New York State Energy Research and Development Authority

Elemental Analysis of Wood Fuels

Final Report

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NYSERDA Report 13-13

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Elemental Analysis of Wood Fuels

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, N.Y.

Sandra Meier, Ph.D.

Senior Project Manager

Prepared by:

Northeast States for Coordinated Air Use Management (NESCAUM)

Boston, Mass.

Lisa R. Rector, Project Manager, NESCAUM

George Allen, Co-investigator, NESCAUM

Prof. Philip K. Hopke, Co-investigator, Clarkson University

Sriraam R. Chandrasekaran, Co-investigator, Clarkson University

Lin Lin, Co-investigator, Clarkson University

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Abstract

The chemical composition of 23 wood chip samples and 132 wood pellet samples manufactured in the United States (U.S.) and Canada were analyzed for energy and chemical properties. The pellet samples came from locations across northern New York and New England and encompassed 100 different manufacturers, with some duplicate sampling. Basic characterization of calorific, moisture and ash content used American Society for Testing and Materials (ASTM) methods. Sulfate and chloride samples were prepared using ASTM methods and analyzed by ion chromatography. Elemental compositions of ashed wood samples were determined using inductively coupled plasma-mass spectrometry. Mercury was measured by direct analysis of wood samples. The major ash-forming elements were calcium, potassium, aluminum, magnesium, and iron. Some pellet samples had unusually high concentrations of several heavy metals, including arsenic, copper, and chromium. This may be due to extraneous materials in the pellets, such as preservative-treated and painted waste wood. Most of the wood pellets tested would meet U.S. voluntary standards but would likely not meet standards for residential use in European markets. Based on these test results, establishing enforceable U.S. standards for elemental compositions of commercial wood pellets and chips would help exclude inappropriate materials and promote cleaner combustion.

Keywords

Elemental analysis, wood chips, wood pellets, wood combustion, elemental analysis, metals, chromium, copper, arsenic, sulfate, mercury, lead, calcium, potassium, aluminum, magnesium, iron.

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Acronyms and Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
Al	aluminum
As	arsenic
ASTM	American Society for Testing and Materials
AFT	Ash fusion temperature
Btu/lb	British thermal unit per pound
Ca	calcium
CCA	Chromated Copper Arsenate
CCT	collision cell technology
Cd	cadmium
Cl^-	chloride ion
CO	carbon monoxide
Co	cobalt
Cr	chromium
Cu	copper
dw	dry weight
EPA	U. S. Environmental Protection Agency
EU	European Union
Fe	iron
FT	fluid temperature
g	grams
Hg	mercury
HT	hemispherical temperature
ICP-MS	inductively coupled plasma mass spectrometry
IT	initial temperature
K	potassium
kg	kilogram
LOD	limit of detection
MDL	minimum detectable level
mg	milligram
Mg	magnesium
MMBtu	million British thermal units

Mn	manganese
Na	sodium
NESCAUM	Northeast States for Coordinated Air Use Management
Ni	nickel
NO_x	nitrogen oxides
NYS	New York State
Pb	lead
PFI	Pellet Fuel Institute
PM	particulate matter
PM10	organic products of incomplete combustion equal or less than 10 micrometers in aerodynamic diameter
POM	Polycyclic organic matter
PPM	parts per million
SO_4^{2-}	sulfate ion
SO_x	sulfur oxides
ST	softening temperature
Ti	titanium
Tl	thallium
U.S.	United States
V	vanadium
VOCs	volatile organic compounds
Zn	zinc

Executive Summary

Wood now ranks as the third most common heating fuel, after gas and electricity, for primary and secondary heating fuel use nationally. According to the United States (U.S.) Census, the number of households using wood heat grew by 34 percent between 2000 and 2010, faster than any other fuel used for residential heating. The northeastern states have seen significantly higher growth in wood used for household heating than the nation at large. New York State (NYS) experienced an increase of 73 percent over the 2000 to 2010 period, but wood only accounts for 4 percent of the State's total heating fuel needs.[1]

With this increasing wood heat demand, wood pellet manufacturing is a growing market opportunity for the Northeast. In 2008, North American companies produced 1.8 million metric tons of wood pellets that largely supplied the domestic wood heating market. Export markets, however, are significant and have largely been untapped by U.S. manufacturers. Canadian firms, in contrast, produced about 1.4 million metric tons mostly for bulk shipment to European markets. Forecasts suggest that by 2015, Europe may annually import upward of 20 million metrics tons of pellets.

Recycled materials such as particle board, treated or painted wood, melamine resin-coated panels and the like are considered particularly unsuitable for use in pellets because of ash-contamination and combustion-related air pollutant emissions. U.S. companies exporting to Europe are precluded from using any of the materials listed because they must meet the European Union (EU) pellet standard (EN 14961-2) that is more stringent than the U.S. pellet standard. The wood pellet standard in Europe is classified into three quality categories: A1, A2 and B. All categories prohibit pellets containing any recycled or adulterated wood. The highest grade of pellet has prohibitions on the use of bark and types of harvesting practices that can be employed to manufacture pellets. It should be noted that pellets imported into Europe from the U.S. are being used in industrial rather than residential applications. Residential applications require the use of A1 pellets, the highest grade of pellets, which are produced within Europe.[2]

The combustion and pyrolysis of wood pellets produce atmospheric emissions of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), mineral residues, and to a lesser extent sulfur oxides (SO_x). In the U.S., air emissions from automatically fed, pellet-fired devices are thought to be cleaner than automatically fed systems using wood chips due in large part to the homogeneity and lower moisture content of the fuel. This thinking is based on the assumption that clean wood is being used to manufacture the pellets. There is limited data for units tested in the U.S., and the data

[1] U.S. Energy Information, "*State Profile and Energy Estimates.*" Accessed at http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/eu/use_eu_NY.html&sid=NY.

[2] Aguilar, F., C. Gaston, R. Hartkamp, W. Mabee, and K. Skog. 2011. "Wood Energy Markets, 2010-2011." In *UNECE/FAO Forest Products Annual Market Review 2010-2011*, Geneva: United Nations, 85-97.

that are available do not provide information on elemental make up of the pellet fuel. In addition, little is known about the relationship between pellets with elevated metals content, such as chromium, arsenic and mercury, and their impact on ambient air emissions and ash. Significant questions remain as to whether or not the metals remain in the bottom ash or are emitted from the stack.

As new biomass fuels are introduced to meet rising demand, the chemical and physical composition of these commercial products has implications for public health and combustion efficiency. The wood pellet and wood chip analysis undertaken in this study is a first step to gain insights into the variability of the physical quality among wood fuel products and to identify chemical elements of concern from a public health perspective.

In this study, the chemical composition of 23 wood chip samples and 132 wood pellet samples manufactured in the U.S. and Canada and currently available in commercial markets were analyzed for energy and chemical properties. The pellet samples came from retail outlets across northern NYS and New England and encompassed 100 different manufacturers, with some duplicate sampling. Additionally, two NYS manufacturers provided pellet samples for this effort. This study covered five analysis categories:

1. Basic characterization of wood fuel calorific value, moisture content, and ash content.
2. Analysis for sulfate and chloride ions.
3. Elemental analysis of trace metals in ash, including vanadium, chromium, manganese, iron, nickel, copper, zinc, arsenic, cadmium, and lead.
4. Separate analysis for mercury content.
5. Measurement of the fuel’s ash fusion temperature as an indicator of potential slag formation in a combustion device.

Most of the wood pellets tested met U.S. voluntary standards but would likely not meet standards for residential use in European markets. Some pellet samples had unusually high concentrations of several heavy metals, including arsenic, copper and chromium. This content may be due to extraneous materials in the pellets, such as preservative-treated and painted waste wood.

The results of this study support the contention that fuel analysis alone cannot sufficiently inform emissions chemistry. To gauge the impacts of fuel variability and elevated element concentrations, stack testing should be conducted to determine the amount and composition of emissions from wood fuels. Establishing enforceable U.S. standards for elemental compositions of commercial wood pellets and chips would also help exclude inappropriate materials and promote cleaner combustion.

With the rapid growth of the wood pellet industry, NYS and other northeast states have an opportunity to establish and expand a wood fuel industry that takes advantage of local wood resources. In pursuing this opportunity, protecting public health and exploiting expanding wood fuel markets have mutually reinforcing needs. Adequate safeguards are needed to exclude inappropriate materials from the wood fuels to ensure public health protection. To satisfy a large and important export market in Europe, mandatory European fuel quality standards must be met. How successfully these needs are addressed will play a large role in determining the sustainability and future scale of the domestic wood fuel industry.

1 Introduction

Wood now ranks as the third most common heating fuel, after gas and electricity, for primary and secondary heating fuel use in the U.S. According to the U.S. Census, the number of households using wood heat grew by 34 percent between 2000 and 2010, faster than any other fuel used for residential heating. In 2010, 2.1 percent of American homes, or about 2.40 million households, used wood as a primary heat source, up from 1.6 percent in 2000. Among the households using wood as their primary heating fuel, 57 percent are in rural areas, 40 percent are in suburban areas, and 3 percent are in urban areas. When also including wood as a secondary heating fuel, approximately 10 to 12 percent of American households now use wood.[3]

The northeastern states have seen significantly higher growth in wood used for household heating than the nation at large. NYS experienced an increase of 73 percent during the 2000 to 2010 period, with some neighboring states seeing even larger increases. For example, households in Connecticut using wood for heating more than doubled. Wood use in Massachusetts and New Hampshire increased by 99 percent, and Maine and Rhode Island grew by 96 percent. New Jersey and Vermont increased by 70 and 71 percent, respectively.[4]

In 2008, U.S. companies produced 1.8 million metric tons of wood pellets, and shipped most of this production in 40-pound bags to serve the domestic home heating market. In contrast, Canadian companies produced about 1.4 million metric tons that were largely exported in bulk to European markets.[5] Exports of wood pellets from North America to Europe reached 2 million tons in 2011 and 3.2 million tons in 2012, a 60 percent increase in one year.[6] Canada has long been the main exporter of pellets to Europe but in the second half of 2011, the U.S. exported an equal volume. Based on the pellet capacity listing in Appendix A, North American capacity increased to almost 5 million tons from 141 wood pellet plants. An additional 24 pellet plants are proposed or under construction. Detailed information on wood pellet production and appliance types is found in Appendix B. Growth in this market is expected to continue over the coming years as fossil fuel prices continue to climb and efforts to incentivize biomass heating take hold. The

[3] Alliance for Green Heat. 2011. "2010 Census Shows Wood is Fastest Growing Heating Fuel." *Biomass Magazine*, October 10. Accessed January 6, 2013.

[4] U.S. Census Bureau. "American FactFinder." US Census Bureau. Accessed January 6, 2013. http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml

2010 data from American Community Survey 1-Year Estimates, House Heating Fuel, ID B25040; 2000 data from Census 2000 Summary File 3 (SF 3), House Heating Fuel, ID H040.

[5] Spelter, H., and D. Toth. "North America's Wood Pellet Sector." Forest Products Laboratory - USDA Forest Service. Last modified 2009. Accessed January 6, 2013. http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp656.pdf.

[6] JOC Staff, "North American Wood Experts on the Rise" Journal of Commerce, April 24, 2013. Accessed May 8, 2013, http://www.joc.com/economy-watch/world-economy-news/report-north-american-wood-exports-europe-rise_20130424.html

Energy Information Administration report[7] estimated the number of households nationwide in winter 2012/2013 that heat with wood at more than 2.6 million. This number represents a 3 percent increase from 2011. The highest growth in use is in the Midwestern U.S., followed by the Northeast region.

Notwithstanding the growing U.S. market, the largest market for wood pellets continues to come from Europe. From 2008 to 2010, total U.S. wood pellet exports to Europe grew from 85,000 tons per year to more than 600,000 tons per year. The expectation is that the European pellet market will continue to grow. Forecasts suggest that by 2020, Europe will need to increase their pellet supply by 45-400 million tons with much of this additional supply coming from imports.[8]

Wood pellet production is estimated to significantly grow in the northeastern U.S. over the next few years, as more wood pellet manufacturing plants come into operation. Every state but Connecticut and Massachusetts has at least one pellet manufacturer (Table 1). The wood pellet industry is poised to continue growing in the Northeast where there is a local woody biomass supply and an existing need for affordable heating due to the region's heavy reliance on home heating oil.

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[7] U.S. Energy Information Administration. 2012. "*Short-Term Energy and Winter Fuels Outlook.*" http://www.eia.gov/forecasts/steo/special/winter/2012_winter_fuels.pdf

[8] Sikemma, R., and Juninger, M., Hiegl, W., Hansen, M., Faaij, A. 2011."The European Wood Pellet Market: Current Status and Prospects for 2020", BioFPR, Society of Chemical Industry and John Wiley & Sons Ltd.

Table 1 Wood Pellet Manufacturing Capacity in the Northeast.

Plant	State	Feedstock	Capacity in tons per year
Northeast Pellets, LLC	Maine	Hardwood and Softwood	40,000
Maine Woods Pellet Co.	Maine	Hardwood and Softwood	10,000
Geneva Wood Fuels	Maine	Hardwood	90,000
Corinth Wood Pellets, LLC	Maine	Hardwood and Softwood	75,000
New England Wood Pellets	New Hampshire	Hardwood and Softwood	84,000
New England Wood Pellets/ Schuyler	New York	Hardwood and Softwood	84,000
New England Wood Pellets /Deposit	New York	Hardwood and Softwood	84,000
Instant Heat Wood Pellets, Inc.	New York	Hardwood	50,000
Hearthside Wood Pellets	New York	Hardwood	600
Essex Pallet & Pellet	New York	Hardwood and Softwood	36,000
Enviro Energy	New York	Grass	1,800
Curran Renewable Energy	New York	Hardwood and Softwood	100,000
Dry Creek Products	New York	Hardwood	100,000
Associated Harvest, Inc.	New York	Hardwood	8,000
American Wood Fibers - Circleville	Ohio	Hardwood and Softwood	50,000
Wood Pellets C&C Smith Lumber	Pennsylvania	Hardwood	30,000
Tri State Biofuels	Pennsylvania	Softwood	50,000
Penn Wood Products, Inc.	Pennsylvania	Hardwood	5,000
Pellheat, Inc.	Pennsylvania	Hardwood	5,000
Log Hard Premium Pellets, Inc.	Pennsylvania	Hardwood	25,000
Greene Team Pellet Fuel Co.	Pennsylvania	Hardwood	50,000
Great American Pellets	Pennsylvania	Hardwood	30,000
Energex Pellet Fuel, Inc.	Pennsylvania	Hardwood	60,000
PA Pellets	Pennsylvania	Softwood	50,000
Nazareth Pellets	Pennsylvania	Softwood	50,000
Barefoot Pellet Co.	Pennsylvania	Hardwood	45,000
Allegheny Pellet Corp.	Pennsylvania	Hardwood	Undisclosed
Alexander Energy, Inc.	Pennsylvania	Hardwood	8,500
Inferno Wood Pellet Co.	Rhode Island	Hardwood and Softwood	14,000
Vermont Wood Pellet Co.	Vermont	Softwood	14,000

The increasing use of wood fuel and specifically wood pellets has raised concerns about potential environmental and public health impacts because little is known about the constituents in these fuels. Unlike other parts of the world, the U.S. has not adopted standards governing wood pellet processing and materials components such as those employed in Europe (detailed information on pellet standards is in Appendix C), leaving the U.S. market unregulated with no enforceable fuel specification requirements.

Biomass combustion has variable emissions, depending on the types and quality of fuel used, combustion technologies and operating conditions.[9] The quality of the fuel depends mainly on its chemical composition, including water and ash contents, plant species, where it grows (origin), fertilizers and pesticides used, harvesting practices, transport, handling and processing, and blending of plant species type.

The largest constituent in wood is carbon, which comprises 45 to 50 percent of its mass, followed by hydrogen, at roughly 6 percent. Other major elements in order of decreasing amount are: nitrogen (N), calcium (Ca), potassium (K), sodium (Na), magnesium (Mg), manganese (Mn), iron (Fe) and aluminum (Al). Minor elements include: cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), arsenic (As), mercury (Hg) and lead (Pb).[10]

The ash content of wood reflects its inorganic content and is highest in the parts of trees where growth occurs (e.g., stem bark and branches). Generally, the ash content of wood or woody biomass ranges from 0.5 to 3 percent dry weight (dw). A few studies have also found ash levels as high as 10 percent dw.[11]

Plants uptake inorganics, such as heavy metals, from soils.[12] Lead, for example, is taken up by the plant root hairs and stored as lead pyrophosphate in the cell wall. The degree of uptake varies with the plant species.[13,14]

Apart from natural uptake, the presence of metals in wood chips and pellets can be the result of contamination during the manufacturing process by including waste wood materials that have been painted

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[9] Luque, R., L. Herrero-Davila, J. M. Campelo, J. H. Clark, J. M. Hidalgo, D. Luna, J. M. Marinas, and A. A. Romero. 2008. "Biofuels: a technological perspective." *Energy Environ. Sci* 1(5): 542-64. doi:10.1039/B807094F.

[10] Telmo, C., J. Lousada, and N. Moriera. 2010. "Proximate analysis, backwards stepwise regression between gross calorific value, ultimate and chemical analysis of wood." *Bioresour. Technol* 101(11): 3808-3815. doi:10.1016/j.biortech.2010.01.021.

[11] Reimann, C., R. T. Ottesen, M. Andersson, A. Arnoldussen, F. Koller, and P. Englmaier. 2008. "Element levels in birch and spruce wood ashes; green energy?" *Sci. Total. Environ* 393(2-3): 191-97. doi:10.1016/j.scitotenv.2008.01.015.

[12] Dunn, C. E. 2007. *Handbook of Exploration and Environmental Geochemistry: Biogeochemistry in Mineral Exploration*, 480. Amsterdam: Elsevier.

13 *Ibid*

[14] Obernberger, I., and F. Biedermann, W. Widmann, R. Riedl. 1997. "Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions." *Biomass Bioenerg* 12(3): 211-24. doi:10.1016/S0961-9534(96)00051-7.

or pressure treated. Contamination may also occur with materials such as soils entrained during harvesting and processing. Combustion of contaminated wood poses environmental and public health problems related to emissions and ash disposal. The emissions mainly depend on the combustion appliance and conditions. Wood ash disposed of as a solid waste or used for soil enrichment can be enriched in metals. This raises concerns about metal content, as there are limits to the concentrations for many metals in fertilizers used on agriculture soils.[15]

The combustion and pyrolysis of wood pellets in stoves produce atmospheric emissions of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds, (VOCs), mineral residues, and to a lesser extent sulfur oxides (SO_x). The quantities and type of emissions are highly variable, depending on a number of factors, including the stage of the combustion cycle. During the initial burning stage, emissions (primarily VOCs) increase dramatically. After the initial period of high burn rate, there is a charcoal stage of the burn cycle characterized by a slower burn rate and decreased emissions. Emission rates during this stage are cyclical, characterized by relatively long periods of low emissions and shorter episodes of emission spikes.

The major concern arising from the combustion of wood pellets as a heating source results from PM. The vast majority of PM emissions are condensed organic products of incomplete combustion equal or less than 10 micrometers in aerodynamic diameter (PM_{10}). SO_x are formed by oxidation of sulfur in the wood. NO_x can be formed by oxidation of nitrogen in the wood or nitrogen air during combustion. Mineral constituents, such as potassium and sodium compounds, are released from the wood matrix during combustion. The high levels of organic compounds and CO emissions result from incomplete combustion of wood pellets. Organic constituents of wood smoke vary considerably in both type and volatility. These constituents include simple hydrocarbons of carbon numbers 1 through 7 (which exist as gases or which volatize at ambient conditions) and complex low-volatility substances that condense at ambient conditions. Polycyclic organic matter (POM) is an ambient component of the condensable fraction of wood smoke. POM contains a wide range of compounds, including organic compounds formed through incomplete combustion by the combination of free radical species in the flame zone. These compounds are classified as hazardous air pollutants (HAPs) by the U. S. Environmental Protection Agency (EPA).[16]

It is generally believed that air emissions from pellet-fired devices are cleaner than those using wood chips or cordwood due in large part to the homogeneity and lower moisture content of the fuel.[17] This is based on

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[15] Washington State Department of Ecology. "Standards for Maximum Allowable Levels of Metals in Fertilizer." Washington State Department of Ecology | Home Page | ECY WA DOE. Accessed January 6, 2013. http://www.ecy.wa.gov/programs/hwtr/dangermat/fert_standards.html

[16] US EPA. "Residential Wood Stoves." Accessed January 6, 2013. http://www.epa.gov/ttnchie1/ap42/ch01/final/c01s10.pdf.

[17] US Department of Energy. "Wood and Pellet Heating | Department of Energy." Last modified June 24, 2012. Accessed January 6, 2013. http://energy.gov/energysaver/articles/wood-and-pellet-heating.

the assumption that clean wood is used to manufacture the pellet. Little data are available to evaluate emissions from pellet units. There is limited PM emissions data on residential pellet stoves and small commercial installations but none of these analyses included elemental analysis of the test fuel. Therefore, little is known about the relationship between pellets with elevated metals content and their impact on air emissions. Significant questions remain as to whether or not the metals remain in the bottom ash or are emitted from the stack.

As new biomass fuels are introduced to meet rising demand, the chemical and physical composition of these commercial products has implications for public health and combustion efficiency. This study is a first step to gain insights into the variability of the physical quality among wood fuel products and to identify chemical elements of concern from a public health perspective. While there have been a few small-scale studies on woody biofuels composition, there has not been a large-scale study of wood chips and pellets using the same analytical methods. In this study, we analyze a relatively large set of wood pellet and wood chip samples to begin gathering better information on their chemical and physical properties. This work begins to lay the foundation for ensuring the quality and safety of wood fuels used for thermal heating in NYS, the Northeast, and the rest of the country as the market for wood use continues to rapidly expand.

2 Fuel Analysis

This section describes the fuel analysis conducted under this project for two types of wood fuels: pellets and chips.

2.1 Pellet Sample Collection

During the 2010-2011 heating season, 40 pound bags of wood pellets were purchased at various retail outlets in five northeastern states: NYS, Connecticut, Vermont, New Hampshire and Massachusetts. A total of 132 bags were obtained, representing approximately 100 different brands or sub-brands (names). The remaining samples were duplicate products purchased independently at different times and places. Additionally, two pellet manufacturers also provided samples from their manufacturing facilities at regularly scheduled intervals. Ten pounds of pellets were taken from each bag, stored in plastic freezer bags, and shipped to Clarkson University for analysis.

