Factors influencing particulate emissions from NES compliant woodburners in Nelson, Rotorua and Taumarunui 2007

Prepared for Ministry of Science & Innovation

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Executive summary

This report evaluates factors influencing variability in "real life" particulate emissions from National Environmental Standard (NES) compliant wood burners in Nelson, Rotorua and Taumaranui.

The key variables impacting on particulate emissions were found to be wood moisture, flue temperature, and oxygen. These explained 67% of the variability in households for which data for all these variables were available. Of these, wood moisture was the most significant accounting for 43% of the variability in particulate emissions. Oxygen data were not available for a number of runs including the high emission households thus the assessed variability considers only 51 of the 90 runs. When oxygen was excluded from the analysis, the key variables were wood moisture and burn duration (minutes). With this larger dataset, less of the variability in emissions was explained by the input variables (50% compared with 67% in the larger dataset) and only 41% was explained by wood moisture.

An evaluation was made of the amount of variability explained by input variables for the oxygen deficient dataset versus the dataset which included oxygen measurements. This is particularly relevant as the emission estimates from the oxygen data deficient dataset contain a higher degree of uncertainty as they were made based on average oxygen content. In the oxygen complete dataset the amount of variability that can be explained by the model input variables was 68% compared with 50% in the oxygen deficient dataset. Based on this observation it is recommended that future particulate emissions data are not calculated based on average (assumed) oxygen data.

The average amount of wood used per day by households in the study was 27 kilograms. This is comparable with fuel use data estimated by households in emission inventory surveys carried out in many urban areas of New Zealand of around 20-25 kilograms (e.g., Wilton, 2006).

The majority (72%) of households in the survey did not appear to increase their fuel consumption when the daily temperature decreased. Four households in Nelson and two households in Rotorua showed a good correlation between outdoor temperature and fuel consumption, with the latter increasing when temperatures decreased.

No clear relationship between "real life" emissions and laboratory test results was observed. This is not surprising given the high proportion of variability in the results found to occur as a result of operational variables such as wood moisture content.

Recommendations from this report include further testing of NES authorised wood burners to enhance and compliment the limited database collected in this project, and investigation of the factors influencing variability in other burner types such as coal burners and assessing the benefits of increased uptake of wood moisture programmes by Regional Councils.

1   Introduction

In New Zealand, the National Environmental Standard (NES) for ambient concentrations of particulate matter less than 10 microns in diameter (PM_{10}) is 50 µg/m^3 when averaged over 24 hours. This standard is regularly exceeded in many of New Zealand's urban areas during the winter months.

Emission inventories have been compiled in many of these urban areas and show that domestic home heating is the major source of particulate air pollution throughout New Zealand (e.g. Wilton 2003, Scott & Gunatilaka 2004, Wilton 2005, Wilton 2005, McCauley & Scott 2006, Smith and Wilton 2007). An exception is Auckland city, where the contribution of domestic heating is equalled by traffic emissions during winter (Metcalfe et al. 2006).

When constructing emission inventories, fuel use data are usually obtained and emissions are then estimated via the application of emission factors that specify grams of particulate emitted for every kilogram of fuel burnt (g/kg). Emission inventories are essential for local authorities to identify the dominant sources that contribute to exceedances of the air quality guidelines and standards. Projections models are also commonly used tools and provide local authorities with predictions of future emissions under various management scenarios. The decisions that Councils make to address air quality issues will often be based on emissions inventories and projections models.

Both emission inventories and projections models are underpinned by emission factors. Representative emissions estimates are therefore essential for local authorities to manage air quality. Using emission factors that are erroneously low would lead to underestimation of the reductions in PM_{10} emissions required to meet NES and regional plan air quality targets.

To address the ambient PM_{10} problem at a national level, the NES also contains a design standard for new woodburner installations in urban areas. From September 2005, all woodburners installed on properties less than 2 ha in size have been required to have a thermal efficiency greater than 65% and emission rate less than 1.5 g/kg, when tested to AS/NZS4012 and AS/NZS4013 respectively. It is essential to identify the real life emissions from these low emission woodburners, because further management measures may be necessary if low emission woodburners are insufficient on their own to achieve air quality objectives.

Current estimates of particulate emission factors from NES compliant woodburners are based largely on laboratory test data and a small number of in-situ tests. The Nelson, Rotorua and Taumarunui in home testing of particulate emissions will allow refinement of the emission factor used in inventories and facilitate a better understanding of the factors that lead to the observed house-to-house and night-to-night variability in emission factors.

1.1   Analysis of emission rate from 2007 testing of NES woodburners

This report follows on from 'In home testing of particulate emissions from NES compliant woodburners: Nelson, Rotorua and Taumarunui 2007', prepared by Smith et. al. (2008).

The objective of that report was to:

identify a robust PM_{10} emission factor for representing low emission woodburners in dispersion modelling applications and emission inventories.

An overview of the method used in the study is outlined in section 2 of this report; it involved in situ emissions testing of 18 wood burners in Nelson, Rotorua and Taumaranui.

