.38	2.51	7.0	0.064	3456	127	3.8
2019120101	1	9	92.9	3.86	0.00	NA	7.2	NA	3396	166	3.6
2019120202	2	9	97.2	2.54	0.41	4.06	9.3	0.046	3558	66	1.7
2019051309	9	10	90.8	4.46	0.53	9.73	6.1	0.023	3304	212	6.2
2019051007	7	13	91.4	2.60	0.32	6.40	5.3	0.017	3322	200	8.8
2019050804	4	21	92.1	3.36	0.08	7.62	6.0	0.021	3352	182	7.2
2021061506	6	21	96.6	4.44	0.38	12.96	4.4	0.012	3514	78	7.0
2019050905	5	24	92.0	4.06	0.55	9.53	6.0	0.020	3348	186	6.0
2021061708	8	27	97.6	2.72	0.19	6.25	3.7	0.013	3572	56	2.9
2021060701	1	28	97.1	4.90	0.40	17.20	4.4	0.010	3542	66	3.0

2021060802	2	35	97.6	2.52	0.17	5.61	3.5	0.013	3562	56	3.6

Table A1 continued

Burn ID	Burn	MC (%)	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^2 Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	EFCO2 (lb ton^{-1})	EFCO (lb ton^{-1})	$EFCH_4$ (lb ton^{-1})
2019120707	7	8	92.6	3.06	0.48	1.86	8.2	0.107	3386	172	4.0
2019120808	8	8	96.6	3.56	0.57	2.16	8.3	0.110	3532	80	3.2
2019051411	11	14	90.0	2.88	0.34	4.23	5.6	0.030	3266	230	11.2
2021062110	10	17	96.7	3.84	0.44	19.24	6.0	0.010	3536	78	5.1
2019051310	10	18	88.9	3.26	0.34	6.70	4.8	0.019	3224	256	11.0
2021062109	9	19	96.9	2.74	0.15	NA	2.7	NA	3548	72	3.8
2021062211	11	23	94.3	10.38	0.44	25.82	2.2	0.007	3434	132	9.1
2021062312	12	26	94.1	9.40	0.44	25.00	2.5	0.007	3428	136	9.5

Table A2. Burndown phase results all burns sorted by firepit and firewood moisture level. Modified combustion efficiency (MCE), PM, CO_2, CO, CH_4 emission factors (EF), PM emission rates (ER), PM emitted normalized to radiant heat flux (RF), fuel consumption (FC). FC is dry mass and MC percent of dry mass.

Burn ID	Burn	MC (%)	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^2 Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	EFCO2 (lb ton^{-1})	EFCO (lb ton^{-1})	EFCH$_4$ (lb ton^{-1})
						Solo					
2019120404	4	6	86.6	4.88	0.92	4.98	9.8	0.077	3174	311	1.4
2019120303	3	7	89.7	3.10	0.50	3.12	8.4	0.067	3284	240	1.8
2019120505	5	8	94.0	4.98	1.11	2.86	6.9	0.097	3440	140	2.4
2019120909	9	9	87.0	4.32	0.65	3.44	7.8	0.078	3180	304	3.3
2019050906	6	11	89.5	3.60	0.55	5.87	6.7	0.033	3258	244	5.6
2019050702	2	14	NA	NA	NA	NA	NA	NA	NA	NA	NA
2019051008	8	14	90.2	2.16	0.28	5.81	6.6	0.020	3280	226	9.8
2021061105	5	14	95.9	2.96	0.30	9.38	5.4	0.014	3502	96	2.5
2021060903	3	24	96.3	2.52	0.32	11.59	7.7	0.013	3518	86	2.6
2021061004	4	25	98.6	1.86	0.19	5.49	5.2	0.014	3608	32	1.2
2019050803	3	27	91.0	1.64	0.25	3.49	6.4	0.024	3324	208	4.0
2021061507	7	30	97.7	2.46	0.13	2.96	2.6	0.017	3576	54	NA
						Breeo					
2019120606	6	8	94.4	2.74	0.38	4.00	7.2	0.039	3454	130	3.4
2019121010	10	8	94.5	2.86	0.38	2.51	7.0	0.064	3456	127	3.8
2019120101	1	9	92.9	3.86	0.00	NA	7.2	NA	3396	166	3.6
2019120202	2	9	97.2	2.54	0.41	4.06	9.3	0.046	3558	66	1.7
2019051309	9	10	90.8	4.46	0.53	9.73	6.1	0.023	3304	212	6.2
2019051007	7	13	91.4	2.60	0.32	6.40	5.3	0.017	3322	200	8.8
2019050804	4	21	92.1	3.36	0.08	7.62	6.0	0.021	3352	182	7.2
2021061506	6	21	96.6	4.44	0.38	12.96	4.4	0.012	3514	78	7.0
2019050905	5	24	92.0	4.06	0.55	9.53	6.0	0.020	3348	186	6.0
2021061708	8	27	97.6	2.72	0.19	6.25	3.7	0.013	3572	56	2.9
2021060701	1	28	97.1	4.90	0.40	17.20	4.4	0.010	3542	66	3.0