2.2 Wood Chip Sample Collection

During the 2010-2011 heating season, three facilities located in NYS that heated with wood chips provided samples for this study. These three facilities each used a different fuel supplier and represented different fuel chip types. One facility received wood chips without bark. A second facility received bole chips, which are wood chips that have not had the bark removed. The third facility received fuels supplies several times a week from a variety of suppliers. Each facility sent a two-gallon sample stored in plastic freezer bags to Clarkson University for analysis. There is no information on duration or storage conditions between chipping and analysis; this time could influence the moisture content of the chip samples.

2.3 Sample Analysis

For most chemical analytes of interest, analysis of wood or other biomass composition can be done on the wood itself or on the wood ash after combustion. For this work, it was determined that the most appropriate method to determine the concentrations of elements in the wood samples was to ash the wood, acid digest the ash, and analyze the elements in the filtered digestion solution. This decision was made because the complete decomposition of cellulose is difficult without using materials such as concentrated zinc chloride. This material would not provide a suitable matrix for inductively coupled plasma-mass spectrometry (ICP-MS) analysis of the resulting solution. Dry ashing is a commonly employed sample preparation technology that has been widely used in elemental analysis.[18,19] Concentrations of non-volatile metals are enhanced by

[18] Hoenig, M. "Chapter 7: Dry Ashing." 2003. In *Wilson & Wilson's Comprehensive Analytical Chemistry. Vol.41, Sample Preparation for Trace Element Analysis*, edited by Z. Mester and R. Sturgeon, 235-55. Amsterdam: London.

100-200 times in ash, making analysis easier and less expensive. Correction back to wood concentration can be made using the percent dry ash value. Most analytes of interest analyzed under this effort were not volatile.

The methods used in this study may have resulted in a potential underestimation of other volatile elements such as As, selenium (Se) and antimony (Sb). The relatively low temperature ashing at 580 ºC, however, should not result in significant losses of other elements. Analysis of whole wood would have captured the volatile elements but is a more complex and uncertain analysis. Thus, the disadvantages of analysis of wood may be larger than the benefits relative to analysis of ashed wood.

Exceptions to these analytical methods were made for sulfate, chloride, and mercury; these volatile analytes were analyzed using techniques to capture the volatile component. Analysis of mercury used a different process because of the potential volatility losses; separate direct analyses were made for mercury in the ground wood samples using a Milestone Model DMA-80 Direct Mercury Analyzer. Project partners at Clarkson University have found that mixing the ground wood with a small amount of potassium hydroxide (KOH) reduces smoking of the wood and provides good precision in the analyses. The results of the chemical analysis reported here are from ash except mercury (total), chloride, and sulfate (SO_4^{2-}).

2.4 Analysis Methods

Five categories of analysis were used:

1. Basic characterization (American Society for Testing and Materials [ASTM] “proximate analysis”) for calorific value, moisture content, ash content
2. Ions: sulfate and chloride by ion chromatography
3. Trace metals by ICP-MS on ash
4. Mercury: gold trap followed by cold vapor atomic absorption (CVAA) analysis
5. Ash fusion temperature per ASTM D1857-04

The following subsections provide detailed information on analysis methods.

2.4.1 Sample Preparation

All samples were stored at 4 °C. The ground samples were also stored in a refrigerator until the analyses were performed. One extra gallon of pellets for each sample was stored in the cold room for follow-up analysis. The samples were ground with a SPEX 6770 Freezer/Mill Model using liquid nitrogen. Each grinding run lasted 15 minutes with a total of 3 runs for each sample with 2 minutes of cooling time

[19] Obernberger, I., F. Biedermann, W. Widmann, and R. Riedl. 1997. "Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions." *Biomass Bioenerg* 12(3): 211-24. doi:10.1016/S0961-9534(96)00051-7.

between each run. Subsamples were obtained in different ways depending on the nature of the original shipment of materials. If a 40-pound bag was provided, three subsamples were placed into separate 1 gallon bags that were obtained from the bottom, top, and the middle of each bag. If the original sample was shipped in a 3-gallon bag, the entire sample was mixed and the subsample obtained for grinding.

Two different sample grinding processes were used depending on the endpoint analyses. One process was for ash content and ICP-MS analysis and the other for ash fusion temperature measurements. For ash content and ICP-MS analysis, 200-250 grams (g) were ground to provide a good representative sample. For the ash fusion temperature analysis, much larger samples were ground. Given the amount of sample needed for ash fusion temperature analysis and the size of the freezer mill, the grinding was done for about 3 to 4 days. These samples were not weighed after grinding. However, the amount of ash was weighed to ensure there was 15 to 20 g of ash. About 10 to 15 g (depending upon density) was required to do the ash fusion temperature analyses for both oxidizing and reducing environments. More material had to be ground than originally expected to provide sufficiently large samples for determining ash fusion temperatures. Thus, only 26 samples were prepared and analyzed.

2.4.2 Calorific, Ash and Moisture Content

The fuel wood analysis procedure is described in ASTM E870-82. The calorific content of the wood pellets was determined using ASTM E711-87. The other methods were ASTM D 1102–84, Standard Test Method for Ash in Wood and ASTM E871-82, Standard Test Method for Moisture Analysis of Particulate Wood Fuels. The wood samples were ground using a SPEX c 6770 Freezer/Mill® to produce a fine powder. The ground material was then pelletized for analysis in a Parr 1341 Plain Jacket Bomb Calorimeter as per the ASTM method.

2.4.3 Sulfur and Chloride Content

The sulfur content was determined by a modified version of the bomb-washing method in ASTM E775–87. Instead of the determination of resulting sulfate by barium sulfate precipitation, sulfate was measured using ion chromatography. Chloride was measured using a modified version of ASTM D4208–02 in which ion chromatography was used in place of the ion selective electrode approach in the ASTM method.

2.4.4 Trace Metals by ICP-MS

The trace metal content of the wood samples was determined using larger samples of ash that are prepared using the modified ASTM procedure. A muffle furnace was used to ash samples in a process identical to the D1102 method. The ICP-MS analysis procedure and protocol follows EPA Method 200.8 as modified for Clarkson University’s specific equipment. The ash samples were then acid digested in concentrated nitric acid using a CEM MARS 5 Microwave Accelerated Reaction System. The resulting solution was filtered using a polytetrafluoroethylene (PTFE) filter and analyzed using a Thermo Scientific X-Series ICP-MS with collision cell technology (CCT) capability. Calibration curves were developed using the instrument software. There were two types of check standards: National Institute of Standards and Technology Standard Reference Materials 1640 and a commercial check standard solution.

2.4.5 Mercury: Gold Trap Followed by Cold Vapor Atomic Absorption (CVAA) Analysis

The wood samples were ground and mixed with a small amount of potassium hydroxide (100 µL of 0.1 percent KOH) to minimize smoke formation. Solid samples were weighed and introduced into the sample boat. The sample was initially dried and then thermally decomposed in a continuous flow of oxygen. Combustion products were carried off and further decomposed in a hot catalyst bed. Mercury vapors were trapped on a gold amalgamator and subsequently desorbed for quantization. Mercury content was determined using atomic absorption spectrophotometry at 254 nanometers with a Milestone DMA80 Direct Mercury Analyzer.

2.4.6 Ash Fusion Temperature

Ash fusion temperature measurements were made according to ASTM D1857–04. The ash was prepared as described in this standard.

2.4.7 Duplicate Sampling

Because there are no accepted standards for analysis of wood or wood ash, and no SRM or similar reference material for wood/ash analysis, existing ASTM methods were modified to meet the needs of the metals analysis. These modifications are described in the following section. Duplicate sampling (a second sample from the same bag) was completed on 15 samples. Although limited, these data can be used to estimate the method reproducibility. Table 2 is a summary of duplicate samples, where the percent difference between duplicates is reported. Replicate sampling (which characterizes the instrumental analysis limit of detection (LOD) or minimum detectable level (MDL) and is much more stable than duplicate data) but data are not included in this report.

Table 2: Summary of ICP-MS Metals Duplicate Analysis (% Difference).

Sample ID Number	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb
45	35	11	3	3	1	10	5	1	2	29	11
59	72	12	15	6	8	3	9	23	48	23	30
3	7	8	14	10	4	9	9	6	12	50	10
6	4	7	2	1	13	3	3	5	31	10	34
24	5	16	4	14	40	3	20	19	39	145	39
123	4	4	3	5	4	4	4	3	6	12	6
73	19	2	21	2	5	20	2	2	0	20	1
96	15	8	34	10	14	10	57	9	4	63	9
74	2	3	8	7	6	8	8	5	30	8	1
92	1	2	3	4	0	1	10	7	6	19	3
82	16	11	7	7	12	11	2	6	24	23	5
69	29	10	8	6	7	3	2	4	32	37	7
77	14	10	5	8	10	10	3	8	45	30	2
131	15	7	5	7	1	2	13	11	16	10	0
132	5	7	6	1	6	5	8	10	11	19	2
Standard deviation	18.4	3.9	8.7	3.5	9.7	4.9	13.9	6.1	16.3	34.6	12.8
Maximum	72.1	15.7	33.9	13.6	40.3	19.7	57.2	23.4	48.2	145.4	39.1
Average	16.2	7.9	9.1	5.9	8.8	6.9	10.2	8.1	20.4	33.1	10.7
90th percentile	32.6	11.5	18.6	9.5	13.3	10.7	16.8	15.7	42.9	57.6	32.2
Confidence Level	**Low**	**High**	**Medium**	**High**	**Low**	**Medium**	Low	**Medium**	**Low**	**Low**	**Low**

3 Results

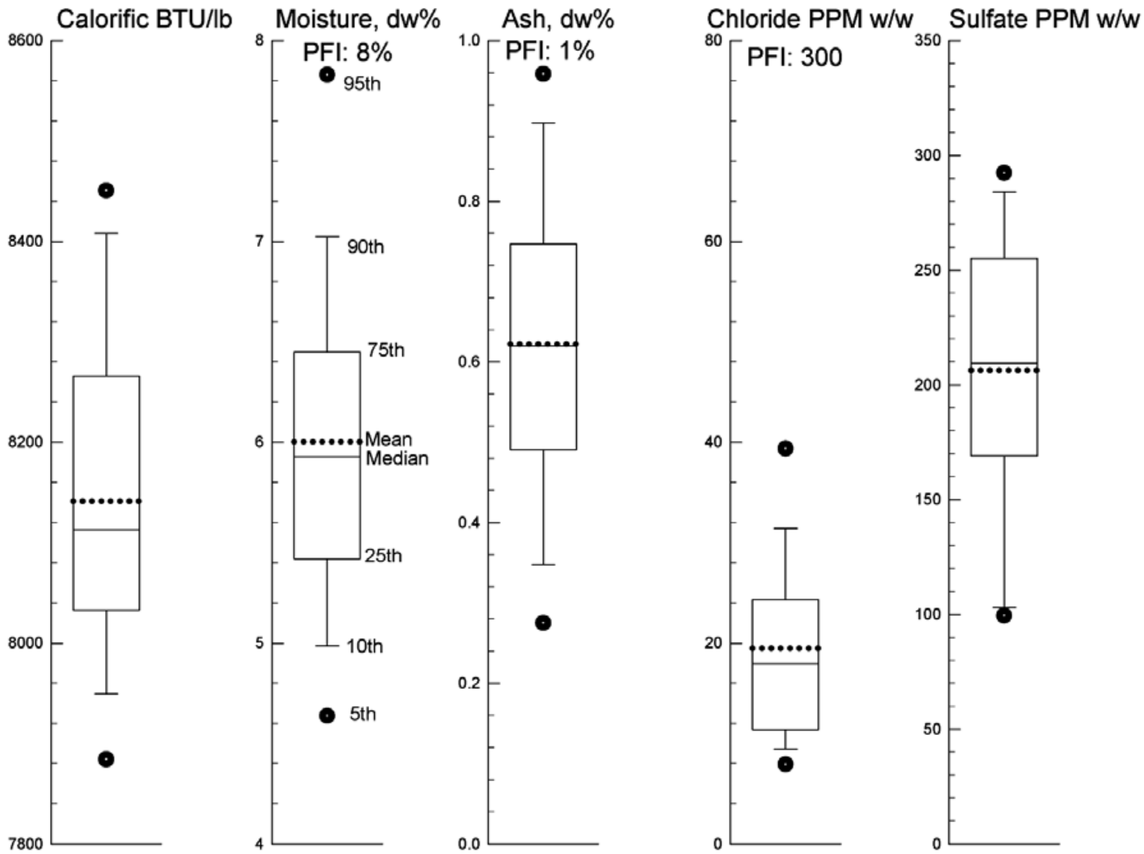
3.1 Pellets

One objective of this work was to determine a range of values for metals and ions that represents uncontaminated wood pellets using the data from the 132 samples analyzed. Sample screening was completed for V, Cr, Ni, Cu, Zn, As, Cd, Pb, Hg, Cl, and SO_4^{2-}. Initial screening of the data for key parameters of interest was done using box plots (Figures 1 through 6) to assess the nature and range of the data across all the samples. Most of the metals and chloride ion had highly skewed distributions. Additional screening was done to assess the characteristics of unusual samples by plotting elements by sample number for all samples. These plots are found in Appendix E. Outlier screening was performed on log-transformed data for all metals and chloride ion. For other parameters, the data were not transformed. The 95th percentile of the data was used as a screening threshold; samples above that value were considered contaminated and removed from the “uncontaminated” subset of samples. No screening was done on Btu. For ash, a single outlier of 7.8 percent was removed. Forty-nine of the 132 samples (37 percent) were removed by this process.

The next step in the data analysis was to estimate working “benchmark” concentrations of uncontaminated pellets by excluding all pellet samples that exceeded the screening threshold for one or more parameters. We considered 83 out of 132 samples as “uncontaminated” (63 percent) based on screening of all analytes; the 95th percentile of this sample subset was used as the benchmark value for uncontaminated pellets. All but ash and calorific value of the resulting distributions failed the Shapiro-Wilk test for normality at $p<.05$. One potential source of a skewed distribution in uncontaminated samples would be pellets with and without bark. The potential for bark in samples was assessed by the color of the pellet, on a scale from 1 to 4 (light to dark, respectively). Eighty-six of the 132 samples had this information; 14 were rated dark (4) and 10 were rated light (1).

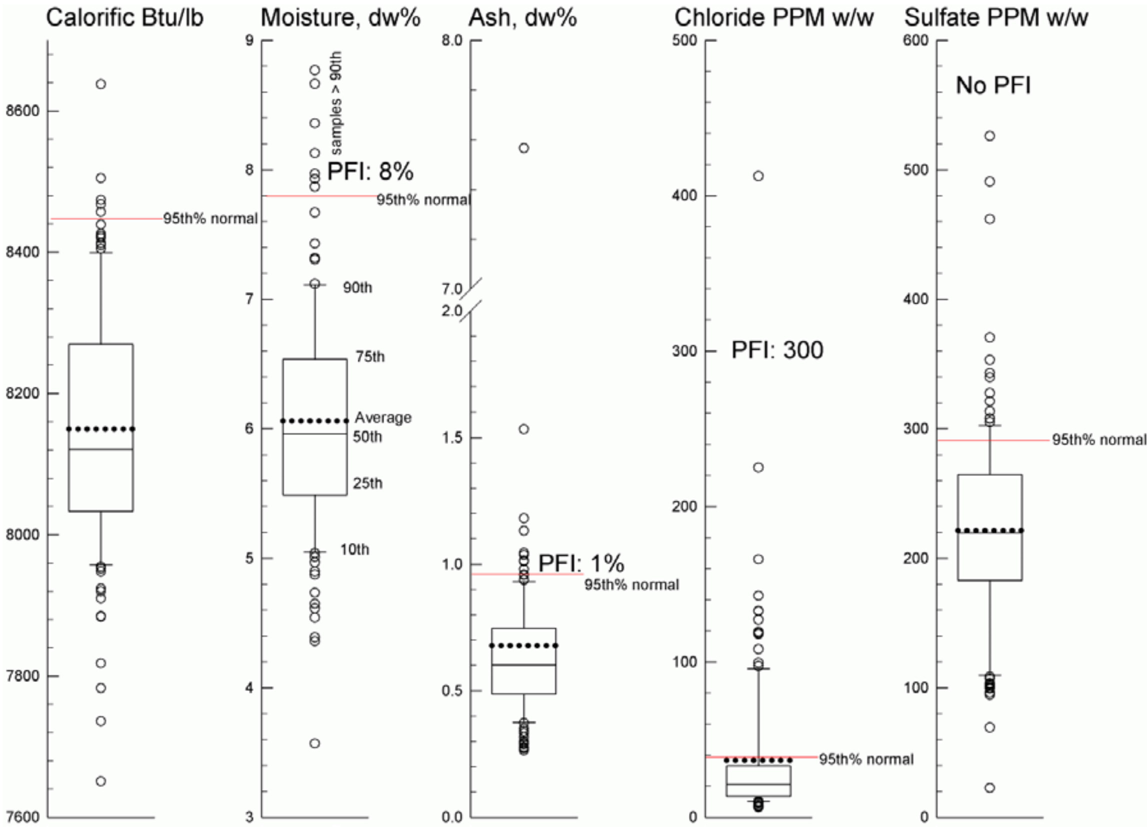
A list of sample ID numbers that were removed is in Appendix E. The 95th percentile of these uncontaminated samples was used as a reasonably conservative “working benchmark” limit; data above this threshold were considered “elevated.” Figures 1 through 6 show box plots of the data distribution for key analytes without the samples that were removed by screening (“uncontaminated” pellets) and then all samples. The latter plots have a line marking the 95th percentile of the “uncontaminated” sample distributions for comparison.

Figure 1: Proximate Analysis Box Plot, Normal Wood Pellet Samples.



Notes: PFI is the Pellet Fuels Institute standard limit. "Normal" excludes samples considered to be contaminated with one or more of the measured parameters as described in Section 3.1. Moisture and ash are reported as percent dry weight throughout this report. Btu/lb is per pound of material as it was processed at a lower heating value.

Figure 2. Proximate Analysis, All Wood Pellet Samples.



Notes: PFI is the Pellet Fuels Institute standard limit. “Normal” excludes samples considered to be contaminated with one or more of the measured parameters as described in Section 3.1. Moisture and ash are reported as percent dry weight throughout this report. Btu/lb is per pound of material as it was processed at a lower heating value.

Figure 3. Cr, Ni, Cu, Zn, Normal Wood Pellet Samples, ash concentrations (mg/kg).

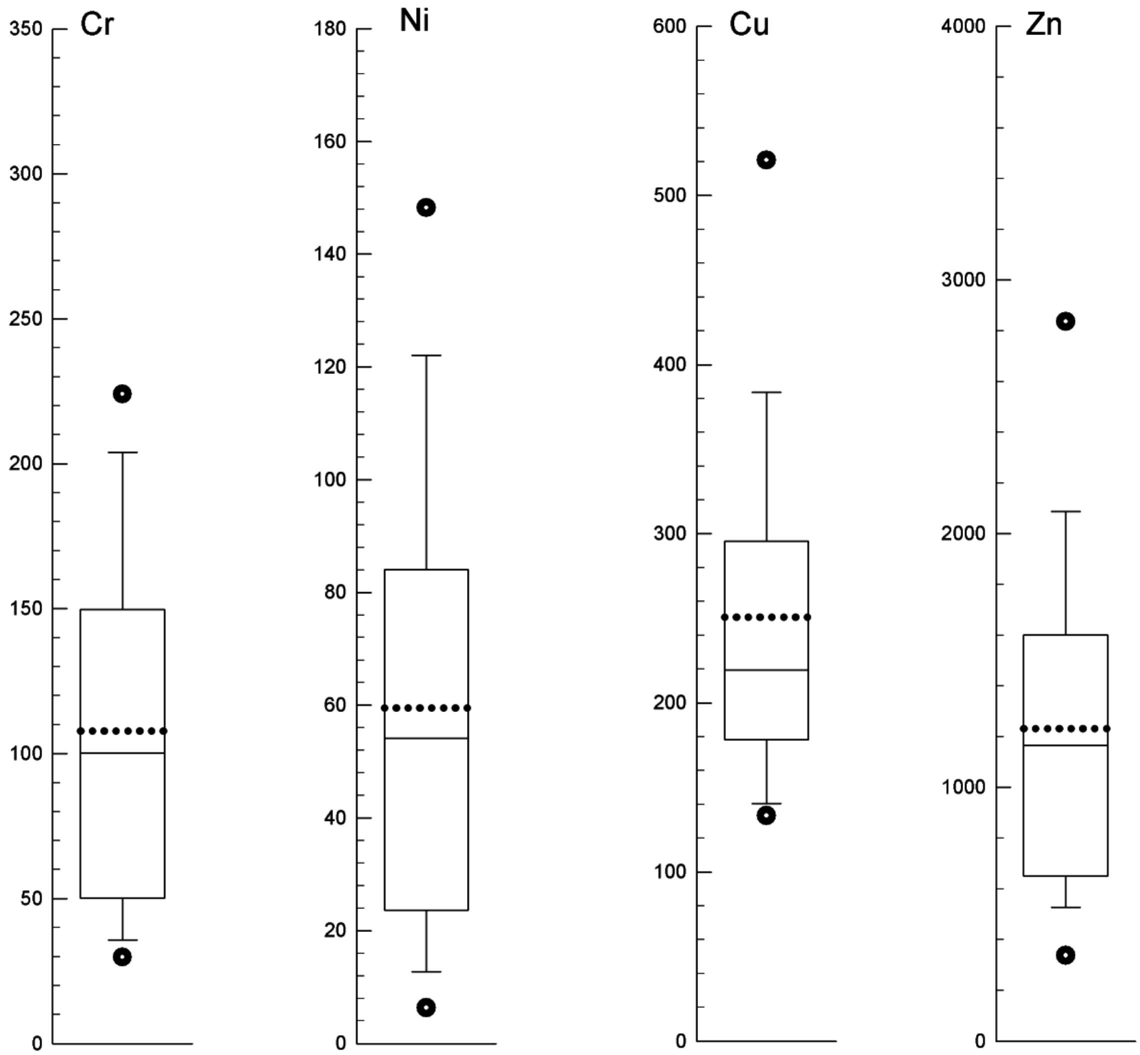


Figure 4: Cr, Ni, Cu, Zn, All Wood Pellet Samples, ash concentrations (mg/kg).