Results were derived from mean of test results on a fuel wet weight basis. The reason for this is that for emission inventory development and projections modelling of air quality management scenarios, it is necessary to use an emission factor with fuel mass expressed on a wet-weight basis. The dry weight basis is comparable with the testing requirements in AS/NZS4013 laboratory measurements of particulate emissions

Mean test results were used as Wilton et al. (2006) and Kelly et al. (2007) note that, while the median may be an appropriate measure of central tendency, the mean provides a more representative emission factor for applications such as emission inventories that will draw on the results from this report.

Average mean dry weight and average mean wet weight emission factors were calculated for each woodburner in the study. The mean emission factor for dry weigh was 4.6 g/kg and the mean emission factor for wet wood was 3.3g/kg

The report identified a 95% confidence interval for the mean emission factor of low-emission woodburners.

The report found that the in situ wet-weight emission factor of 3.3 g/kg is around three times smaller than the emission factor of 11 g/kg identified for pre-1994 woodburners (Wilton et al. 2006).

1.2   Summary of 2006 report on factors related to variability

In 2005, Wilton et al., (2006) undertook research to determine the factors that relate to variability in the real life testing of wood burner emissions. The research was designed to evaluate the suitability of emission factors being used for inventory investigations in New Zealand. An in situ emission-testing programme was carried out during winter 2005 to test the validity of existing emission factors for solid fuel burners installed before 1994. A total of 96 measurements were made from across 12 households.

The research involved using a new method of sampling emissions from solid fuel burners that was established by Applied Research Services for the sustainable management fund burner testing collaboration (Scott, 2005). The sampler included a sampling head that captured the sample of particulates. In addition flue temperature was measured, flue gases were analysed continuously for oxygen and carbon dioxide content and the carbon dioxide content of the diluted gas stream was analysed. The sampler also contained gauges to monitor and set gas flows through the sample head and flue gas analysers, canisters of drying agent to remove water vapour from the gas streams, a gas meter to quantify the sample flow and a vacuum sensor to monitor filter loadings.

Apart from the probe and manifold assembly the sampling method was essentially the same as used in AS/NZS 4012/3. As with NZS4013 two glass fibre filters were used to collect the particulate materials. The flue gas composition was also measured and used to calculate the total volume of gas which passed up the flue per kilogram of fuel burnt. The total emissions were then calculated from rate at which material is collected on the filter and the dilution ratio.

The burner testing was aligned with the Ministry for the Environment (MfE) "warm homes" pilot project for Tokoroa for 2005. The MfE project involved the replacement of 19 existing older burners and open fires (in separate households) with NES compliant burners, wood pellet fires and non-solid fuel alternatives.

Two samplers were operated contemporaneously for at least seven days at separate households during the sampling period July-September 2005. Testing was carried out using firewood belonging to the homeowners, who operated burners as they would normally on each day of the testing period. Householders weighed each log of wood prior to it being placed in the fire.

Householders recorded fuel weight, wood species, loading times and burner control settings (e.g., proportion of each day on high, medium and low).

The results showed that the average emissions were 14 g/kg (dry weight) or 11 g/kg (wet weight). The median emission was 10 g/kg (dry weight) and 7 g/kg (wet weight).

The main factors influencing emissions were average flue temperature and flue oxygen. Operational aspects that influenced these variables were kilograms of fuel burnt, sample duration, fuel moisture content, operational setting, and number of pieces and weight of wood used throughout the sample period.

1.3 PM_{10} versus TSP emission

The results from the Wilton et. al. 2006 research on the factors related to variability in the real life testing of wood burner emissions and the test requirements in NZS4031 measures TSP. In deriving emission factors for PM_{10}, it was assumed that 100% of the TSP was in the PM_{10} size fraction.

In 2007, Davy carried out additional studies into the particulate size fractions of wood smoke from domestic burners. The research involved collecting fifteen samples from the most commonly used wood in New Zealand – pine and blue gum (Scott 2005).

The samples were run through a series of woodburner phases including start up, low burn and high burn. The elemental concentration of the particles were then determined through the New Zealand Ion Beam Facility at Gracefield, Wellington.

The research found that particles from woodburners are mainly elemental carbon with traces of Si, S, K, Ca, Fe, Zn and Na. Particulate matter emissions were measured during the start up period and the wood burner that burnt commercial pine recorded the highest level of PM. The lowest level of PM was recorded by the woodburner using kiln dried pine during the mid burn cycle.

The Teflon filers that were used during sampling were examined. Particles were found in large aggregates of much smaller spherule 30 – 100 nm in diameter. The study found that while some particle agglomeration was likely to occur in the flue through collision processes, most of the agglomeration would occur on the filter surface itself by impaction.

In terms of particle size, the research found that emissions from woodbuners have particles that are mostly in the sub micron size range, and therefore the importance of using isokinetic sampling during wood burner testing is of less significance than has been assumed.