Table A2 continued

Burn ID	Burn	MC (%)	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^{2} Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	EFCO2 (lb ton^{-1})	EFCO (lb ton^{-1})	$EFCH_4$ (lb ton^{-1})
2021060802	2	35	97.6	2.52	0.17	5.61	3.5	0.013	3562	56	3.6
						Pilot Rock					
2019120707	7	8	92.6	3.06	0.48	1.86	8.2	0.107	3386	172	4.0
2019120808	8	8	96.6	3.56	0.57	2.16	8.3	0.110	3532	80	3.2
2019051411	11	14	90.0	2.88	0.34	4.23	5.6	0.030	3266	230	11.2
2021062110	10	17	96.7	3.84	0.44	19.24	6.0	0.010	3536	78	5.1
2019051310	10	18	88.9	3.26	0.34	6.70	4.8	0.019	3224	256	11.0
2021062109	9	19	96.9	2.74	0.15	NA	2.7	NA	3548	72	3.8
2021062211	11	23	94.3	10.38	0.44	25.82	2.2	0.007	3434	132	9.1
2021062312	12	26	94.1	9.40	0.44	25.00	2.5	0.007	3428	136	9.5

Table A3. Burnup phase results all burns sorted by firepit and firewood moisture level. Modified combustion efficiency (MCE), PM, CO_2, CO, CH_4 emission factors (EF), PM emission rates (ER), PM emitted normalized to radiant heat flux (RF), fuel consumption (FC). FC is dry mass and MC percent of dry mass.

Burn ID	Burn	MC (%)	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^2 Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	EFCO2 (lb ton^{-1})	EFCO (lb ton^{-1})	$EFCH_4$ (lb ton^{-1})
						Solo					
2019120404	4	6	99.4	3.86	0.82	8.61	12.1	0.044	3642	14	0.4
2019120303	3	7	99.4	5.24	1.06	10.28	11.6	0.047	3642	14	0.4
2019120505	5	8	99.5	3.60	0.91	6.58	14.5	0.063	3648	11	0.3
2019120909	9	9	99.5	5.14	1.28	4.62	11.7	0.104	3648	12	0.4
2019050906	6	11	98.5	3.38	0.55	10.85	10.0	0.025	3600	34	1.2
2019050702	2	14	88.8	23.96	NA	NA	NA	0.005	3152	254	18.4
2019051008	8	14	99.1	3.72	1.04	7.65	17.0	0.066	3624	20	0.6
2021061105	5	14	97.8	8.56	0.66	67.63	4.0	0.004	3558	52	2.3
2021060903	3	24	96.6	14.98	0.87	110.89	3.0	0.003	3494	80	4.0
2021061004	4	25	96.6	16.38	0.74	112.21	2.4	0.003	3492	78	4.2
2019050803	3	27	97.6	7.46	0.85	34.58	6.0	0.010	3552	56	2.2
2021061507	7	30	95.8	18.16	0.91	122.15	2.6	0.003	3470	96	NA
						Breeo					
2019120606	6	8	98.7	3.50	0.77	8.17	10.4	0.036	3616	30	1.4
2019121010	10	8	98.9	3.32	0.72	5.62	10.1	0.048	3626	25	1.1
2019120101	1	9	99.0	3.84	NA	NA	8.1	NA	3626	24	1.0
2019120202	2	9	99.2	2.54	0.59	4.79	12.0	0.051	3634	20	0.9
2019051309	9	10	95.8	6.66	1.04	29.77	10.1	0.018	3476	98	6.4
2019051007	7	13	94.4	18.78	1.74	193.21	5.5	0.004	3392	128	7.4
2019050804	4	21	95.7	15.04	0.68	110.57	6.9	0.008	3456	100	4.6
2021061506	6	21	97.9	7.50	0.66	57.97	4.6	0.005	3564	50	2.0
2019050905	5	24	96.1	10.96	1.35	53.12	7.8	0.013	3482	90	4.8
2021061708	8	27	98.1	4.12	0.55	24.58	7.0	0.009	3588	44	2.4
2021060701	1	28	96.7	10.78	0.78	90.59	3.8	0.004	3510	76	3.8
2021060802	2	35	97.6	10.66	0.42	44.01	2.0	0.004	3548	56	2.4