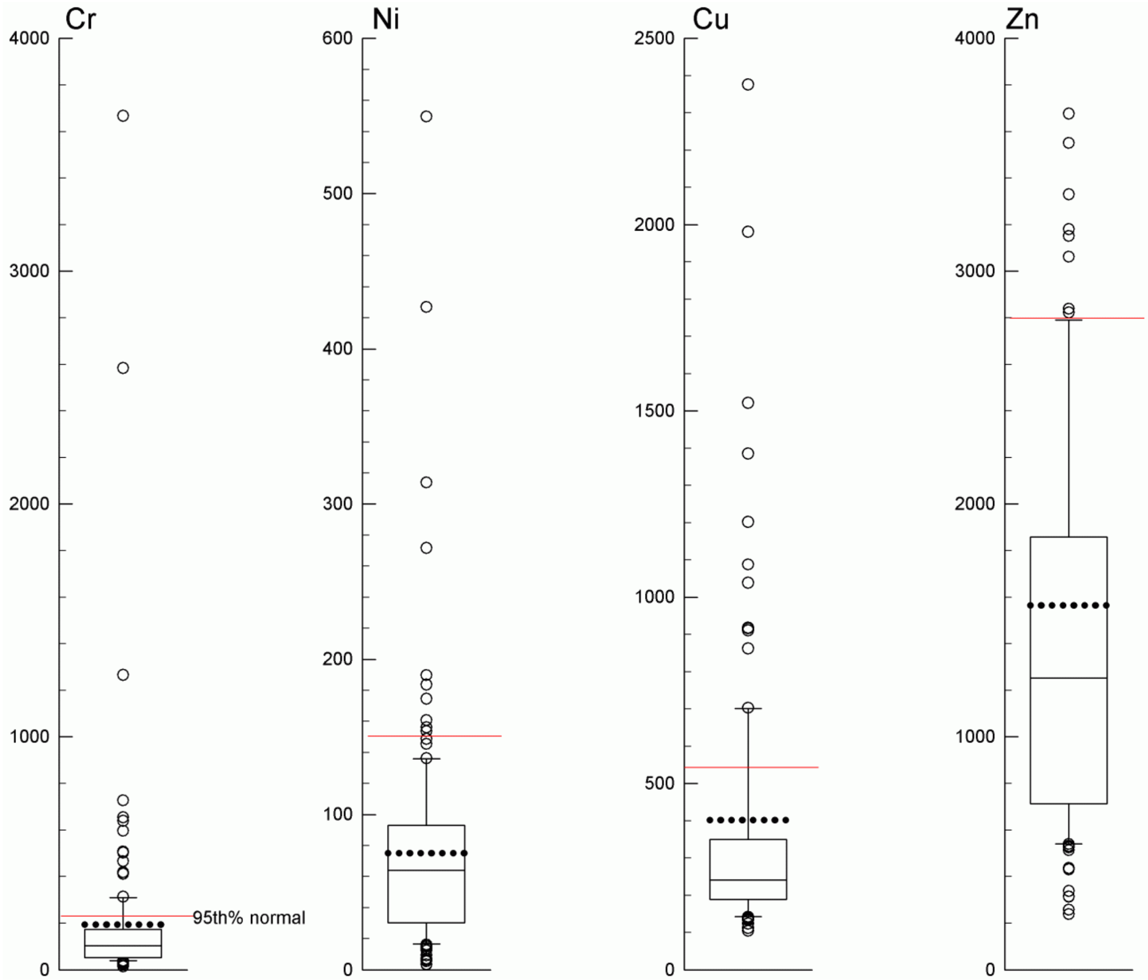


Figure 5: As, Cd, Pb, Hg Normal Wood Pellet Samples, ash concentrations (mg/kg).

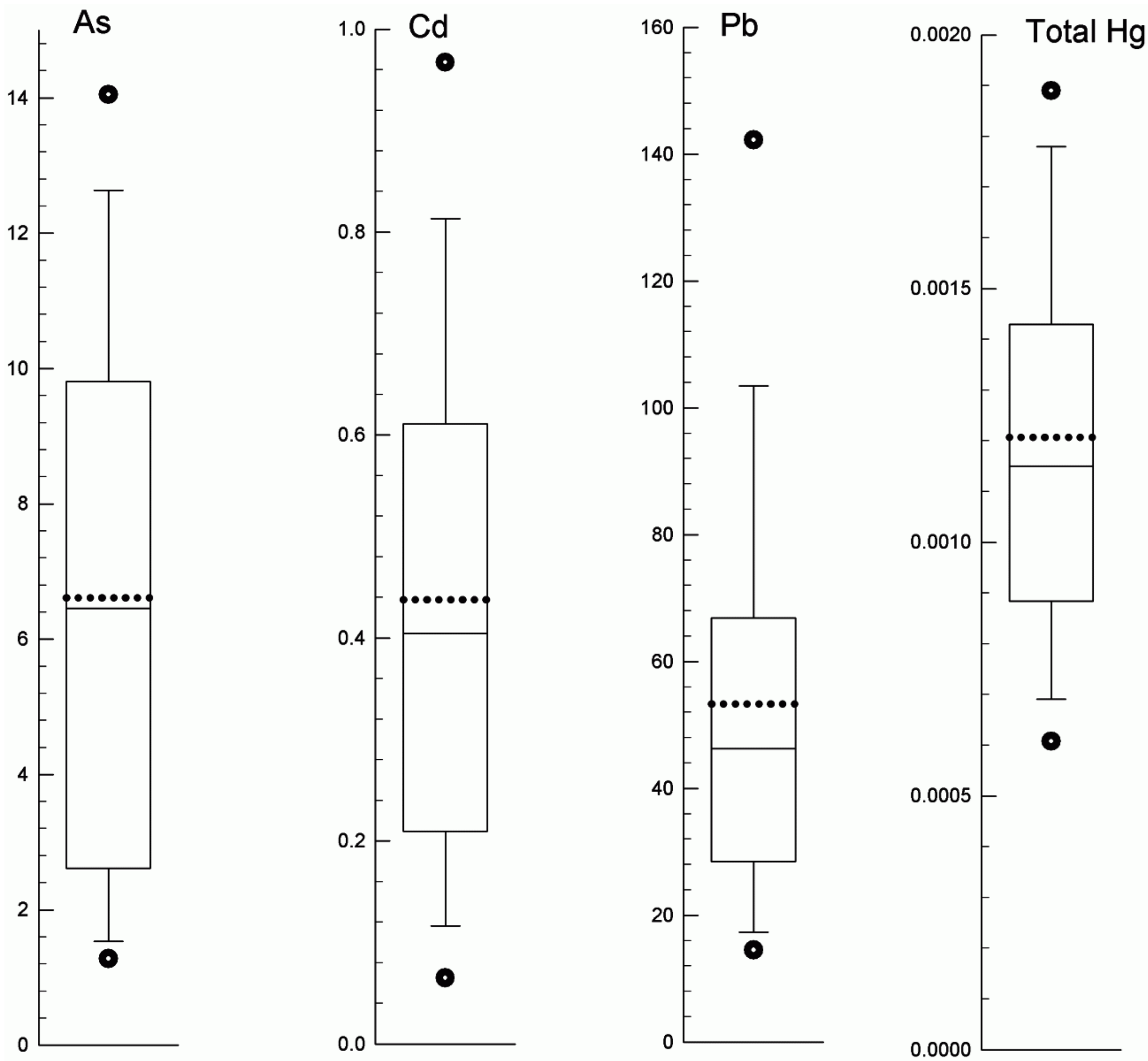
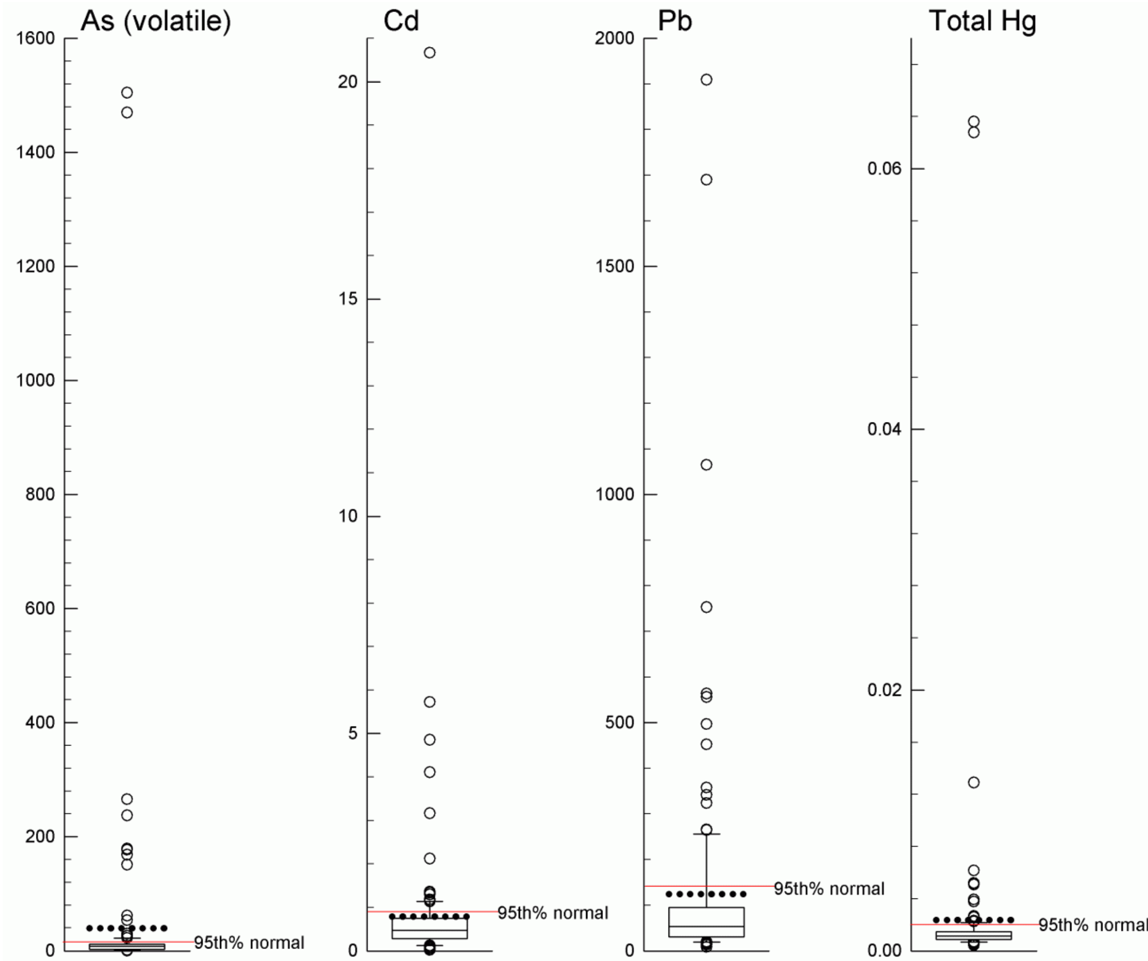


Figure 6: As, Cd, Pb, Hg All Wood Pellet Samples, ash concentrations (mg/kg).



3.1.1 Proximate Analysis

For the proximate analysis, of the 132 samples analyzed, 7 samples exceeded the Pellet Fuel Institute (PFI) Standards limit for moisture and 7 exceeded the 1 percent ash limit. One sample had 7.6 percent ash and had a very dark color (shown in Figure 7). Of the 132 samples analyzed, only one sample exceeded the PFI Standard for chloride. The sulfate analysis showed wide variation, from 21 to 525 ppm w/w. This is plausible because sulfate deposition has substantial spatial variability on the North American scale. The PFI does not include sulfate in its standard.

Figure 7: Example of a Wood Pellet Sample with High Ash Content.

3.1.2 Metals Analysis

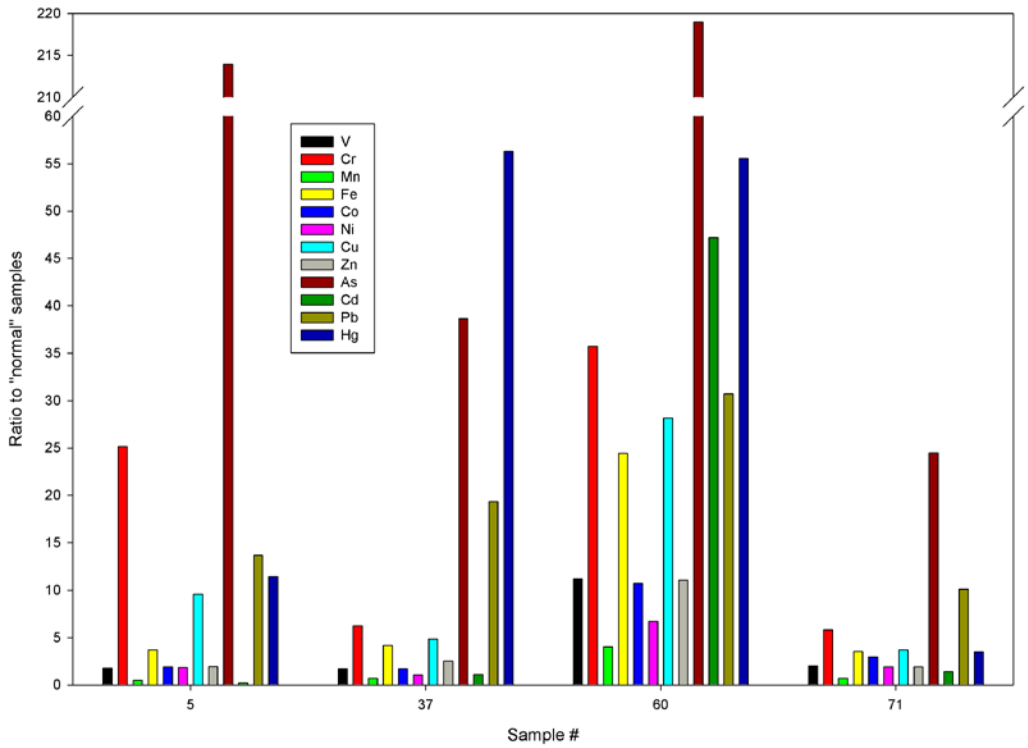
For metals, there was a very large range in results. With the exception of Zn, many samples were much higher than the "normal" benchmark value. For As, Cd, and Hg, some samples had values four to seven times higher than the next highest sample.

Chemical analysis of one brand showed contamination with many analytes including several metals; visual inspection of the pellets showed what appeared to be paint. Figure 8 shows the appearance of pellets from one sample bag of this brand. Four sample bags were collected for this brand, at four different locations over the study period.

Figure 8: Example of an Exceptional Elevated Wood Pellet Sample for Metals.

Whereas all samples from the manufacturer exhibited high levels of metals, there was substantial variation across the four bags of this brand. Figure 9 compares key metals by sample.

Figure 9. Comparison of Wood Pellet Elemental Composition of Four Bags From the Same Manufacturer With Elevated Components.



As highlighted in Figure 9, Sample 71 is "relatively" clean except for As and Pb. Sample 60 is elevated for all metals. Samples 5 and 60 have As levels more than 200 times the benchmark concentration.

3.1.3 Ash Fusion Tests

Ash fusion temperature (AFT) analysis was conducted on 26 samples. This measures the temperature at which the ash will fuse. Ideally, when wood pellets are burned, the remaining ash is removed as a powder. The ash, however, can melt at temperatures below prevailing combustion temperatures in a wood burning appliance and fuse into a glass. This results in a slag within the combustion chamber. The AFT is an indication of the suitability of a wood pellet fuel for combustion.

The AFT characteristic is directly related to the pellet's composition, and primarily affected by SiO_2, Al_2O_3, CaO and Fe_2O_3. Under oxidizing conditions, alkali oxides such as K_2O and Na_2O also contribute to the fusion temperature of the ash when present in sufficient amounts. Wood with relatively low basic oxide/silica ratios (possibly from soil contamination) tends to have lower fusion temperatures.[20]

Analysis was conducted in both oxidizing and reducing conditions, as results can be somewhat different. Fusion temperatures are reported for four conditions: initial temperature (IT), softening temperature (ST), hemispherical temperature (HT), and fluid temperature (FT) ash-fusion. The maximum temperature used for the testing was 2700 ºF (1480 ºC). Research indicates that AFT values higher than 2000 ºF are generally not of concern for wood pellet combustion devices, even for appliances with a secondary combustion chamber.

The temperatures reported here are the mean of two runs. Sample numbers are the same as used for the other analyses. Of the 26 samples, six had some degree of fusion below 2,700 ºF. The temperature difference from IT to FT ranged from 90 ºF to 380 ºF. Three samples had an IT lower than 2200 ºF, and only sample 5 had any AFT low enough to be of clear concern (2000 ºF). Table 3 shows results for all samples that had any fusion temperature below 2,700 ºF, and is sorted by increasing IT. Samples 2, 5, 9 and 10 had lower reproducibility, with at least one fusion temperature different by more than 100 ºF on the two test runs.

Table 3: Overview of Results for AFT Analysis.

Sample Number	Ash Fusion, Reducing Atmosphere (ºF)				Ash Fusion, Oxidizing Atmosphere (ºF)			
	IT	ST	HT	FT	IT	ST	HT	FT
5	1990	2038	2060	2102	2010	2135	2157	2176
26	2042	2130	2163	2205	2128	2200	2241	2285
9	2189	2238	2254	2287	2201	2221	2240	2290
10	2258	2322	2362	2450	2380	2420	2468	2525
2	2278	2325	2340	2376	2191	2323	2329	2354
6	2297	2507	2639	2680	2330	2649	2653	2680
15*	2627							

* No reported temperature represents no fusion up to 2,700 ºF.

[20] Boström D., and N. Skoglund, A. Grimm, C. Boman, M. Öhman, M. Broström, R. Backman. "Ash Transformation Chemistry during Combustion of Biomass"*Energy Fuels* 26: 85-93. doi: 10.1021/ef201205b.

3.2 Seasonal Variation of Wood Pellets

Wood pellet samples from two different manufacturers were acquired over a six month period to examine the variation in their properties over the season and between sample batches. One manufacturer (M1) sent four samples each of hardwood, softwood and a blend of undisclosed proportions (mixture of hardwood and softwood). A second manufacturer (M2) sent samples each month from November 2010 until June 2011. There were no observable trends in the elements over time from either manufacturer. However, the heavy metal concentration from softwood was higher than that in the hardwood from manufacturer M1 in all of the samples (Figure 10). In general, the pure hardwood or the blend had lower heavy metal concentrations. There was little variation in elemental composition in wood pellets from manufacturer M2 over time (Figure 11).

Figure 10: Variation in Elemental Concentration in Pellets From Manufacturer 1.

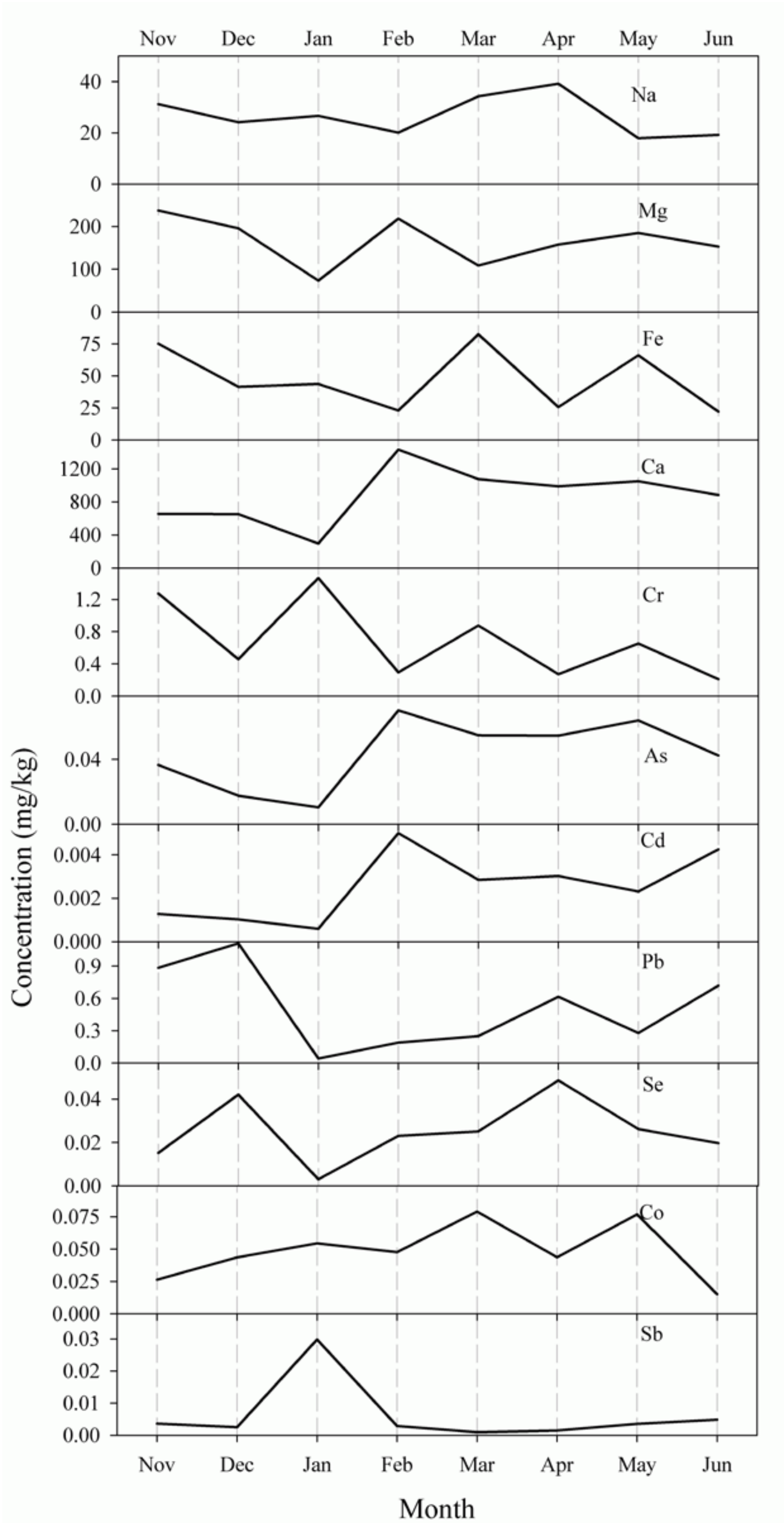
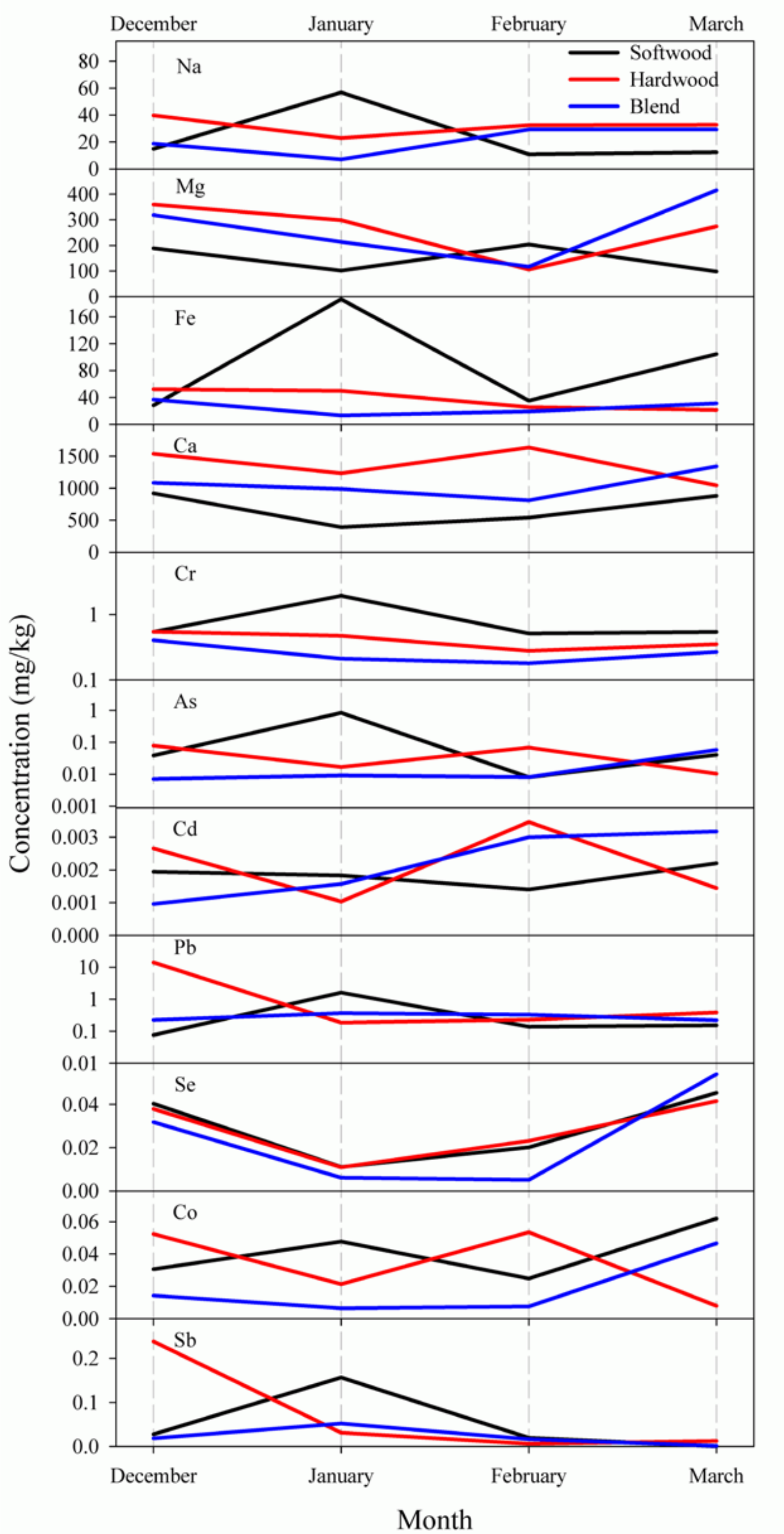


Figure 11: Variation in Elemental Concentration in Pellets From Manufacturer 2.



3.3 Wood Chips

Twenty-three wood chip samples from three end users were analyzed using the methods described for wood pellets. Seven or eight samples from each source were collected from different deliveries between November 2010 and March 2011. Unlike the pellets, the wood for these chip samples was from relatively local sources (NYS and Vermont). Both mill (without bark) and bole (with bark) chip samples were analyzed. Another major difference was moisture content; the wood chips were mostly green wood with substantially higher moisture content than the wood pellets.

The end users described the wood as follows:

- A Samples: Debarked wood (8 samples).
- B Samples: Debarked hardwood (8 samples).
- C Samples: Whole tree chips, mostly hardwood but some softwood (7 samples).

Sample preparation and analysis for the wood chips was the same as for the wood pellets, which is described earlier in this section.

3.4 Results of Wood Chip Analysis

Figures 12 through 15 show distributions of proximate analysis (moisture content, calorific value, ash content), chloride and sulfate ions, and Hg as well as results of ICP-MS analysis for metals. Each box plot has the two lowest and highest samples plotted.

Figure 12: Wood Chip Proximate, Ions, and Hg Analysis (N = 23).

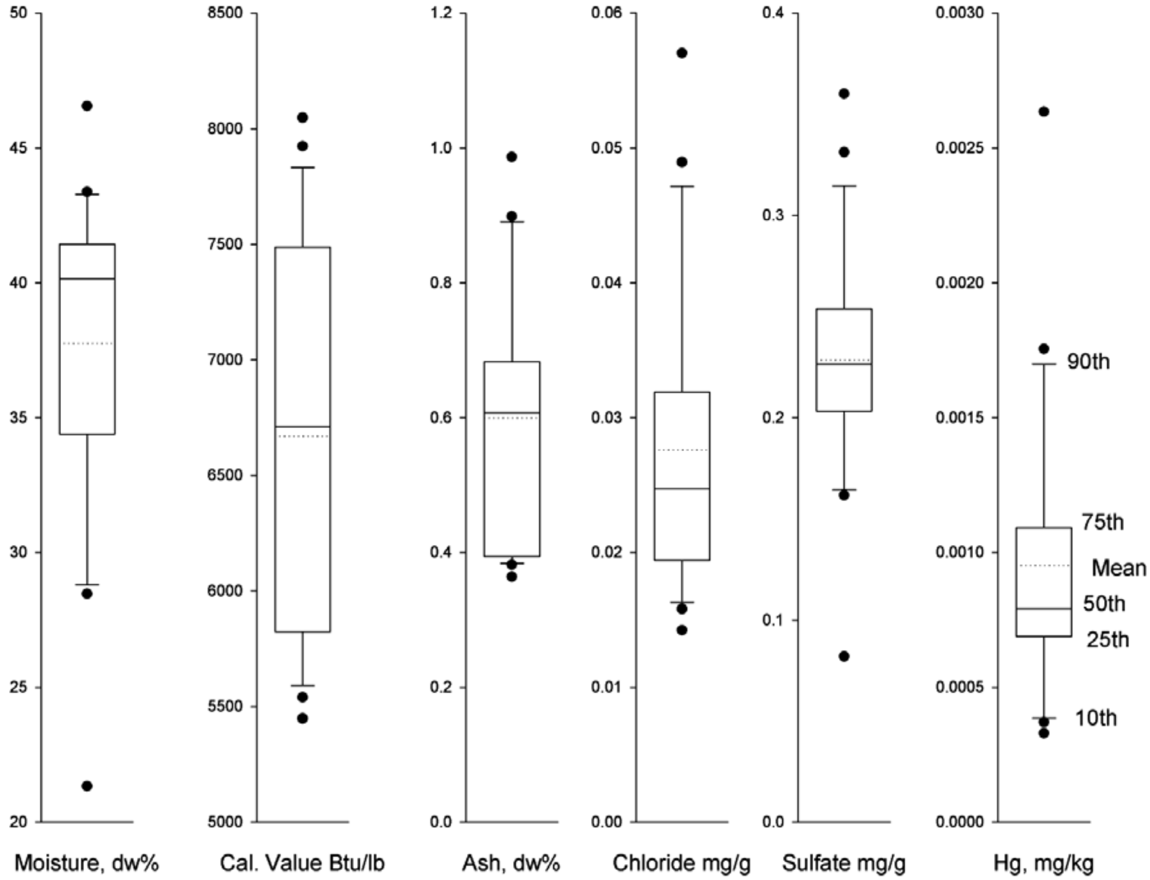


Figure 13: Wood Chip ICP-MS Analysis, mg/kg ash.

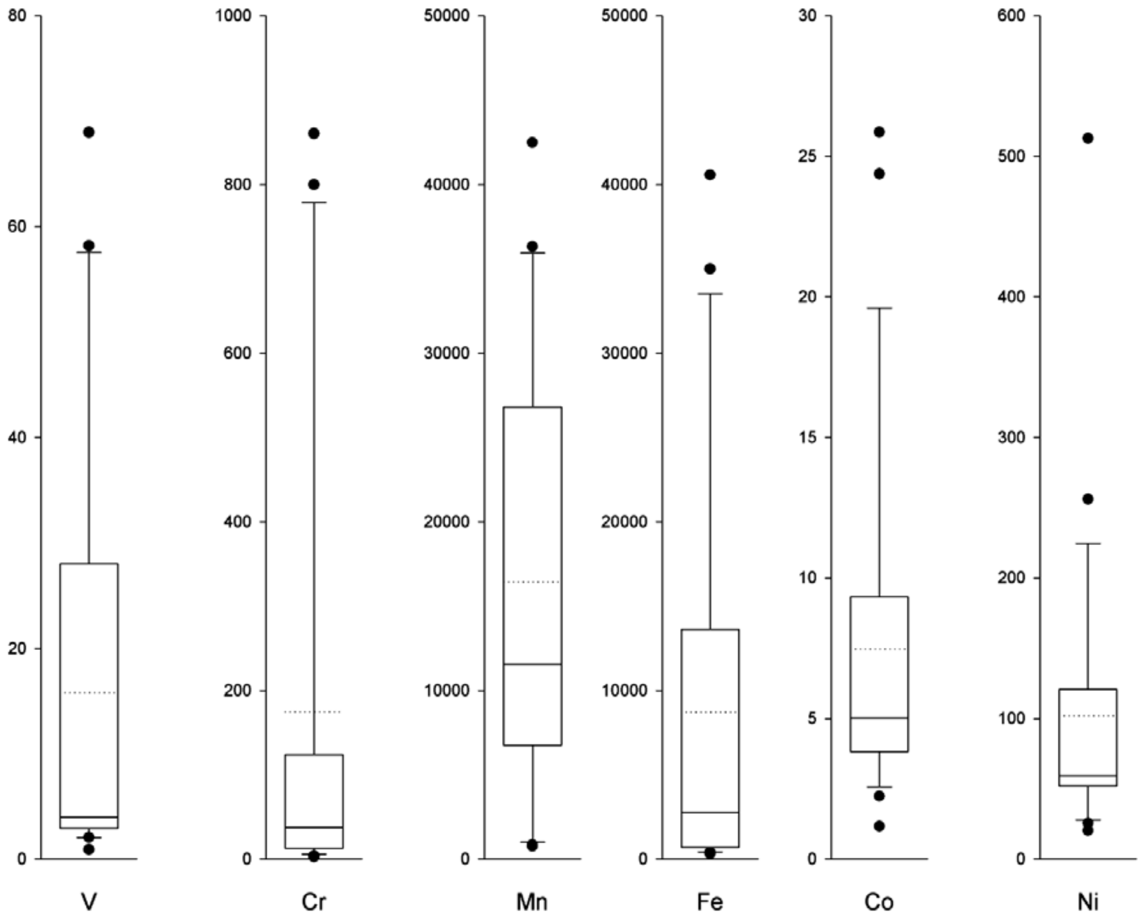
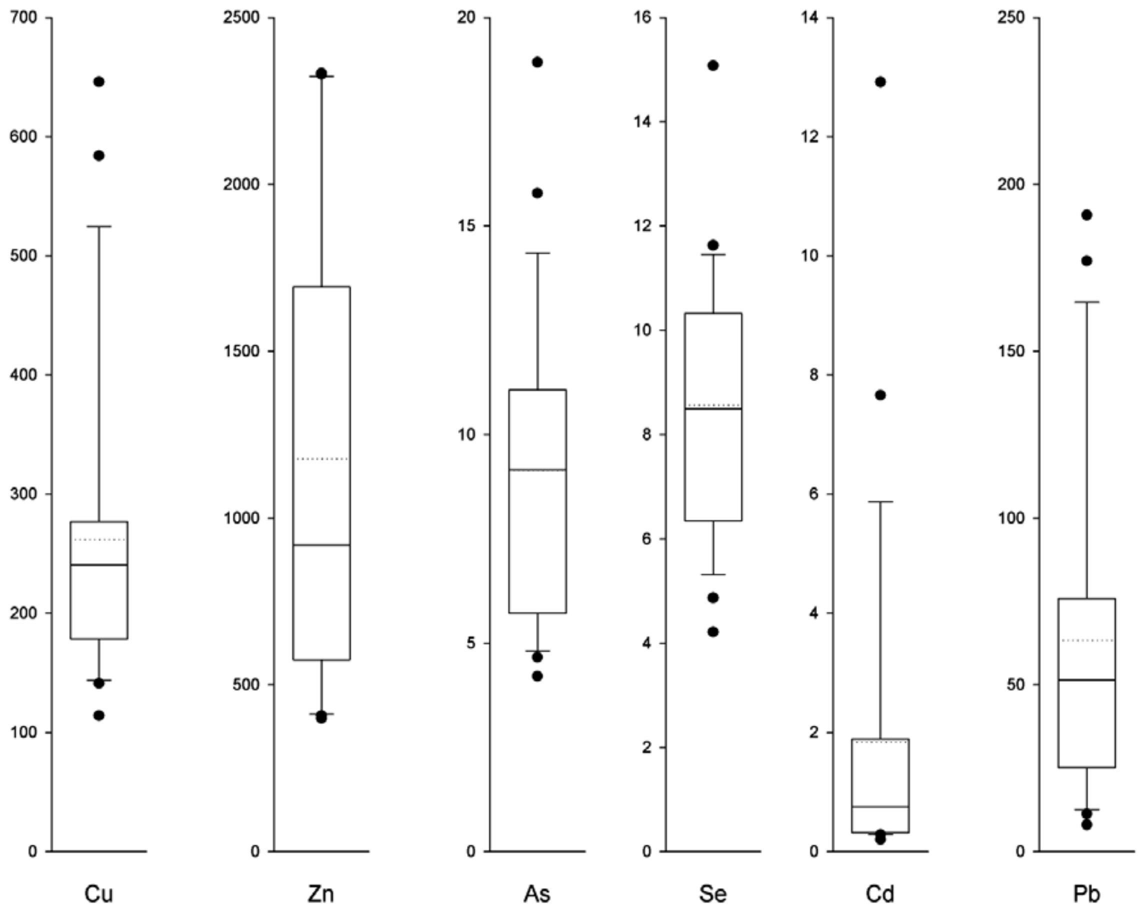
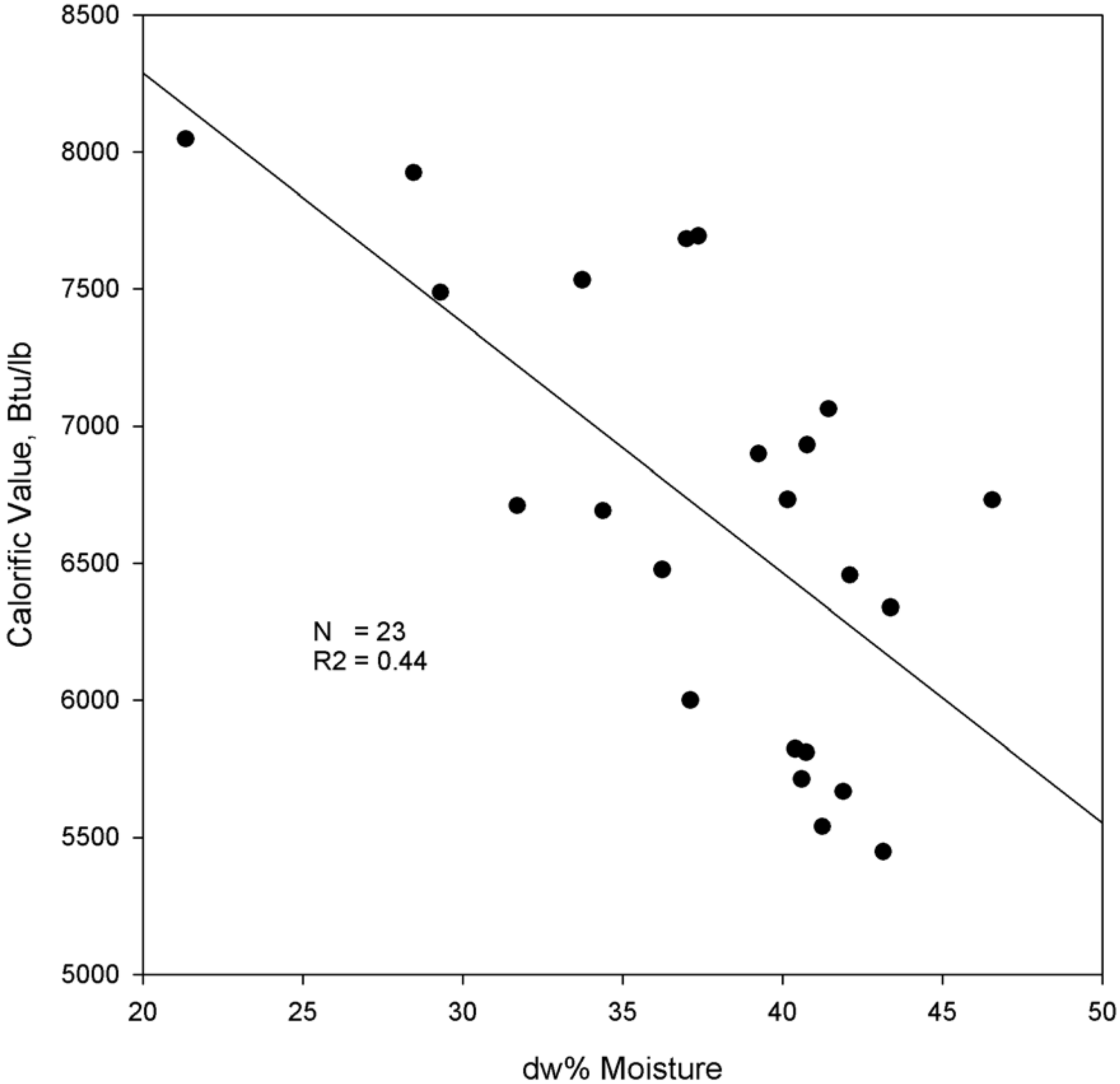


Figure 14: Wood Chip ICP-MS Analysis, mg/kg ash.



Moisture in the wood chips ranged from dry to green (21 to 47 percent). Calorific value had a substantial range, from 5500 to 8000 Btu/lb. Moisture is a major factor in calorific value; Figure 15 shows the regression of calorific value versus percent moisture, with $R^2 = 0.44$. Ash ranged from 0.4 to 1 percent dry weight.

Figure 15: Wood Chips Calorific Value vs. Percent Moisture.



Results of proximate analysis, ions, Hg and metals are shown by sample ID in Figures 16 through 19. Source A, (debarked wood) is distinctly elevated for many metals for the first five samples despite being debarked wood. The last three samples are normal, implying a change in the wood source over time. Source B, also debarked wood, is relatively clean. Cu was the highest value of all samples in one sample, Cd was the highest in another sample, and Pb was elevated in a third sample (almost the highest value). Source C (whole tree) has one sample elevated for V, Cr and Fe and a second sample elevated for Ni only.

Overall, there is no clear pattern relative to barked or debarked wood and elevated levels of metals as might be expected. Source A is elevated for the first five of the eight samples, but the last three are normal. Source B and C are cleaner, but have two or more samples with at least one metal that is elevated. One possible source of contamination could be harvesting practices.

Results for proximate analysis, ions, Hg and metals are shown by sample ID in Figures 16 through 19. Sample sets A and B are debarked, and sample set C is whole tree.

Figure 16: Wood Chip Proximate, Ions, and Hg Analysis.

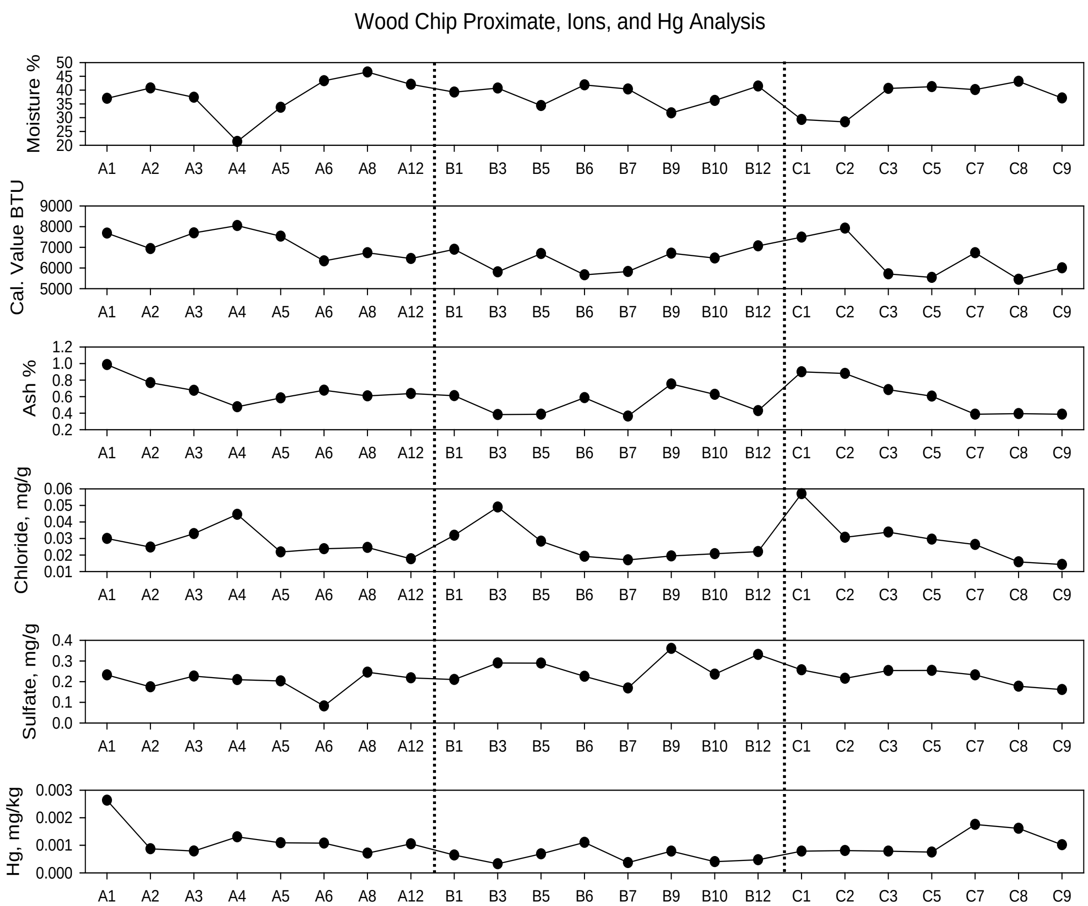


Figure 17: Wood Chip ICP-MS Ash Analysis (1 of 3).