Table A3 continued												
Burn ID	Burn	MC (%)	MCE (%)	EFPM (lb ton^{-1})	ER PM (oz hr^{-1})	NE PM (oz min in^2 Btu^{-1})	FC (lb)	RF (Btu min^{-1} in^{-2})	EFCO2 (lb ton^{-1})	EFCO (lb ton^{-1})	$EFCH_4$ (lb ton^{-1})
Pilot Rock											
2019120707	7	8	98.3	4.84	1.03	7.27	10.0	0.053	3598	40	1.8
2019120808	8	8	98.5	5.02	0.81	7.32	7.6	0.042	3608	35	1.6
2019051411	11	14	97.7	4.56	0.78	20.75	11.1	0.020	3560	54	3.0
2021062110	10	17	96.9	9.86	1.16	81.55	6.2	0.006	3532	70	3.9
2019051310	10	18	97.5	6.86	1.10	31.51	10.1	0.018	3546	58	3.2
2021062109	9	19	97.0	11.56	1.33	NA	6.0	NA	3528	70	3.7
2021062211	11	23	97.3	7.76	0.55	33.27	3.7	0.007	3548	64	3.6
2021062312	12	26	98.1	7.42	0.47	30.72	3.2	0.006	3578	46	2.1

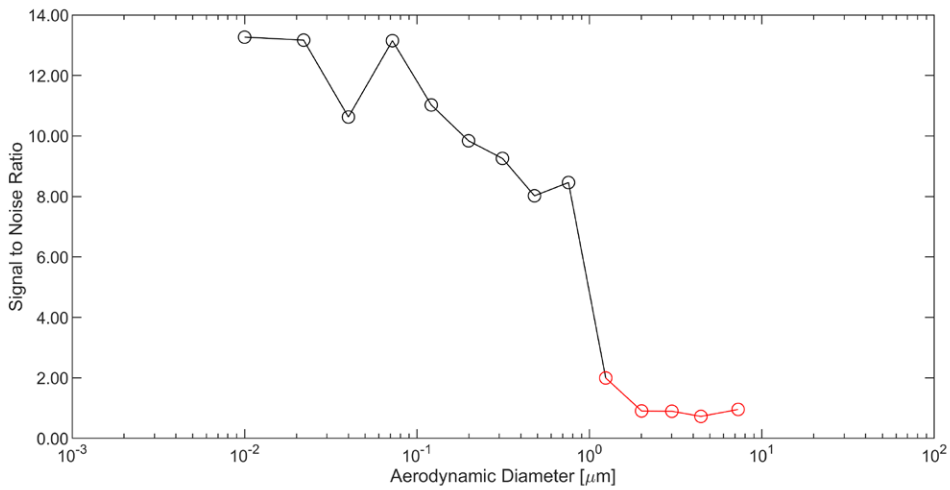

Figure A1. Signal-to-Noise ratio (SNR) for partcile number counts by partciel size bin from a representative firepit test during round 3. The particle count drops dramatically for sizes greater than 1 µm and SNR plummets. Measured taken using a Dekatu electrical low-pressure impactor. SNR for each size bin was specifically determined from a ratio of the mean and standard deviation of raw electrometer measurements for each impactor stage during a steady 100 second period of aerosol collection. The red bins were removed from the analysis and the black bins were kept.