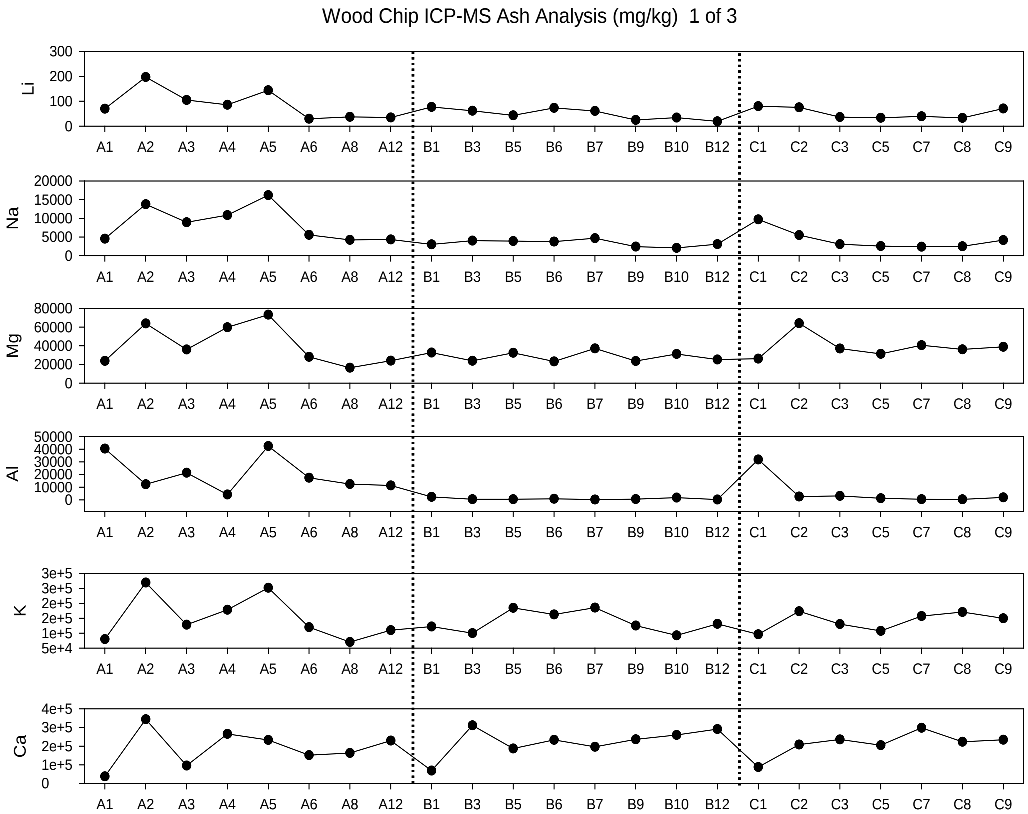


Figure 18: Wood Chip ICP-MS Ash Analysis (2 of 3)

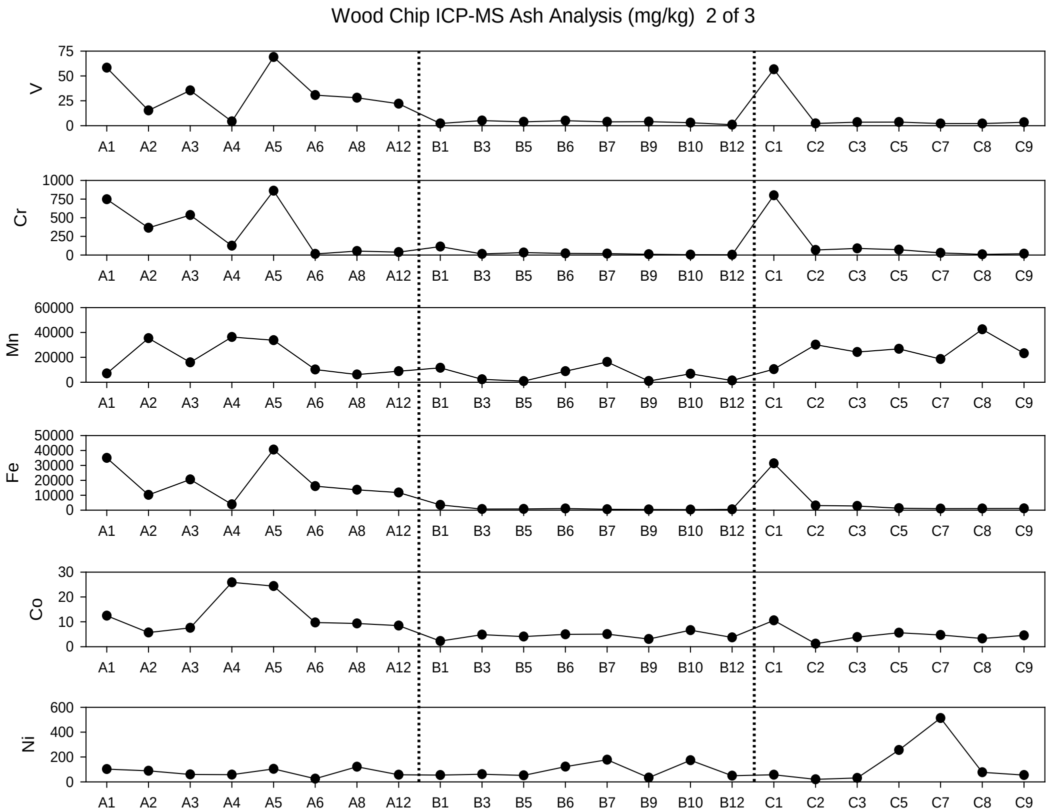
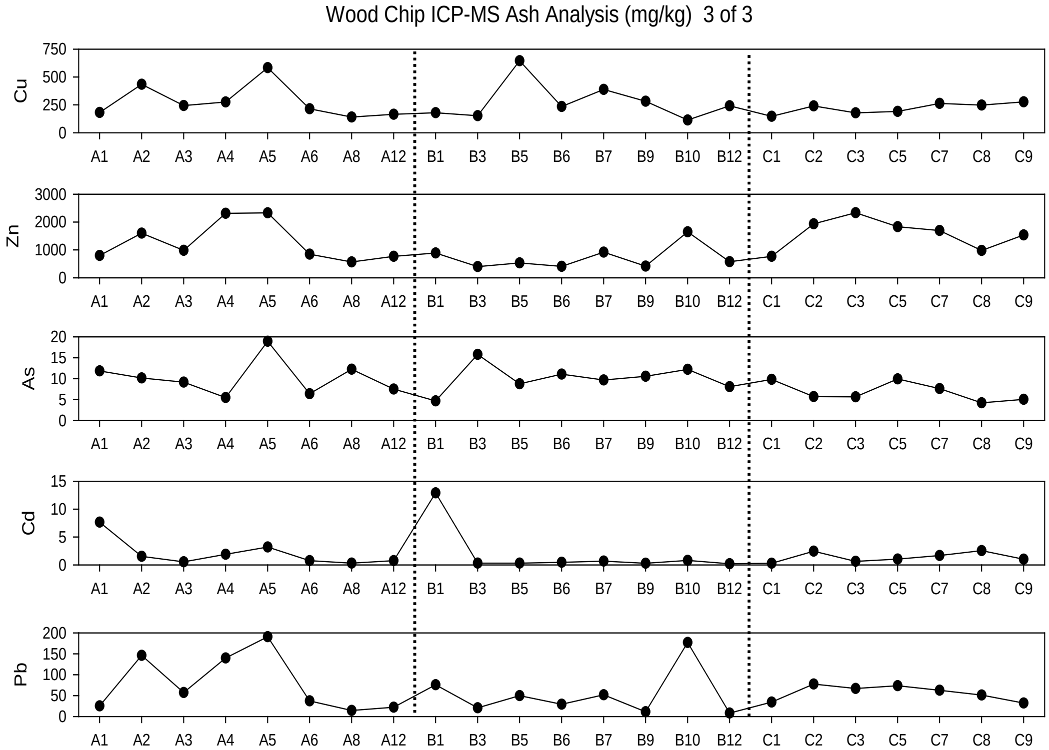


Figure 19: Wood Chip ICP-MS Ash Analysis (3 of 3).



There were not enough samples or range of suppliers to allow estimation of “normal” benchmark values for metals as was done for pellets, thus unusual samples are best identified by comparison to the median value. There were no extreme outliers for chloride, sulfate, or mercury, although one sample had mercury more than three times the median value. Metals showed modest variation except for V, Cd and Cr. The maximum values for these metals were 17, 17 and 23 times the medians, respectively. Table 4 reports the mean/median and max/median ratios for analytes of interest.

Table 4: Mean/Median and Max/Median Ratios for Analytes of Interest for Wood Chips (N=23).

	Mean/Median	Max/Median	Standard Deviation
Moisture	0.94	1.16	
Caloric value	0.99	1.20	799
Ash	0.99	1.62	0.18
Chloride	1.12	2.31	0.011
Sulfate	1.01	1.59	0.058
Hg	1.20	3.32	0.00051
Na	1.30	3.88	3819
Mg	1.11	2.26	15125
Al	3.87	17.95	13081
K	1.10	2.07	49949
Ca	0.91	1.50	78453
V	3.97	17.30	20.7
Cr	4.68	23.01	278
Mn	1.42	3.68	12726
Fe	3.15	14.63	12171
Co	1.48	5.14	6.23
Ni	1.73	8.66	105.8
Cu	1.09	2.69	134.5
Zn	1.28	2.54	656
As	1.00	2.07	3.61
Cd	2.43	17.07	2.90
Sb	13.86	50.20	17.14
Pb	1.23	3.71	52.04

3.5 Summary of Pellet and Chip Concentrations in Wood

Tables 5 and 6summarize the component concentrations in wood. For components that were analyzed from ash, wood concentrations were calculated by dividing the ash analysis by the ash content.

Table 5: Variation in Wood Pellet Component Concentrations (mg/kg of wood) With Mean, Median, Standard Deviation, Maximum and Minimum Values.

Element	Mean	Median	Std Dev	Maximum	Minimum
Cl^-	36.6	21	48.9	413	6.5
SO_4^{2-}	222	220	76	530	23
S	73.9	73	25.5	175	7.6
Hg	0.00736	0.0012	0.0432	0.44	0.0004
Li	0.772	0.57	0.696	4.7	0.035
Na	60.0	30	113	973	8.4
Mg	216	188	155	1620	58
Al	60.2	31	127	1360	4.9
K	777	709	840	9833	167
Ca	1139	916	1399	16000	303
V	0.151	0.085	0.235	2.1	0.011
Cr	1.46	0.58	3.45	27	0.083
Mn	91.1	78	71.1	702	22
Fe	91.7	48	171	1460	9.5
Co	0.077	0.054	0.117	1.2	0.0044
Ni	0.520	0.36	0.823	8.3	0.017
Cu	2.72	1.50	5.01	46	0.36
Zn	9.28	7.2	8.92	90	1.2
As	0.31	0.040	1.58	15	0.0016
Se	0.0340	0.023	0.0434	0.37	0.00011
Rb	2.00	1.7	1.92	18	0.29
Sr	8.38	6.5	9.21	101	2.9
Cd	0.00501	0.0029	0.0126	0.14	8.9E-05
Sb	0.032	0.0063	0.137	1.5	0.00043
Ba	17.9	14	25.8	292	1.9
Tl	0.00111	0.00041	0.00171	0.011	0.0000
Pb	0.81	0.34	1.65	11.0	0.040

Table 6: Variation in Wood Chip Component Concentration (mg/kg of wood) With Mean, Median, Standard Deviation, Maximum and Minimum Values.

Element	Mean	Median	Std Dev	Maximum	Minimum
Cl^-	27.6	24.7	10.7	57	14
S	76.1	75.5	19.4	120	27.3
Hg	0.000951	0.000792	0.000512	0.0026	0.0003
Li	0.399	0.235	0.330	1.51	0.081
Na	34.2	20.9	28.3	106	9.2
Mg	216	189	123	563	91
Al	68	14.4	107	399	0.85
K	839	745	380	2066	381
Ca	1184	1190	512	2639	373
V	0.114	0.022	0.168	0.574	0.004
Cr	1.31	0.24	2.28	7.36	0.012
Mn	97.5	70.6	78.8	272	3.0
Fe	64.0	18.1	98.2	345	2.0
Co	0.0456	0.029	0.0392	0.142	0.010
Ni	0.560	0.362	0.468	1.98	0.17
Cu	1.50	1.32	0.75	3.41	0.58
Zn	7.11	5.93	4.54	17.0	1.53
As	0.0554	0.050	0.0277	0.117	0.017
Se	0.0498	0.043	0.0168	0.088	0.026
Rb	1.83	1.55	1.04	4.57	0.59
Sr	6.67	5.83	3.70	17.9	2.39
Cd	0.0122	0.0048	0.0212	0.079	0.0009
Sb	0.0872	0.0053	0.122	0.397	0.00064
Ba	19.0	17.4	10.2	45.9	6.3
Tl	0.000563	0.000329	0.00064	0.0027	7.47E-05
Pb	0.383	0.249	0.338	1.12	0.035

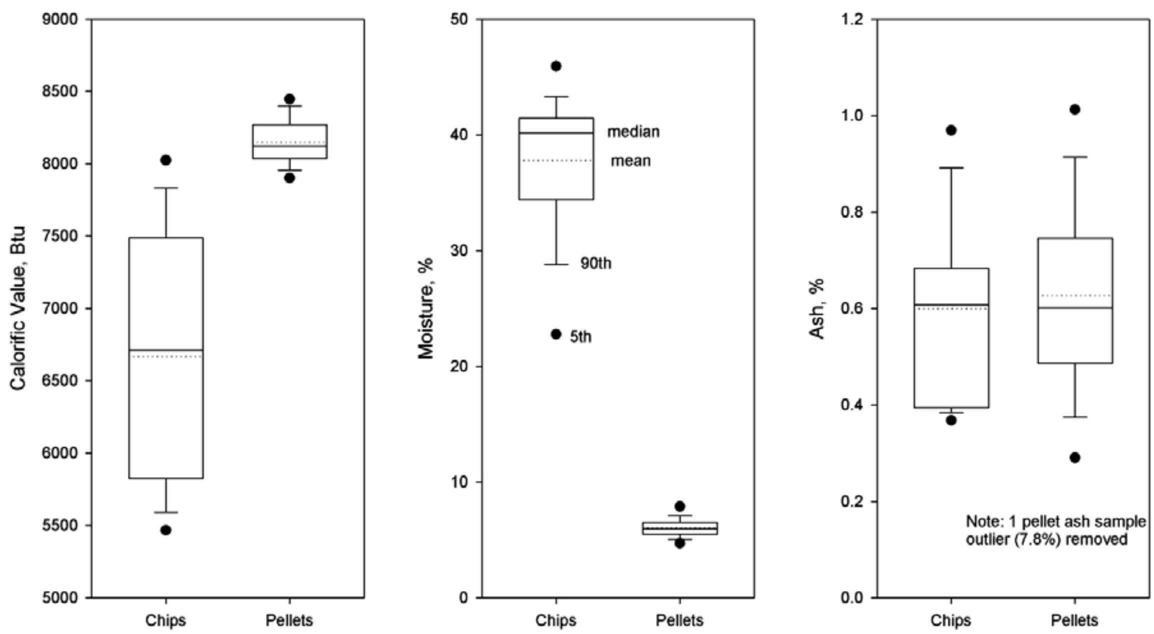
3.6 Pellet to Chip Comparison

The results of the 132 wood pellet samples were compared with the results from the 23 wood chip samples.

3.6.1 Physical Characteristics (moisture, ash, calorific values)

The basic analysis results (gross calorific value, ash, and moisture) of all the wood pellets and wood chip samples are shown in the following figures. As expected, moisture content in the wood chips is significantly higher than for the wood pellets (more than five times higher). All wood pellets had moisture contents less than 9 percent while wood chip moisture content ranged from 20 to 47 percent. Increased moisture levels reduce the heating value of the wood chips. Analysis found that there was limited variation in wood chip ash content although there were a relatively limited number of samples. In the wood pellets, however, the ash content ranged from 0.29 percent to 1.53 percent with only 1 of the 132 samples as an outlier, where the ash content was about 7.8 percent. The distributions of calorific value, ash and moisture are plotted in Figure 20.

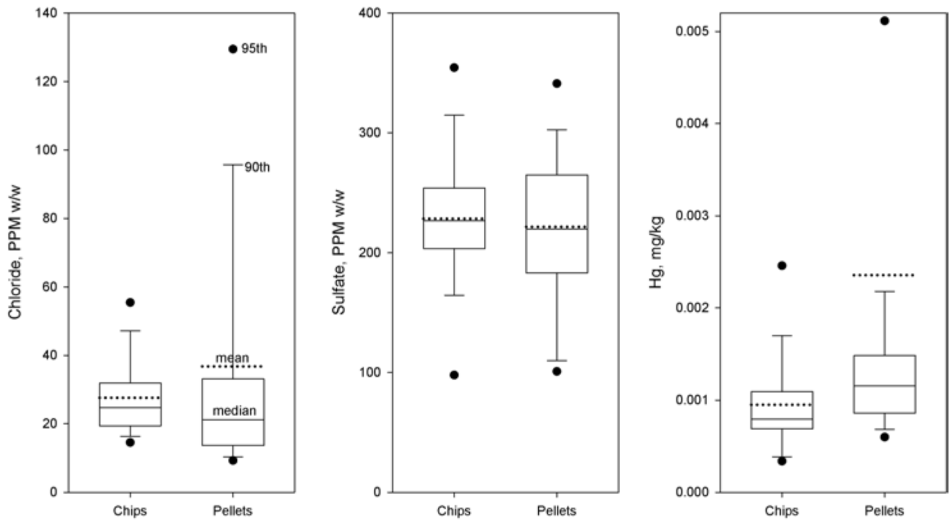
Figure 20. Comparison of Calorific Value, Moisture and Ash Values for Wood Chips and Pellets.



3.6.2 Chloride and Sulfate

Median chloride concentration was similar in wood pellets and chips but pellets had many samples with concentrations two to six times higher than any chip sample, perhaps from salt contamination. However, this result indicates that these elevated levels are not due to the virgin wood component. Sulfate was similar between wood pellets and chips. Figure 21 shows the distribution of chloride and sulfate ion concentrations, as well as elemental mercury, for both wood chips and pellets.

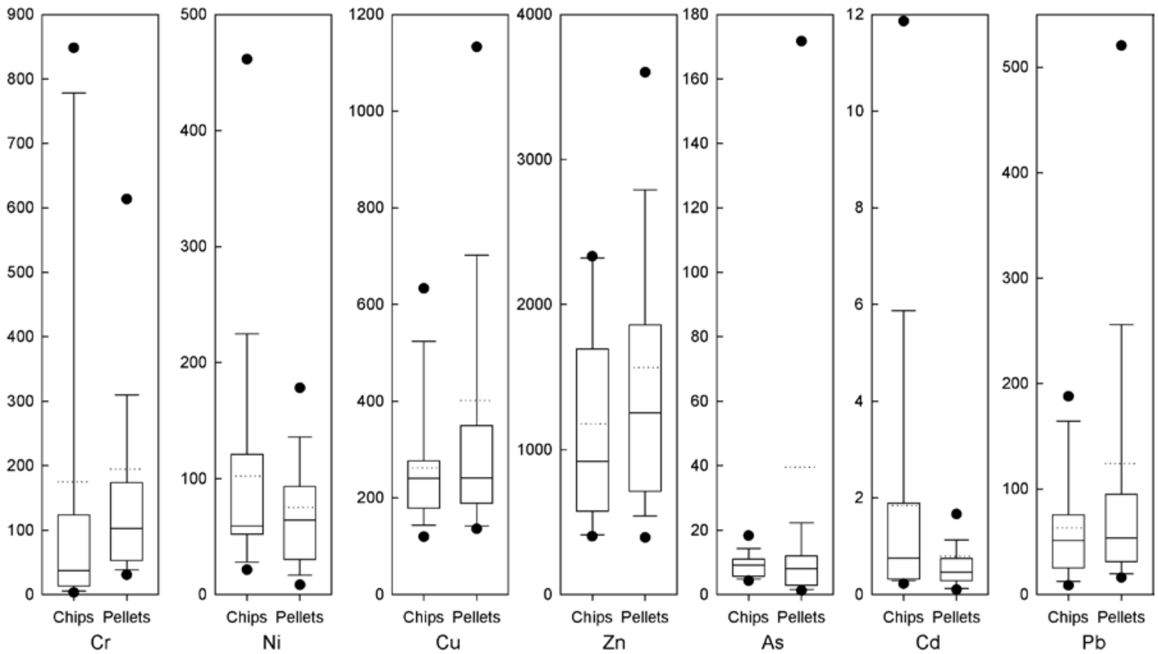
Figure 21. Distributions of Chloride, Sulfate and Mercury in Wood.



3.6.3 Elemental Analysis

The large number of sources and samples of wood pellets relative to chips results in much larger variability in metal concentrations in the pellets. The distributions of the measured elemental concentrations in the wood pellets and chips are plotted in Figure 22. The mean concentration, standard deviation, median, maximum, and minimum concentrations of the elements in the wood pellet and chips samples are summarized in Tables 2 through 4. There are substantial similarities to the distributions of elements between the pellets and chips. Large variations are observed in Al and Fe for the wood chips (Table 4). The major ash-forming elements in wood pellets and wood chips are identified to be Ca (45 percent), K (37 percent) and Mg (8 percent) expressed as dry weight percent of ash; other elements are Mn (4 percent), Fe (3 percent), Al (1 percent), and Na (1-2 percent). Some of the wood chip samples contained visible coarse sand particles, which lead to higher concentrations of Al and Fe. Generally, low vapor pressure compounds, alkali earth metals (Ca, Mg), alkaline earth oxides, phosphates and silicates that are not easily volatilized remain in the ash. Alkali chloride, sulfate and silicates are harmful to the combustion device because they cause slagging, and corrosion in the combustion appliances.[21] The reaction between the alkali metals, chloride and sulfate depends on the fuel composition and combustion conditions.[22,23]

Figure 22. Concentrations of Key Metals in Chips and Pellets in Ash (mg/kg).



The following is a summary of results of the elemental analysis:

- Cd is found naturally in wood, and concentration is similar between pellets and chips. Both types had a large range of concentrations, with similar median and maximum values.
- Cr in wood chips was elevated for five samples relative to the ash benchmark value of 200 mg/kg; two samples were higher than 800 mg/kg.
- Ni was similar for wood pellets and chips.
- Cu in wood chips did not appear to be elevated relative to the ash benchmark value of 500 mg/kg.
- Zn was relatively similar between wood pellets and chips.
- As was not elevated in wood chips relative to the ash benchmark value of 15 mg/kg.
- Three samples had Pb values over the ash benchmark value of 140 mg/kg, but these samples were all between 150 and 180 mg/kg, not extreme outliers and thus not indications of wood chip contamination.

[21] Pasanen, J., K. Louekari, and J. Malm. 2001. *Cadmium in Wood Ash Used as Fertilizer in Forestry: Risks to the Environment and Human Health*. Helsinki: PrintLink Oy Ab.
[22] Sippula, O., K. Hytonen, J. Tissari, T. Raunemaa, and J. Jokiniemi. 2007. "Effect of Wood Fuel on the Emissions from a Top-Feed Pellet Stove." *Energy Fuels* 21(2): 1151-60. doi:10.1021/ef060286e.
[23] Pasanen, J., K. Louekari, and J. Malm. 2001. *Cadmium in Wood Ash Used as Fertilizer in Forestry: Risks to the Environment and Human Health*. Helsinki: PrintLink Oy Ab.

- Hg in chips was similar to the “clean” wood pellet distribution, and no chip samples exceeded the benchmark value of 0.0017 mg/kg.
- A few wood chip samples had elevated Cd and Cr concentrations.
- Ni and V were relatively low in both wood chips and pellets compared to heavy oil.[24]

Some heavy metals (such as As, Cu and Cr) were found to be higher in several wood pellet samples. High concentrations of these heavy metals in wood pellets indicate the likely use of preservative-treated wood. It is possible that some CCA-treated[25] scrap wood might have been included in pellet production. The information gathered from the manufacturers of the wood pellets suggested that some of them used recycled wood products, wood waste and wood residues. The inability to track the pellet material from “cradle to grave” limits the capacity to determine if the elevated levels result from use of treated wood products, harvesting practices or elemental composition.

In 2003, EPA and the wood preservative registrants entered a voluntary agreement to terminate the use of CCA in almost all wood products for consumer purchase after December of that year. Products using these alternative preservatives can contain Cu but no As or Cr. CCA-treated wood, however, still is captured as a waste wood product. A subset of wood pellet samples (13 samples) was also analyzed for titanium (Ti). Four samples had higher Ti concentrations (up to 3,000 ppm). The Ti contamination was likely from the inclusion of painted wood. High concentrations of Pb in samples could be due to Pb-based paint on old wood or uptake of Pb from soil contaminated by lead arsenate pesticide.[26]

Cd concentrations have been found to be high in bark from coniferous trees, debarked pine and willow.[27,28] A few samples (both wood pellets and chips) that were very dark in color had higher Cd concentrations, suggesting that they might include bark. Most of the high heavy metal concentrations were found in samples that were darker. In general, the heavy metal uptake from the roots of trees is deposited in the bark and is substantially higher than in core wood.[29]

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[24] NESCAUM analysis contained in NYSERDA Report 10-31 (Determination Of Sulfur and Toxic Metals Content of Distillates and Residual Oil in the State of New York) found that Ni levels in #2 distillate oil were 3.2 ppb and 16,988 ppb for heavy oil. Vanadium levels were only examined for heavy oil which found levels of 2,967 ppb.

[25] Chromated Copper Arsenate

[26] Sander, B.1997. "Properties of Danish biofuels and the requirements for power production." *Biomass Bioenerg* 12(3): 177-83. doi:10.1016/S0961-9534(96)00072-4.

[27] Vassilev, S. V., D. Baxter, L. K. Andersen, and C. G. Vassileva. 2010. "An overview of the chemical composition of biomass." *Fuel* 89(5): 913-33. doi:10.1016/j.fuel.2009.10.022.

[28] Tissari, J., et al. "Fine particle and gaseous emissions from normal and smoldering wood combustion in a conventional masonry heater." *Atmos. Environ* 42, no. 34 (2008): 7862-73. doi:10.1016/j.atmosenv.2008.07.019.

[29] *Ibid*

The concentration of Hg is lower in the ash than that in the wood itself. Hg in wood is present mostly in organic form. It can be assumed that about 90 percent of Hg is lost to the atmosphere during the combustion process.[30]

Other than possibly Cr, contamination of wood fuels in this study was only found in pellet samples. This result is consistent with the expected wider range of feedstocks that include waste material and by-products from other manufacturing operations. However the wood chip analysis is from a small number of suppliers and samples (3 and 23 respectively), and may not be as representative of regional fuels compared to the pellet samples (132 samples from 100 suppliers).

[30] Vassilev, S. V., D. Baxter, L. K. Andersen, and C. G. Vassileva. "An overview of the chemical composition of biomass." *Fuel* 89, no. 5 (2010): 913-33. doi:10.1016/j.fuel.2009.10.022.

4 Conclusions and Recommendations

The main focus of this study was determining the elemental constituents of the wood pellets and chips. The purpose of this study was to analyze materials to determine if there was a potential for air emissions issues, primarily heavy metals from wood pellet and chip combustion to warrant further stack testing analysis. However, because the primary wood chemical analysis done for this work was on ash, the issue of contaminants in the ash (solid waste) is also relevant. The study has significant limitations due to the inability to track the origins of the feedstock prior to mill delivery. Although analysis yielded results showing elevated levels, it is impossible for this study to understand with certainty where the impurities or increased undesired elements originate. Possible contamination could come from the elemental make up of the wood, use of treated waste materials, or contamination in the harvesting or manufacturing process.

4.1 Stack Emissions

Work completed during the course of this study supports the contention that fuel analysis alone cannot sufficiently inform speciated air emissions for particulate matter, sulfur and metals. To gauge the impacts of fuel variability and elevated element concentrations, stack testing should be conducted to determine the amount and composition of emissions from normal and non-normal pellets using the 95th percentile delineation discussed in the Results section.

In theory, another approach to apportioning the fate of metals between stack emissions and ash without stack testing could be completed by analyzing both the wood and the wood ash, with the difference being the stack emissions. There are significant limitations to this method, however. First, there may be substantial uncertainty in elemental analysis on wood due to extraction methods and efficiencies as well as lower concentrations (by a factor of 100 to 300) relative to ash. Second, any fly ash emissions are not typically incorporated into the stack testing analysis. Although the latter may be a relatively small amount, it may contain substantial loads of certain elements and may be of great import for solid waste applications given that many states have approved the use of wood ash for soil amendment purposes. Finally, concerns about the variability across laboratories for trace metals analysis would need to be assessed to gain a better understanding of the precision and potential variability in the analysis. A significant constraint is the lack of trace standards for the key metals of interest in wood; all that could be done at this time is to assess the relative accuracy between laboratories using “round-robin” testing comparisons. Other factors to consider when characterizing different fuel types, such as hardwood versus softwood, bark versus debarked, and “dirty floor scraps” versus virgin wood. Whereas pellet technologies offer the potential for lower emissions performance, only when clean fuels with advanced designs are used in conjunction can the lowest possible emission be achieved.

4.2 Solid Waste Concerns

What remains in the ash when the wood is burned is another relevant question raised by this study. Air pollution occurs through the stack, and what remains in the ash is solid waste needing to be disposed of. For stack emissions, there are three categories: gas, fine-mode particle (combustion-related), and large particles (ash). From an air pollution perspective, the gas and fine-mode PM are of most concern. The large ash particles would settle out rapidly, are less likely to get into the lung, and do not efficiently penetrate indoors. Without chemical characterization of stack emission metals, it can only be assumed that most or all of the Hg and sulfate and some of the As are stack emissions, with the remaining contaminants being mostly in the ash.

Concentrations from ash analysis can be reported in several ways, depending on the intended use of the data. For ash used as fertilizer, the actual ash concentrations in mass/mass units are appropriate. If the concern is the amount of metals in ash that has to be disposed of, the ash concentration could be normalized for percent ash and Btu/pound (Btu/lb), because those parameters determine the fuel-related mass of ash generated for a given amount of heat generated. For comparisons to wood fuel standards that are expressed as wood concentrations, the ash data can be corrected back to wood concentrations with the percent ash content (with the exception of As). It is likely that the As results from the ash analysis are under-reported. A 2005 study indicated that when CCA wood is burnt between 11 and 14 percent of the As present is emitted with air emissions.[31]

Wood combustion is gaining interest for heating, and it is important to understand the elemental composition of commercial pellets and chips. Wood pellets were found to have higher concentrations of heavy metals than wood chips although the number of chip samples was substantially smaller than the number of pellet samples. In general, metal content of the wood samples were low. However, some samples were found to have unusually high values of heavy metal concentrations. It is likely there was inclusion of extraneous materials such as painted or pressure-treated lumber leading to the observed high concentrations. Although the wood pellet samples generally meet the quality standards of the European Union, some samples would fail the ash content requirements. Only Germany has standards containing extensive trace element limits. Most of the tested samples of this study would meet these standards, but some would fail based on their As, Cd, and Cu concentrations. The PFI ash standard of 1 percent identifies eight pellet samples from this sample set of 132, including one with 7.8 percent ash. Of these eight, five are among those identified as contaminated.

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[31] Wasson, S.J., and Linak, W.P., Gullett, B.K., King, C.J., Touati, A., Huggins, F.E., Chen, Y., Shah, N., and Huffman, G.P. 2005. Emissions of Chromium, Copper, Arsenic, and PCDDs/Fs from Open Burning of CCA Treated Wood." *Environmental Science & Technology*, 39(22):8865-8876.

Given the interest in increasing the use of pellets as a renewable fuel, standards need to be established in the U.S. for elemental composition of commercial wood pellets and chips to avoid the inclusion of extraneous materials. Such standards would reduce the environmental impact of toxic species that would be released when the wood is burned.

4.3 Recommendations

The results of this study support the contention that fuel analysis alone cannot sufficiently inform emissions chemistry. To gauge the impacts of fuel variability and elevated element concentrations, stack testing should be conducted to determine the amount and composition of emissions from wood fuels. Additionally, the findings raise heightened concern about the use of waste wood products and other materials in pellet production. Elevated As levels in ash should be an area of further analysis. A prior study completed in 2005 indicated that between 11 and 14 percent of the As present in CCA-treated wood was emitted with air emissions.[32] This indicates that air emissions from wood containing elevated levels of As may create issues for both solid waste disposal and combustion.[32] Elevated levels of As, Cd and Cr raise concerns about the use of CCA-treated wood in pellets. Elevated levels of Cd may indicate the use of plastics as a binding agent. These issues along with the lack of independent analysis of pellet manufacturing highlight the need for further study of this product category.

Establishing enforceable U.S. standards for elemental compositions of commercial wood pellets and chips would also help exclude inappropriate materials and promote cleaner combustion. While the study found potential contamination due to the inability to track beyond the pellet production process to the source of processing materials and to determine if elevated elements result from harvesting practices, use of waste materials, processing impurities or inappropriate handling during production and distribution. Only through the use of programs or regulations that look beyond the current voluntary pellet standards will NYS be able to assure the use of clean wood pellets. Inappropriate storing conditions of the raw material, poor handling concepts, use of waste woods and lack of standards for raw materials as well as binders are likely contributors to product quality issues. Working with environmental organizations and industry to develop appropriate quality assurance concepts for their production rather than those developed solely by industry would support the development of robust product standards. Strong product standards will also limit

[32] Wasson, S.J., and Linak, W.P., Gullett, B.K., King, C.J., Touati, A., Huggins, F.E., Chen, Y., Shah, N., and Huffman, G.P. 2005. "Emissions of Chromium, Copper, Arsenic, and PCDDs/Fs from Open Burning of CCA Treated Wood." *Environmental Science & Technology,* 39(22):8865-8876.

concerns about use of ash materials in the solid waste stream. Certain elements may still remain in elevated concentrations in the ash; therefore, further analysis of clean pellets should be completed to support the development of policies to assure appropriate use of wood ash for soil supplementation or solid waste disposal. Given these issues, the authors recommend the development of:

- Robust standards that address raw material, processing and end product analysis such as those currently employed in Europe.
- Education programs to inform industry and the general public regarding the issues associated with clean production.

Appendix A

Complete Listing of Proposed or Operational Pellet Plants in the U.S. and Canada

Source: Biomass Magazine (http://biomassmagazine.com/plants/listplants/pellet/US/)

Table A-1: Pellet Plants in Operation in the United States.

Company	Plant	State	Feedstock	Capacity (metric tons/year)
Ace Pellet Co., LLC	Ace Pellet Co., LLC	Tennessee	Hardwood	4,000
Alexander Energy, Inc.	Alexander Energy, Inc.	Pennsylvania	Hardwood	8,500
Allegheny Pellet Corp.	Allegheny Pellet Corp.	Pennsylvania	Hardwood	Undisclosed
American Pellet Co.	American Pellet Co.	Michigan	Hardwood and Softwood	12,000
American Pellet Supply, LLC	APS-Indiana	Indiana	Hardwood and Softwood	300,000
American Wood Fibers	American Wood Fibers - Wisconsin	Wisconsin	Hardwood and Softwood	25,000
American Wood Fibers	American Wood Fibers - Marion	Virginia	Hardwood and Softwood	75,000
American Wood Fibers	American Wood Fibers - Circleville	Ohio	Hardwood and Softwood	50,000
Anderson Wood Products Co.	Anderson Hardwood Pellets	Kentucky	Hardwood	25,000
Appalachian Wood Pellets	Appalachian Wood Pellets	West Virginia	Hardwood	Undisclosed
Arbor Pellet, LLC	Arbor Pellet, LLC	Utah	Hardwood and Softwood	20,000
Associated Harvest, Inc.	Associated Harvest, Inc.	New York	Hardwood	8,000
B D Schutte Farms	Wolverine Harwood Pellets	Michigan	Hardwood	750
Barefoot Pellet Co.	Barefoot Pellet Co.	Pennsylvania	Hardwood	45,000
Bear Mountain Forest Products	Bear Mountain Forest Products - Cascade Locks	Oregon	Softwood	100,000

Bear Mountain Forest Products	Bear Mountain Forest Products - Brownsville	Oregon	Softwood	30,000
Bearlodge Forest Products, Inc.	Bearlodge Forest Products, Inc.	Wyoming	Softwood	5,000
BioMaxx, Inc.	PA Pellets	Pennsylvania	Softwood	50,000
BioMaxx, Inc.	Nazareth Pellets	Pennsylvania	Softwood	50,000
BioMaxx, Inc.	Dry Creek Products	New York	Hardwood	100,000
Blue Mountain Lumber Products	Blue Mountain Lumber Products	Oregon	Softwood	20,000
Confluence Energy	Confluence Energy	Colorado	Softwood	100,000
Corinth Wood Pellets, LLC	Corinth Wood Pellets, LLC	Maine	Hardwood and Softwood	75,000
Curran Renewable Energy	Curran Renewable Energy	New York	Hardwood and Softwood	100,000
Deadwood Biofuels, LLC	Deadwood Biofuels, LLC	South Dakota	Softwood	71,000
Energex, Inc.	Energex Pellet Fuel, Inc.	Pennsylvania	Hardwood	60,000
Ensign-Bickford Renewable Energies, Inc.	Biomass Energy, LLC	Virginia	Hardwood and Softwood	110,000
Enviro Energy	Enviro Energy	New York	Ag	1,800
Enviva LP	Enviva Pellets Northampton	North Carolina	Hardwood and Softwood	402,000
Enviva LP	Enviva Pellets Amory	Mississippi	Hardwood and Softwood	150,000
Enviva LP	Enviva Pellets Ahoskie	North Carolina	Hardwood and Softwood	99,000
Equustock Wood Fibers, LLC	Equustock - Troy	Virginia	Hardwood and Softwood	36,000
Equustock Wood Fibers, LLC	Equustock - Raton	New Mexico	Hardwood and Softwood	50,000
Equustock Wood Fibers, LLC	Equustock - Nacogdoches	Texas	Hardwood and Softwood	36,000
Equustock Wood Fibers, LLC	Equustock - Jasper	Alabama	Hardwood and Softwood	40,000
Equustock Wood Fibers, LLC	Equustock - Clare	Michigan	Hardwood and Softwood	80,000
Equustock Wood Fibers, LLC	Equustock - Chester	Virginia	Hardwood and Softwood	5,000
Essex Pallet & Pellet	Essex Pallet & Pellet	New York	Hardwood and Softwood	36,000
Eureka Pellet Mills, Inc.	Eureka Pellet Mills	Montana	Softwood	Undisclosed
Eureka Pellet Mills, Inc.	Eureka Pellet Mills	Montana	Softwood	Undisclosed
Fiber By-Products Corp.	Fiber By-Products	MI	Hardwood	60,000
Fiber Energy Products AR, LLC	Fiber Energy Products AR, LLC	Arkansas	Hardwood	11,000
Fiber Recovery, Inc.	Fiber Recovery, Inc.	Wisconsin	Hardwood	12,000
Fram Renewable Fuels, LLC	Appling County Pellets, LLC	Georgia	Hardwood and Softwood	220,460
Frank Pellets	Frank Pellets	Oregon	Softwood	21,000
Geneva Wood Fuels, LLC	Geneva Wood Fuels	Maine	Hardwood	90,000
Georgia Biomass	Georgia Biomass	Georgia	Undisclosed	827,000
Great American Pellets	Great American Pellets	Pennsylvania	Hardwood	30,000
Great Lakes Renewable Energy, Inc.	Great Lakes Renewable Energy, Inc.	Wisconsin	Hardwood and Softwood	82,000
Green Circle Bio Energy, Inc.	Green Circle Bio Energy,	Florida	Hardwood and	560,000

	Inc.		Softwood	
Green Friendly Pellets, LLC	Green Friendly Pellets, LLC	Wisconsin	Hardwood	17,000
Greene Team Pellet Fuel Co.	Greene Team Pellet Fuel Co.	Pennsylvania	Hardwood	50,000
Greenwood Fuels	Greenwood Fuels	Wisconsin	Paper Waste	140,000
Hamer Pellet Fuel	Hamer Pellet Fuel Elkins	West Virginia	Hardwood	60,000
Hassell & Hughes Lumber Co.	Hassell & Hughes Lumber Co.	Tennessee	Hardwood	30,000
Hearthside Wood Pellets	Hearthside Wood Pellets	New York	Hardwood	600
Heartland Pellet	Heartland Pellet	South Dakota	Softwood	45,000
Henry County Hardwoods, Inc.	Henry County Hardwoods, Inc.	Tennessee	Hardwood	40,000
Horizon Biofuels, Inc.	Horizon Biofuels, Inc.	Nebraska	Hardwood and Softwood	12,000
Indeck Energy Services, Inc.	Indeck Energy Ladysmith Biofuel Center, LLC	Wisconsin	Hardwood	90,000
Inferno Wood Pellet	Inferno Wood Pellet Co.	Rhode Island	Hardwood and Softwood	Undisclosed
Instantheat Wood Pellets, Inc.	Instant Heat Wood Pellets, Inc.	New York	Hardwood	50,000
Jensen Lumber Co.	Jensen Lumber Co.	Idaho	Softwood	15,000
Kirtland Products, LLC	Kirtland Products, LLC	Michigan	Hardwood and Softwood	35,000
Koetter & Smith, Inc.	Koetter & Smith, Inc.	Indiana	Hardwood	Undisclosed
Lee Energy Solutions	Lee Energy Solutions	Alabama	Hardwood	110,000
Lignetics	Lignetics of West Virginia, Inc.	West Virginia	Hardwood	Undisclosed
Lignetics	Lignetics of Virgina, Inc.	Virginia	Softwood	Undisclosed
Lignetics	Lignetics of Idaho, Inc	Idaho	Hardwood	Undisclosed
Log Hard Premium Pellets, Inc.	Log Hard Premium Pellets, Inc.	Pennsylvania	Hardwood	25,000
Maine Woods Pellet Co.	Maine Woods Pellet Co.	Maine	Hardwood and Softwood	10,000
Mallard Creek, Inc.	Mallard Creek, Inc.	California	Softwood	30,000-60,000
Manke Lumber Co.	Manke Lumber Co.	Washington	Hardwood	38,000
Marth Peshtigo Pellet Co.	Marth Wood Shavings Supply	Wisconsin	Hardwood	31,000
Marth Peshtigo Pellet Co.	Marth Peshtigo Pellet Co.	Wisconsin	Hardwood	25,000
Michigan Timber	Michigan Timber	Michigan	Softwood	18,000
Michigan Wood Fuels	Michigan Wood Fuels	Michigan	Hardwood	48,000
Mt. Taylor Machine	Mt. Taylor Machine	New Mexico	Hardwood and Softwood	7,000
Nature’s Earth Pellet Energy, LLC	Nature’s Earth Pellets	Alabama	Hardwood and Softwood	100,000
Nature's Earth Pellet Energy, LLC	Nature’s Earth Pellets NC	North Carolina	Softwood	75,000
New England Wood Pellet, LLC	Schuyler Manufacturing Facility	New York	Hardwood and Softwood	84,000
New England Wood Pellet, LLC	Jaffrey Manufacturing Facility	New Hampshire	Hardwood and Softwood	84,000
New England Wood Pellet, LLC	Deposit Manufacturing Facility	New York	Hardwood and Softwood	84,000
North Idaho Energy Logs	North Idaho Energy Logs	Idaho	Softwood	60,000

Northeast Pellets, LLC	Northeast Pellets, LLC	Maine	Hardwood and Softwood	40,000
O'Malley Wood Pellets	O'Malley Wood Pellets	Virginia	Hardwood	85,000
Ochoco Lumber Co.	Malheur Pellet Mill	Oregon	Softwood	18,000
Olympus Pellets	Olympus Pellets - Omak	Washington	Softwood	40,000
Ozark Hardwood Products	Ozark Hardwood Products	Missouri	Hardwood	40,000
Pacific Pellet, LLC	Pacific Pellet, LLC	Oregon	Hardwood	40,000
Patterson Wood Products, Inc.	Patterson Wood Products, Inc.	Texas	Softwood	40,000
Pellet America Corp.	Pellet America Corp.	Wisconsin	Paper Wste	50,000
Pellheat, Inc.	Pellheat, Inc.	Pennsylvania	Hardwood	5,000
Penn Wood Products, Inc.	Penn Wood Products, Inc.	Pennsylvania	Hardwood	5,000
Potomac Supply Corp.	Potomac Supply Corp.	Virginia	Softwood	Undisclosed
Qb Corp.	Lemhi Valley Pellets	Idaho	Softwood	1,000
Rocky Canyon Pellet Co.	Rocky Canyon Pellet Co.	Idaho	Hardwood and Softwood	10,000
Rocky Mountain Pellet Co., Inc.	Rocky Mountain Pellet Co., Inc.	Colorado	Softwood	40,000-65,000
Roseburg Forest Products	Dillard Composite Specialties	Oregon	Softwood	40,000
Somerset Pellet Fuel	Somerset Pellet Fuel	Kentucky	Hardwood	Undisclosed
South & Jones Timber	South & Jones Timber	Wyoming	Softwood	7,000
Southern Indiana Hardwoods	Southern Indiana Hardwoods	Indiana	Hardwood	10,000
Southern Kentucky Pellet Mill, Inc.	Southern Kentucky Pellet Mill, Inc.	Kentucky	Hardwood	12,000
Superior Pellet Fuels, LLC	Superior Pellet Fuels, LLC	Alaska	Hardwood	12,000
Tri State Biofuels	Tri State Biofuels	Pennsylvania	Softwood	50,000
Turman Hardwood Pellets	Turman Hardwood Pellets	Virginia	Hardwood	25,000
Vermont Wood Pellet Co., LLC	Vermont Wood Pellet Co., LLC	Vermont	Softwood	14,000
Vulcan Wood Products	Vulcan Wood Products	Michigan	Hardwood and Softwood	9,000
West Oregon Wood Products, Inc.	West Oregon Wood Products, Inc.	Oregon	Softwood	50,000
West Oregon Wood Products, Inc.	West Oregon Wood Products, Inc.	Oregon	Softwood	30,000
Wood Pellet Coop	Wood Pellet Coop	Minnesota	Hardwood	Undisclosed
Wood Pellets C&C Smith Lumber	Wood Pellets C&C Smith Lumber	Pennsylvania	Hardwood	30,000
Woodgrain Millwork, Inc.	Woodgrain Millwork, Inc.	Oregon	Softwood	Undisclosed
Zilkha Biomass Fuels, LLC	Crockett Plant	Texas	Hardwood and Softwood	44,000
Total Plants: 114			**Total capacity in millions:**	**7,801.00**

Table A-2: Proposed Pellet Plants in the United States.

Company	Plant	State	Feedstock	Capacity (metric tons/year)
Beaver Wood Energy	Beaver Wood Energy	Vermont	Hardwood and Softwood	110,000
Enviva LP	Enviva Pellets Wiggins	Mississippi	Hardwood and Softwood	551,000
Enviva LP	Enviva Pellets Southampton	Virginia	Hardwood and Softwood	551,000
F.E. Wood & Sons - Natural Energy	F.E. Wood & Sons - Natural Energy	Maine	Hardwood and Softwood	343,920
First Georgia BioEnergy	First Georgia BioEnergy	Georgia	Softwood	374,785
Franklin Pellets	Franklin Pellets	Virginia	Hardwood and Softwood	500,000
German Pellets GmbH	German Pellets Texas	Texas	Hardwood and Softwood	551,155
Highland Biofuels, LLC	Highland Biofuels, LLC	Kentucky	Hardwood	100,000
Nex Gen Biomass	Nex Gen Biomass	Arkansas	Softwood	496,00
Riverside Pellets, LLC	Riverside Pellets, LLC	North Carolina	Hardwood and Softwood	50,000
SEGA Biofuels, LLC	SEGA Biofuels, LLC	Georgia	Softwood	100,000
Woodlands Resources	Woodlands Resources	Georgia	Hardwood and Softwood	165,300
Zilkha Biomass Fuels, LLC	Selma Plant	Alabama	Hardwood and Softwood	303,100
Total Plants: 13			**Total capacity in millions:**	**554,798.00**

Table A-3: Idle Pellet Plants in the United States.

Company	Plant	State	Feedstock	Capacity metric tons/yr
Fulghum Fibres, Inc.	Fulghum Fibres, Inc.	Georgia	Hardwood and Softwood	200,000
Varn Wood Products	Varn Wood Products	Georgia	Softwood	80,000
Westervelt Renewable Energy, LLC	Westervelt Renewable Energy	Alabama	Softwood	309,000
Total Plants: 3			**Total capacity in millions:**	**589.00**

Table A-4: Pellet Plants Operating in Canada.

Company	Plant	State	Feedstock	Capacity (metric tons/year)
Canadian Biofuel	Canadian Biofuel	Ontario	Hardwood and Softwood	190,000
Direct Pellet Industries, Inc.	Direct Pellet Industries	Ontario	Hardwood and Softwood	6,500
Energex, Inc.	Granules Combustibles Energex, Inc.	Quebec	Softwood	60,000
Foothills Forest Products, Inc.	Foothills Forest Products, Inc.	Alberta	Softwood	10,000
Gildale Farms	Gildale Farms	Ontario	Hardwood and Softwood	12,000
Granules LG	Granules LG, Inc.	Quebec	Hardwood and Softwood	85,000
Granules LG	Granules LG International	Quebec	Hardwood and Softwood	85,000
Groupe Savoie, Inc.	Groupe Savoie, Inc.	New Brunswick	Hardwood and Softwood	55,000
La Crete Sawmills, Ltd.	La Crete Sawmills, Ltd.	Alberta	Softwood	45,000
LacWood Industries	LacWood Industries	Ontario	Softwood	10,000
Lauzon Recycled Wood Energy, Inc.	Lauzon Recycled Wood Energy, Inc.	Quebec	Hardwood	58,000
Lauzon Recycled Wood Energy, Inc.	Lauzon Recycled Wood Energy, Inc.	Quebec	Hardwood	58,000
Pinnacle Pellet	Houston Pellet LP	British Columbia	Hardwood and Softwood	400,000
Pinnacle Pellet	Pinnacle Renewable Energy Group-Armstrong Division	British Columbia	Hardwood and Softwood	22,000
Pinnacle Pellet	Pinnacle Renewable Energy Group-Burns Lake Division	British Columbia	Hardwood and Softwood	60,000
Pinnacle Pellet	Pinnacle Renewable Energy Group-Meadowbank Division	British Columbia	Hardwood and Softwood	90,000
Pinnacle Pellet	Pinnacle Renewable Energy Group-Quesnel Division	British Columbia	Hardwood and Softwood	22,000
Pinnacle Pellet	Pinnacle Renewable Energy Group-Williams Lake Division	British Columbia	Hardwood and Softwood	200,000
Princeton Co-Generation Corp.	Princeton Co-Generation Corp.	British Columbia	Softwood	108,000
Shaw Resources	Shaw Resources	New Brunswick	Hardwood and Softwood	100,000
Shaw Resources	Shaw Resources	Nova Scotia	Hardwood and Softwood	50,000
SPB Solutions	SPB Bio Materials	Ontario	Ag	Undisclosed

T.P. Downey	T.P. Downey	New Brunswick	Hardwood and Softwood	Undisclosed
Trebio	Trebio	Quebec	Hardwood and Softwood	130,000
Vanderwell Contractors Ltd.	Vanderwell Contractors Ltd.	Alberta	Softwood	20,000
Viridis Energy, Inc.	Okanagan Pellet Co., Inc.	British Columbia	Hardwood and Softwood	110,000
Viridis Energy, Inc.	Scotia Atlantic Biomass Co., Inc.	Nova Scotia	Softwood	120,000
Total Plants: 27			**Total capacity in millions:**	**2,106.00**

Table A-5: Proposed Pellets Plants in Canada.

Company	Plant	State	Feedstock	Capacity (metric tons/year)
Dansons	Friendly Fuels Ltd.	Alberta	Softwood	27,216
Muskoka Timber Mills Ltd.	Muskoka Timber Mills Ltd.	Ontario	Hardwood and Softwood	1,000
New Forest Industries	New Forest Industries	Quebec	Hardwood and Softwood	125,000
Protocol Biomass Corp.	Protocol Biomass Corp.	Ontario	Hardwood	500,000
Wagner Ontario Forest Management Ltd.	Wagner Ontario Forest Management Ltd.	Ontario	Hardwood and Softwood	85,000
Wawasum Group	Wawasum Group	Ontario	Hardwood	67,000
Whitesand First Nation	Whitesand First Nation	Ontario	Hardwood and Softwood	80,000
Total Plants: 7			**Total capacity in millions:**	**885.00**

Table A-6: Pellet Plants Under Construction in Canada.

Company	Plant	State	Feedstock	Capacity (metric tons/year)
Atikokan Renewable Fuels, Inc.	Atikokan Renewable Fuels	Ontario	Hardwood	120,000
Canadian Northern Timber Group	Atlantic Fiber Resources	Quebec	Hardwood and Softwood	30,000
KD Quality Pellets	KD Quality Pellets	Ontario	Hardwood and Softwood	75,000
Viridis Energy, Inc.	Monte Lake Pellet Co., Inc.	British Columbia	Softwood	60,000
Total Plants: 4			**Total capacity in millions:**	**285.00**

Appendix B

Wood Pellet Production, Supply and Demand

Most North American pellet operations are relatively small in size compared to other wood fiber operations such as pulp and paper products, paper board plants or wood-fired power plants. This stems from a business model largely based on the use of wastes from sawmills and other wood processing plants. Proximity to such sources of fiber is important, because the relatively low bulk densities and high moisture contents of those wastes make hauling over long distances prohibitive. Normally, sawdust is incinerated if no pellet plants, pulp mills, or other suitable outlets are nearby.

In general, most sawmills and other woodworking plants process moderate amounts of wood, and thus generate proportionally moderate volumes of residues. Where the concentration of sawmills is high, as in some locations in interior British Columbia, this constraint eases, and plants are bigger. Additionally, several new mills have been built to process chipped green roundwood, so that they are not constrained by residue availability. These facilities tend to have capacities three to four times as large as most of the residue-reliant facilities. Low grade forest floor residues and other forest residues are also being used to increase access to wood materials for pellet manufacturing.

Within the U.S., the South accounted for the largest amount of pellet production (46 percent), followed by the Northeast (24 percent), the West (16 percent), and the Midwest (14 percent). In 2008, more than 80 percent of U.S. manufactured pellets were shipped to domestic destinations. Most of the remainder was exported to Europe from a few large plants geared toward exports.[33] The pellets shipped from the U.S. to Europe, however, are not used in residential installations but rather in power production, where pellets are used in industrial applications such as co-fire with coal for electricity production.[34] Additionally, most U.S. pellets are packaged in 40-pound sacks, indicating residential space heating use rather than bulk applications. This contrasts with Canada where over 80 percent of Canadian pellet production was shipped in bulk. The large flux of wood pellets exported from Canada (particularly British Columbia) to Europe is mainly due to the relatively low cost of feedstock in Canada and the high selling price in Europe.[35]

[33] Spelter, H., and D. Toth. "North America's Wood Pellet Sector." Forest Products Laboratory - USDA Forest Service. Last modified 2009. Accessed January 6, 2013. http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp656.pdf.

[34] Sikemma, R; Juninger, M.; Hiegl, W.; Hansen, M; Faaij, A. 2011. “The European Wood Pellet Market: Current Status and Prospects for 2020”, BioFPR, Society of Chemical Industry and John Wiley & Sons Ltd.

[35] PaperAge. "Paper Industry News - Wood Pellet Market Grows, Raw Materials in Demand." PaperAge Magazine. Last modified February 26, 2009. Accessed January 6, 2013. http://www.paperage.com/2009news/02_26_2009wood_pellets.html.

More than 10 million tons of wood pellets were manufactured worldwide in 2008, and of that, 25 percent was exported from the country in which they were produced.[36] Exporting usually requires bulk shipments of at least 10,000 metric tons, which favors larger firms.[37] For example, the largest wood pellet plants in the US are located in the Southeast. They are owned by Green Cycle Bio Energy Inc. and Dixie Pellets and can produce 560,000 and 500,000 tons of pellets per year, respectively. These companies plan to ship most, if not all, of their supply to European markets.[38]

In the Northeast, New England Wood Pellet, LLC has three facilities that produce approximately 252,000 tons of wood pellets per year. The majority of these pellets are bagged and sold to consumers in the Northeast.[39] Although New England Wood Pellet is one of the larger biomass companies in the Northeast, there are many other companies in the region producing in the 30,000 to 100,000 ton per year range for the domestic market.

Location plays a large role in domestic wood pellet supply and pricing. Sales from larger wood pellet manufacturers that are national pellet brands, such as Energex and Lignitics, can be sold anywhere for a relatively low price. In contrast, wood pellets from smaller operations, such as a company's sister sawmill business, become unreasonably expensive outside the 50 mile radius from the plant.[40]

Wood residues have been a significant source of feedstock for wood pellet manufacturing, however, as the market changes this may change. Wood residue fiber comes from two major sources; 1) primary woodworking plants, such as sawmills and plywood mills, and 2) secondary woodworking plants, such as furniture and millwork factories. On average, sawmills and plywood plants create 0.25 and 0.025 tons of sawdust, shavings and sander dust per thousand board or square feet of production, respectively. Considerably more volumes of other chippable residues are also generated, but they are generally used by pulp mills for paper. Other secondary wood manufacturing facilities, such as furniture and mill work factories, supply 14 percent of fiber, reflecting the large share of wood pellet plants located in predominantly hardwood growing regions where furniture activity is greatest. Green material sourced from pulpwood or logging residues comprises 16 percent of the fiber supply, and only about 1 percent of fiber

[36] Kotrba, R. "WRQ releases wood pellet stats." Biomass Magazine. Last modified March 5, 2009. Accessed January 6, 2013. http://www.biomassmagazine.com/article.jsp?article_id=2482.

[37] Spelter, H., and D. Toth. "North America's Wood Pellet Sector." Forest Products Laboratory - USDA Forest Service. Last modified 2009. Accessed January 6, 2013. http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp656.pdf.

[38] Marinescu, M., and T. Bush. "Wood to Energy: Use of the Forest Biomass for Wood." University of Florida IFAS Extension. Last modified February, 2009. Accessed January 6, 2013. http://edis.ifas.ufl.edu/pdffiles/FR/FR26900.pdf.

[39] Jesmer, G. "Creating Bioheat: A Look Inside New England Wood Pellet | Renewable Energy News Article." RenewableEnergyWorld.com. Last modified April 30, 2008. Accessed January 6, 2013. http://www.renewableenergyworld.com/rea/news/article/2008/04/creating-bioheat-a-look-inside-new-england-wood-pellet-52330.

[40] Biomass Energy Resource Center. "Wood Pellet Heating Guidebook." Massachusetts Division of Energy Resources. Last modified June, 2007. Accessed January 6, 2013. http://www.mass.gov/eea/docs/doer/publications/doer-pellet-guidebook.pdf.

supply was from urban or salvaged wood. Use of agricultural residue is negligible, but interest in this material for pelletizing is increasing.[41]

Fiber demand is derived from pellet demand, which in turn can be estimated from the inventory of installed wood pellet stoves. These devices consist mostly of fireplace inserts and freestanding stoves as opposed to furnaces tied into central heating systems. As such, they primarily heat a localized area rather than distribute heat evenly throughout a structure. Consequently, wood pellet stoves are often used as auxiliary heating devices, allowing for the main fossil fuel furnace or electrical heater to be turned down or off.

Heating an average home for a winter season exclusively with wood pellets in NYS requires about 4 tons of pellets. In colder regions, the estimate could run as high as 7 tons. For the purposes of demand estimation, an average consumption per unit of 2 tons is more realistic. This is because of the above-noted auxiliary nature of most wood pellet stoves, as well as their use in milder climates, both of which decrease the average. As use of wood pellet appliances increase, however, the use per household will likely increase.

Wood pellet use for home heating is relatively new, and over the 10 years since shipping data have been compiled, 735,000 pellet stoves have been shipped. Estimates of underlying demand for wood pellets are obtained by multiplying the accumulating stock of stoves over the years by the 2 tons per stove factor. The close correspondence between estimated demand and capacity through 2007 validates the 2 ton per stove assumption. A gap opened up, however, between production and derived demand in 2008. This reflects the start-up of a handful of larger plants focused primarily on the bulk European export market. It may also indicate an expanding market into institutional heating and power generating where usage is not dependent on pellet stoves. The surplus of supply over consumption exaggerates the availability of residues because many mills use the residues themselves for process heat or co-generation activities. The supply-consumption gap narrowed through the years 2007 through 2009, a fact that illustrates the drawback of the wood pellet industry’s reliance on residue fibers. The residue-generating industries are cyclical, whereas wood pellet demand for heat energy is more static. Mismatches can develop between residue availability on the one hand and fiber needs for pellet making on the other. In 2008, this resulted in shortfalls that forced some plants to operate below their capability and at least one to cease operations because of the closure of a supplier. Others extended their procurement radii or installed equipment to process roundwood. Despite these measures, wood pellet shortages were reported, and some users hoarded pellets.

Future growth of wood pellet manufacturing will inevitably have to spread to alternative fibers, chiefly roundwood, as that resource is available in concentrated volume in compact areas. Due to widespread beetle epidemics in the western U.S. and British Columbia that render timber unsuitable for higher value

[41] Kirk, R. E., D. F. Othmer, J. I. Kroschwitz, and M. Howe-Grant. 1998. *Encyclopedia of Chemical Technology. Volume 25, Vitamins to Zone Refining,* 4th ed. New York: J. Wiley & Sons.

uses such as lumber and plywood, this resource is increasingly becoming available at advantageous rates. Two plants in Colorado have recently been built to take advantage of this resource opportunity.

Another large source of pellet demand is as a fuel in power generation overseas where co-firing wood pellets help countries meet carbon dioxide reduction goals. This poses both an opportunity and risk for wood pellet manufacturing. In the U.S., 80 electricity generating facilities in 16 states use biomass as fuel, however in the U.S., chipped biomass fuels are more commonly used that pelletized fuels. However, unless cheap biomass in the form of waste by-products from another activity is available nearby, power plants fueled entirely by wood have difficulty competing with coal- and gas-fired plants without tax subsidies or mandates. The drive to reduce carbon emissions, however, has created opportunities for biomass in general and wood in particular. Demonstrations and trials have shown that an effective, minimally disruptive way to use biomass in power plants is as an amendment to coal. Up to about 15 percent of the total energy input can be substituted without incurring major equipment or modification costs. Woody biomass is most appropriate because of availability, costs, and operating parameters. Compared with agricultural biomass, the alkali and chlorine contents of bark-free wood are low, which minimizes slagging, fouling and corrosion in boilers.[42]

In power plants, the size of the biomass is critical. Biomass that does not meet the specific requirements is likely to cause flow problems in the fuel-handling equipment or result in incomplete burn of the material. Pulverized coal boilers, typical of larger power plants, require the smallest sized particles and offer the greatest potential for wood pellets. Dry palletized wood works most seamlessly because it pulverizes easily in contrast with wood in its raw fibrous, non-friable state. Such use of wood pellets has become widespread in Europe but is only beginning to emerge in North America. It is likely to accelerate in the future as governments establish renewable fuel portfolio standards for the use of renewable fuels in power generation.

In contrast to co-firing pellets with pulverized coal, biomass in larger sized pieces can be fired in smaller, stoker-type boilers. In this application, chipped or chunked wood can be used, which costs less than pellets. This is a potential threat to wood pellet-making because of the possibility that these types of users could bid away and divert fibers, including residues, from pellet manufacturers, making fiber more scarce and expensive. The proposed conversion of a 312-megawatt power plant in Ohio to biofuels illustrates the potential impact of this shift. This particular facility would require 725,000 tons of biomass per year, and,

[42] Melin, Staffin. 2008.Bark as Feedstock for Production of Wood Pellets. Wood Pellet Association of Canada. December 27.

in this instance, wood briquettes made from dedicated fast-growing plantation trees are being considered to supply the plant.[43]

1.1 Fuel Types

Wood pellets are generally made from compacted sawdust from hardwood and softwood, usually produced as a by-product of sawmilling, planer shaving, and other wood transformation activities. Wood pellets are extremely dense and can be produced with a low humidity content (below 10 percent), which allows them to be burned with a very high combustion efficiency (more than 90 percent). Pellets can be produced from nearly any wood variety.[44] Although not limited to these alternative sources, biomass pellets can and have also been manufactured using the following feedstocks: switchgrass, grain, corn cobs, corn stalks, paper, distiller grain. The use of these alternatives will be influenced by the feedstocks available in the region.

1.2 Wood Pellet Manufacturing Process

In the U.S., wood pellets are typically made of sawdust or waste materials from wood product processing such as sawmills, flooring and furniture. The wood must be debarked prior to passing through the sawmill. Sawdust from hardwoods can be mixed in with softwood, but successful production of hardwood pellets without binders is more difficult. The use of various binders has been a question raised in U.S. pellet production. In Europe, strict standards are in place for what can be used to bind pellets. In the U.S., no such standard exists and in current voluntary industry standard does not define standards for types of materials that can be used as binding agents.

The wood pellet production steps are:

- Reception and intermediate storage of sawdust.
- Drying and possibly intermediate storage again.
- Screening of foreign materials such as stones and metal.
- Hammer milling and possibly intermediate storage.
- Pressing of the pellets.
- Cooling of the pellets.
- Screening of fines.
- Storage.
- Bagging.
- Loading out for delivery.

[43] Spelter, H., and D. Toth. "North America's Wood Pellet Sector." Forest Products Laboratory - USDA Forest Service. Last modified 2009. Accessed January 6, 2013. http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp656.pdf.
[44] Pellet Fuels Institute. "What are Pellets?." Pellet Fuels Institute. Accessed January 6, 2013. http://pelletheat.org/pellets/what-are-pellets/.

At reception, arriving sawdust is typically weighed and samples taken to determine the moisture content. For storage, it is preferable to separate wet and dry sawdust. Hardwood sawdust may be mixed into the material at this point before it is sent through the hammer mill process. Alternatively, where production of wood pellets is directly done from roundwood, additional debarking and chipping steps are required.

When possible, dry sawdust and shavings (less than 15 percent moisture content) are used to avoid the drying step. If the sawdust is wetter, a drying process is needed before wood pellets can be pressed into their uniform shape, as more energy is required to reduce the particle size of wet sawdust than when dry. Wet sawdust may also clog or smear equipment screens during processing.

Drying is accomplished through a drum dryer that rotates, a flash dryer that works at very high temperatures, or a flatbed dryer that works at comparatively low temperatures. The flash dryer option is better suited for fine material like sawdust. A flatbed dryer is preferable for drying coarser material such as wood chips, which need a lower temperature for proper drying. Wood chips also dry at a slower rate than sawdust and require a much larger drying capacity.

Before the sawdust is passed to the hammer mill for further processing, it is screened for stones, pieces of metal, plastic and other foreign materials. Foreign materials in the sawdust can damage the press or cause sparks in the hammer mill, raising the risk of a dust explosion.

The hammer mill transforms sawdust into an even-sized pellet while also pulverizing wood chips, dead knots and other wood bits before passing through the presses. Because wood chips are many times larger in size than sawdust, more than one pass through the hammer mill may be needed to obtain sufficiently fine material for the pressing process.

During the pressing process, the sawdust is warmed to 120-130 ºC using dry steam to make the naturally-occurring lignin in the wood more pliable, so that the material will stick together. The sawdust is extruded under high pressure through a matrix where the wood pellets are shaped and then cut.[45] Wood pellet forms are typically cylindrical with a diameter ranging from 0.230 to 0.285 inches and a length up to 1.5 inches.[46]

[45] Kofman, P. "The production of wood pellets." COFORD. Last modified 2007. Accessed January 6, 2013. http://www.coford.ie/media/coford/content/publications/projectreports/cofordconnects/ccnpellet_production.pdf.

[46] Pellet Fuel Institute. "PFI Standard Specification for Residential/Commercial Densified Fuel Proposed Revisions." Pellet Fuels Institute. Last modified June 23, 2010. Accessed January 6, 2013. http://pelletheat.org/wp-content/uploads/2010/08/Draft-PFI-StandardSpecification-for-Residential-Commercial-Densified-Fuel-Revised-June-23-2010.pdf

Once the wood pellets have been pressed, they are put through a cooling process after which they are transferred to a storage facility. After screening for fines, the pellets are bagged for distribution to consumers unless destined for bulk sale.

1.3 Wood Pellet Combustion Appliances

Wood pellet combustion appliances are primarily divided into pellet stoves for residential use, and pellet boilers for larger commercial and institutional use. Pellet furnaces are also utilized for residential heating, but on a much smaller scale. The focus of this discussion will be on the two most widely used systems for wood pellet combustion; stoves and boilers.

A wood pellet stove normally consists of:

- A hopper.
- An auger system.
- Two blower fans (combustion and convection).
- A firebox (burn-pot and ash collection system), sometimes lined with ceramic fiber panels.
- Various safety features, such as a vacuum switch and heat sensors.
- A main control box/board.

Pellet stoves can be stand-alone units or applied as inserts into existing fireplaces. They require electricity and can be plugged into a normal wall outlet. Most pellet stoves are consistent heat sources that consume fuel fed evenly from a refillable hopper with a motorized auger system. A combustion fan blows air into the burn-pot as well as pushes the exhaust gases through the chimney system. A convection fan circulates room air through heat exchangers and directs the heat into the living space. As safeguards, all pellet stoves are equipped with heat sensors, and sometimes vacuum switches, enabling the controller to shut down if an unsafe condition is detected.

A wood pellet boiler is sized for larger commercial building heating requirements than required with pellet stoves for residential heating. The use of pellet boilers has been increasing in recent years, especially in the northeastern US. The concept of a wood pellet stove and boiler are the same, but in addition to being sized for larger commercial heating loads, pellet boilers differ from pellet stoves in the degree of automation and fuel storage, as well as fuel handling.[47]

[47] Biomass Energy Resource Center. "Wood Pellet Heating Guidebook." Massachusetts Division of Energy Resources. Last modified June, 2007. Accessed January 6, 2013. http://www.mass.gov/eea/docs/doer/publications/doer-pellet-guidebook.pdf.

1.4 Pellet Pricing

Fuel costs for wood pellets vary. The fuel can be purchased in three primary ways: 40 pound bags, by the ton, or in limited areas via bulk delivery. Prices range from $219 to $280 per ton ($4.60 to $5.60 per bag) and averages $250 per ton ($5.20 per bag).[48] The costs of wood pellets can be compared to other home heating fuels using the Energy Information Administration's fuel cost calculator.[49] Wood pellets are estimated to cost $19.43 per million British thermal unit (MMBtu) compared to fuel oil #2 at $36.33/MMBtu; electricity $35.03/MMBtu; natural gas $12.96/MMBtu; propane $39.94/MMBtu; cordwood $12.63/MMBtu; coal $10.67/MMBtu; corn (kernels) $18.32/MMBtu; and kerosene $31.75/MMBtu. Currently, natural gas offers the lowest heating costs, equipment is readily available, and use is easy, however, in the Northeast access may not be available but where it is, natural gas is likely to be a preferred option to wood pellet so long as prices remain low. [50]

[48] Cocchi, M. "Global Wood Pellet Industry Market and Trade Study." IEA Bioenergy. Last modified December, 2011. Accessed January 6, 2013. http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final.pdf.

[49] US Energy Information Administration. "Heating Fuel Comparison Calculator." US Energy Information Administration (EIA). Last modified January, 2013. Accessed January 6, 2013. http://www.eia.doe.gov/neic/experts/heatcalc.xls.

[50] Cocchi, M. "Global Wood Pellet Industry Market and Trade Study." IEA Bioenergy. Last modified December, 2011. Accessed January 6, 2013. http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final.pdf.

Appendix C

Pellet Standard Information

The following appendix provides information on European and U.S. pellet fuel standards. Sample preparation method is a key variable in the elemental analysis of wood pellets. In Europe, manufacturers are given a choice of conducting chemical analysis via digestion of the wood or on the ash of the pellet, while in the U.S. the chemical analysis is typically conducted on the ash only. Analysis on ash is likely to be more replicable and precise due to concentration of the elements. Questions have also been raised about the ability to properly digest the wood matrix for a complete analysis. This issue is discussed in further detail in the Sample Analysis discussion.

Europe

In 2010, the European Union created three quality classes for wood pellets (Table C-1) that replaced existing country-specific regulations [CEN/TC 335 Biomass Standards]. The European Union approach also includes a compliance assurance mechanism. Under this mechanism, an independent auditor annually evaluates the pellet plant and its quality management, while there is some limited pellet analysis throughout the year in lieu of testing every delivered batch of pellets.

Table C-1: Overview of the European Union Pellet Quality Classes[51]

A1	A2	B
1.1.3 Stem wood 1.2.1 Chemically untreated residues from the wood processing industry	1.1.1 Whole trees without roots 1.1.3 Stem wood 1.1.4 Logging residues 1.2.1.5 Bark 1.2.1 Chemically untreated by-products and residues from the wood processing industry	1.1 Forest, plantation and other virgin wood 1.2.1 Chemically untreated, by-products and residues from the wood processing industry 1.3.1 Chemically untreated, used wood

The relevant wood pellet class for residential end users is A1 under the European Union approach. It contains the most stringent requirements overall. A1 wood pellets must have an ash content of under 0.5 percent when using wood from conifers and under 0.7 percent when using other types of wood. Apparent density is specified rather than bulk density. Apparent density better reflects the quantity of wood pellets conveyed into a pellet stove's combustion chamber if the rotation speed of the automatic stove feeder is constant. European residential applications use A1 graded pellets exclusively.[52] The primary feedstock for the A1 wood pellets comes from saw mill byproducts.

The European A2 and B1 wood pellet classes apply primarily to industrial applications, such as pellets burned at power plants or other large installations. Class A2 covers a wider spectrum of raw materials having an ash content up to 1 percent. The industrial standard Class B allows for even higher ash content and the expanded use of other raw materials, such as bark.

[51] European Committee for Standardization. CEN 14961-2: Solid biofuels - Fuel specifications and classes Part 2: Wood pellets for non-industrial use, 2011.

[52] BioEnergy 2020 presentation materials provided to NESCAUM

Table C- 2: Physical Fuel Specifications for European Pellets[51]

Property	Unit	A1	A2	B	Analysis method
Diameter	mm	6 (±1) 8 (±1)	6 (±1) 8 (±1)	6 (±1) 8 (±1)	EN 16127
Length (L)	mm	≤ 402	≤ 402	≤ 402	EN 16127
Moisture (M)	as received, weight% wet basis	≤ 10	≤ 10	≤ 10	EN 14774-1, EN 14774-2
Ash (A)	dw%	≤ 0.7	≤1.5	≤ 3.0	EN 14775
Mechanical durability (DU)	dw%	≥ 97.5	≥ 97.5	≥ 96.5	EN 15210-1
Fines (F) (<3.15 mm)	dw%	≤ 1.0	≤ 1.0	≤ 1.0	EN 15210-1
Additives	dw%	<2 m-%; type and amount to be stated			
Net calorific value (Q)	MJ/kg or kWh/kg	≤ 16.5 or Q4.6,4.6 ≤ Q ≤ 5.3	Q16.3, 16.3 ≤ Q ≤ 19 or Q4.5,4.5 ≤ Q ≤ 5.3	Q16.0, 16.0 ≤ Q ≤ 19 or Q4.4,4.4 ≤ Q ≤ 5.3	EN 14918
Bulk density	kg/m³	≥ 600	≥ 600	≥ 600	EN 15103

Table C- 3: Elemental Fuel Specifications for European Pellets [51]

Property	Unit	A1	A2	B	Analysis method
Nitrogen (N)	% dw	≤ 0.3	≤ 0.5	≤ 1.0	EN 15104
Sulfur (S)	% dw	≤ 0.03	≤ 0.03	≤ 0.04	EN 15289
Chlorine (Cl)	% dw	≤ 0.02	≤ 0.02	≤ 0.03	EN 15289
Arsenic (As)	mg/kg dw	≤1	≤1	≤1	EN 15297
Cadmium (Cd)	mg/kg dw	≤0.5	≤0.5	≤0.5	EN 15297
Chromium (Cr)	mg/kg dw	≤10	≤10	≤10	EN 15297
Copper (Cu)	mg/kg dw	≤10	≤10	≤10	EN 15297
Lead (Pb)	mg/kg dw	≤10	≤10	≤10	EN 15297
Mercury (Hg)	mg/kg dw	≤0.1	≤0.1	≤0.1	EN 15297
Nickel (Ni)	mg/kg dw	≤10	≤10	≤10	EN 15297
Zinc (Zn)	mg/kg dw	≤100	≤100	≤100	EN 15297
Ash melting point	°C	characteristic temperatures should be stated (voluntary)			EN 15370

The European Union standards are more stringent than those of the US. The standards prohibit pellets containing any recycled wood or outside contaminants. Recycled materials such as particle board, treated or painted wood, melamine resin-coated panels and the like are considered particularly unsuitable for use in wood pellets because of noxious air emissions and uncontrollable variations in the burning characteristics of the pellets.

United States

In the U.S., PFI has created a series of voluntary standards for wood pellet production. These voluntary standards are primarily for labeling purposes and quality control. Although the standards are voluntary, many manufacturers comply with them, as warranties on US-manufactured or imported combustion equipment may not cover damage of equipment by non-conforming pellets.[53]

The quality grades that the PFI has designated are mostly based on ash content (the amount of ash left behind after fuel burning) and are as follows: Premium (less than 1.0 percent ash), Standard (less than 2.0 percent ash), and Utility (less than 6.0 percent ash).[54] The PFI has designated 10 labs throughout the US and Canada to test wood pellets for compliance with its standards.[55]

Table C-4: PFI Fuel Grade Requirements.

	Residential/Commercial Densified Fuel Standards See Notes 1 - 3		
Fuel Property	PFI Premium	PFI Standard	PFI Utility
Normative Information - Mandatory			
Bulk Density, lb./cubic foot	40.0 - 46.0	38.0 - 46.0	38.0 - 46.0
Diameter, inches	0.230 - 0.285	0.230 - 0.285	0.230 - 0.285
Diameter, mm	5.84 - 7.25	5.84 - 7.25	5.84 - 7.25
Pellet Durability Index	≥ 96.5	≥ 95.0	≥ 95.0
Fines, % (at the mill gate)	≤ 0.50	≤ 1.0	≤ 1.0
Inorganic Ash, %	≤ 1.0	≤ 2.0	≤ 6.0
Length, % greater than 1.50 inches	≤ 1.0	≤ 1.0	≤ 1.0
Moisture, %	≤ 8.0	≤ 10.0	≤ 10.0
Chloride, ppm	≤ 300	≤ 300	≤ 300
Heating Value	NA	NA	NA
Informative Only - Not Mandatory			
Ash Fusion	NA	NA	NA

Source: http://pelletheat.org/wp-content/uploads/2011/11/PFI-Standard-Specification-November-2011.pdf

[53] Pellet Fuels Institute. "PFI Standards Program." Pellet Fuels Institute. Accessed January 6, 2013. http://pelletheat.org/pfi-standards/pfi-standards-program/.

[54] Pellet Fuels Institute. "PFI Standard Specification for Residential/Commercial Densified Fuel." Pellet Fuels Institute. Last modified June 18, 2008. Accessed January 6, 2013. http://pelletheat.org/pdfs/StandardSpecificationWithCopyright.pdf.

[55] Pellet Fuels Institute. "Pellet Fuels Institute: Homepage." Pellet Fuels Institute. Last modified 2011. Accessed January 6, 2013. http:// www.pelletheat.org/3/industry/index.html.

Third-party testing and inspection are the basis for assuring compliance with the PFI program requirements. The program prohibits the use of chemically treated materials, but does not include testing for elements that would indicate the use of non-compliant materials. The program also allows the use of up to 2 percent of additives whose compositions are not explicitly defined. Manufacturers meeting the PFI program requirements display the PFI quality label on the front lower third of their product bags.

Appendix D

Literature Review

A review of available literature on metals in woody biomass ash was conducted. We identified 50 potential publications using a wide range of key-words on scholar.google.com; abstracts were then reviewed for relevancy. Six publications were candidates for additional review. Of these six, we were only able to obtain three in full text document form. Only one of these had elemental data on ash analysis. These results are summarized below for key metals of interest, and are from Table 2 in Reimann, C.; Ottesen. R. T.; Andersson, M.; Arnoldussen, A.; Kollen, F.; Englmaier, P.; Sci. Total Environ. (2008), 393, 191-197, http://dx.doi.org/10.1016/j.scitotenv.2008.01.015.

Table D-1. Median Concentrations in birch and spruce wood ashes (mg/kg)

Metal	Birch Median	Spruce Median	Birch/Spruce Ratio
Cu	473	594	.8
As	10	12	.8
Hg	0.6	0.6	1.0
Cr	306	268	1.1
Ni	37	28	1.3
Cd	57	31	1.8
S	58,800	26,100	2.3
Zn	14,600	5060	2.9
Co	34	8	4.3
Pb	516	67.5	7.6

Other potentially relevant literature where the full publication was not available is listed below:

http://dx.doi.org/10.1016/j.atmosenv.2011.02.072 "Physicochemical characterization of fine particles from small-scale wood combustion" (Lamberg) gives elements from pellet and Birch log wood (not ash) analysis but with no detail of analytical procedures.

http://dx.doi.org/10.1016/S0961-9534(96)00051-7 "Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions" (Obernberger) may have useful ash metal data.

http://dx.doi.org/10.1016/j.biombioe.2006.06.011 "Chemical properties of solid biofuels—significance and impact" (Obernberger) is large scale combustion.

http://dx.doi.org/10.1016/j.biombioe.2011.05.027 Particle emissions from pellets stoves and modern and old-type wood stoves (Bäfver); doesn't mention heavy metals in abstract

http://dx.doi.org/10.1016/j.biombioe.2006.06.007 Determination of major and minor ash forming elements in solid biofuels (Baernthalera); analysis is on wood, not ash.

Other literature considered during this review:

http://dx.doi.org/10.1021/es981277q

http://dx.doi.org/10.1016/j.biombioe.2003.08.019

http://dx.doi.org/10.1016/j.scitotenv.2008.01.019

http://www.tandfonline.com/doi/abs/10.1080/02786820802716743

http://dx.doi.org/10.1016/j.biombioe.2008.04.003

http://dx.doi.org/10.1016/S0378-3820(97)00059-3

http://pubs.acs.org/doi/abs/10.1021/ef060286e

http://dx.doi.org/10.1016/j.pecs.2003.10.004

http://dx.doi.org/10.1016/S0304-3894(01)00311-9

http://dx.doi.org/10.1016/j.biombioe.2003.08.016

http://pubs.acs.org/doi/abs/10.1021/es071279n

http://dx.doi.org/10.1016/j.atmosenv.2010.11.053

http://pubs.acs.org/doi/abs/10.1021/es9909632

http://dx.doi.org/10.1016/j.biombioe.2008.12.003

http://dx.doi.org/10.1016/j.atmosenv.2007.06.018

http://dx.doi.org/10.1016/j.fuel.2006.07.001

http://pubs.acs.org/doi/abs/10.1021/es001466k

http://pubs.acs.org/doi/abs/10.1021/es9909632

http://pubs.acs.org/doi/abs/10.1021/es0108988

http://pubs.acs.org/doi/abs/10.1021/es00104a003

http://thesis.library.caltech.edu/6123/

http://online.liebertpub.com/doi/abs/10.1089/ees.2004.21.705

http://dx.doi.org/10.1016/j.atmosenv.2008.09.006

http://dx.doi.org/10.1016/j.atmosres.2011.04.015

http://dx.doi.org/10.1029/2001JD000661

http://www.sciencedirect.com/science/article/pii/S1352231010010241

http://dx.doi.org/10.1016/j.atmosenv.2008.09.013

http://dx.doi.org/10.1016/j.atmosenv.2004.04.020

http://dx.doi.org/10.1016/j.atmosenv.2005.01.016

http://dx.doi.org/10.1016/j.scitotenv.2004.09.043

http://dx.doi.org/10.1016/j.atmosenv.2007.09.028

http://dx.doi.org/10.1016/j.atmosenv.2009.07.022

http://dx.doi.org/10.1016/j.atmosenv.2008.07.019

http://dx.doi.org/10.1016/S0961-9534(03)00036-9

http://dx.doi.org/10.1016/j.biombioe.2003.08.018

http://dx.doi.org/10.1016/j.fuproc.2011.08.020

http://www.springerlink.com/content/x24u20700552231v/

http://www.tandfonline.com/doi/abs/10.1080/00102200590917257

http://www.tandfonline.com/doi/abs/10.1080/00908310600712406

http://www.tandfonline.com/doi/abs/10.1080/02772248.2011.562898

Additionally, we attempted to identify other sources of data for elemental analysis. We reviewed data in the International Energy Agency’s (IEA) biomass database (available at http://www.ieabcc.nl/database/biobank.html), the BIOBI database (available at www.vt.tuwien.ac.at/biobib/) developed by the University of Vienna, and the Phyllis Database [Netherlands Energy Research Foundation (ECN)] (available at http://www.ecn.nl/phyllis). We reviewed the data in these databases and concluded that the limited available data in these sources could not be meaningfully compared to our results.

Appendix E

Selected Pellet Metal Diagnostic Screening Plots for all Samples.

List of sample IDs removed to create the distribution of "uncontaminated" samples for use in generating benchmark value distributions:

5, 22, 23, 25, 30, 31, 32, 33, 37, 42, 43, 44, 45, 50, 51, 53, 54, 59, 60, 61, 63, 66, 68, 70, 71, 72, 75, 78, 80, 84, 94, 95, 96, 97, 98, 102, 105, 114, 115, 116, 117, 120, 122, 123, 125, 126, 128, 129, 130

Figure Error! No text of specified style in document.**-1. Selected pellet metal diagnostic screening plots for all samples.**

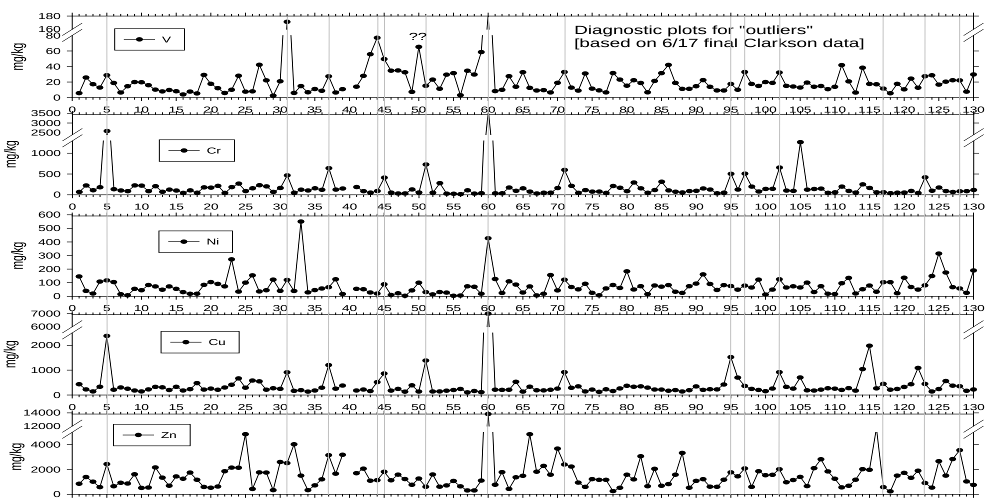
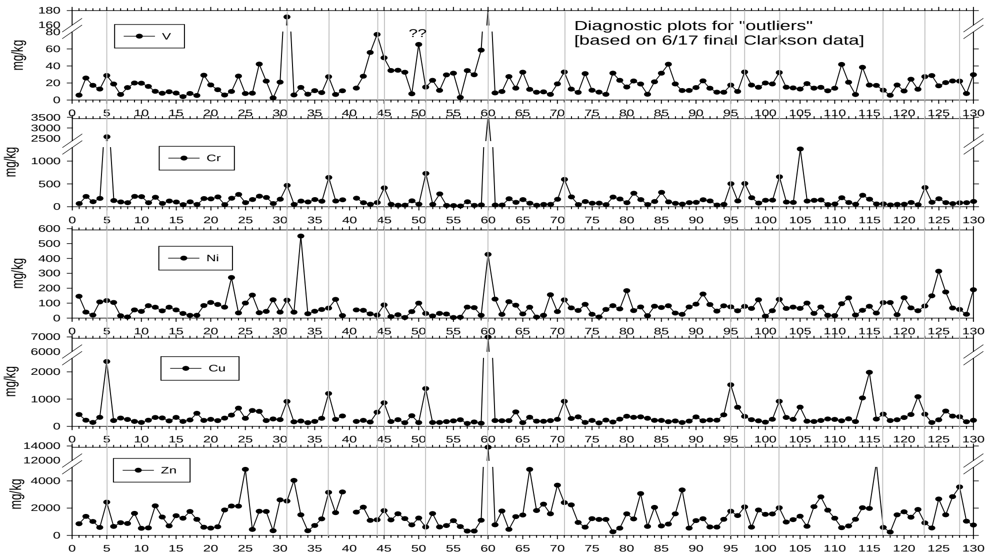


Figure Error! No text of specified style in document.**-2. Selected pellet metal diagnostic screening plots for all samples**



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17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.ny.gov
nyserda.ny.gov

Elemental Analysis of Wood Fuels

Final Report
June 2013

State of New York
Andrew M. Cuomo, Governor

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Richard L. Kauffman, Chairman | Francis J. Murray, Jr., President and CEO