1.4   Study Objectives

The objective of this research was to:

Investigate the factors that influence PM_{10} emissions from NES compliant woodburners

2   Method

2.1   Sampling Programme

2.1.1   Household details

Eighteen households with NES compliant burners were selected for testing. The households were located in Rotorua, Taumarunui and Nelson – six houses within each town. In Nelson and Rotorua, council records were used to identify a list of homes where new log burners had been installed over the last two years and households were chosen randomly from the list. In Taumaranui, the burner testing was aligned with a Warm Homes air quality pilot project funded by the Ministry for the Environment, along with support from local heating appliance dealers and manufacturers. A total of 16 retrofit NES compliant woodburners, pellet fires and gas appliances were provided free to low-income Taumarunui participants, with six NES compliant woodburners selected for this study.

Two samplers were operated contemporaneously at separate households and monitoring was conducted daily for at least seven days. The seven day monitoring period was required to give a reasonable number of data per burner to account for daily variations in operation and, consequently, emissions. To compensate households for inconvenience, all were offered a $50 gift voucher per night of testing, along with an additional $10 voucher to compensate for electricity costs over seven days. Filters were changed daily and weighed at the ARS laboratory in Nelson.

Testing was carried out using firewood belonging to the home owners and burners were operated by the householders as they would in real life, on each day of the testing period. An exception to this was one household in Taumarunui who were provided with an NES compliant woodburner just prior to winter, as part of the Warm Homes programme. As the household did not have any firewood and winter was upon them, they immediately cut and gathered some wood from a nearby living willow tree and were attempting to operate their appliance with this freshly cut green wood. The moisture content of the willow was measured at around 40% and was considered to be very unrepresentative of firewood normally used in

real life. Moreover, it was considered that if the woodburner had been installed earlier in the year, this household may have been more motivated to gather their firewood earlier and season it more appropriately. Therefore, it was considered more representative to supply this particular household with fuel from a local firewood merchant, rather than continuing to use the extremely wet willow.

Householders were also asked to keep records of fuel weight and loading times.

2.2   In-situ emissions testing

The in-situ emissions testing was identical to that carried out for the 2006 analysis described in section 1.2.

2.3   Data collected

The following variables were available for some or all of the households:

Average flue temperature (°C)

Maximum flue temperature (°C)

Minimum flue temperature (°C)

Average oxygen content (%)

Duration of burn time (minutes)

Percentage of time at high, medium and low control settings.

Amount of wood burnt (kg)

Wood species.

Approximate moisture content of wood in woodpile.

Number of times the firebox was reloaded.

Number of pieces of wood loaded.

Wood types used were recorded as pine, willow, belian, matai, native, oregan, rata, kanuka and other. Pine was used by seven of the 18 households with other wood types typically used only by one or two households. Fuel type included in the variability analysis was either recorded as pine or other.

2.4   Data Analysis

The analytical method used in Wilton et al (2006) was regression trees. The regression tree method was also considered appropriate for the analysis of NES authorised wood burners because many of the variables being examined (e.g., oxygen, moisture content) were likely to have non linear relationships with TSP.

Data were analysed with SYSTAT (Version 12) using Classification and Regression Trees and Multiple Linear Regression. A Regression Tree uses an iterative process known as binary recursive partitioning, whereby data are split into partitions, which are then split further on each of the branches. The algorithm used in SYSTAT is Brieman (1984) which chooses the split that partitions the data into two parts such that it minimises the sum of the squared deviations from the mean in the separate parts. This splitting or partitioning is then applied to each of the new branches. After completing an exhaustive tree the programme eliminates nodes that do not contribute to the overall prediction. In SYSTAT stopping criteria are used to determine the size of the tree. The following stopping criteria were used: minimum reduction in proportional reduction in error (PRE) of 0.05, minimum number of samples per node of 5.

3 Results and discussion

3.1 Emissions data

Emissions data (g/kg TSP) were available for a total of 90 runs across the 18 households included in the study. For 39 of these, the oxygen analyser was not working and emissions data were calculated using the average flue oxygen of 15.2%. This resulted in an increase in the uncertainty for these runs.

Many households did not record the number of pieces loaded onto the fire each time it was reloaded. For these households the average wood weight per piece (an indicator of log size) was unable to be calculated. Consequently analysis of the impact of the variables wood size and number of pieces loaded was limited.

Table 3.1 shows summary data by household, including burner make and model. Results show average household TSP emissions (g/kg) of 1.2 g/kg or less for all households in Nelson with the exception of household six (average emission 5.8 g/kg). There are two notable differences with this household. Firstly although an NES authorised wood burner has been installed the bricks inside the firebox have been removed, negating its NES compliance status. The second obvious difference with this household relative to other Nelson households is the higher wood moisture content (21%). It is likely that a combination of these factors is resulting in the higher TSP emissions for household six.

Rotorua data included two households recording average emissions data less than 2 g/kg with the remaining households all giving averages between 2.8 g/kg and 3.4 g/kg. In comparison results for Taumarunui were highly variable ranging from a low of 1.8 g/kg TSP (average of only two runs) to 29 g/kg TSP for household 16 (average of only three runs). The latter result is questionable because the three runs were for durations of less than 100 minutes because of problems with the sampling equipment. This compares with average sample durations of over 700 minutes for the remainder of the dataset.

3.2 Moisture contents

The impact of wood moisture is difficult to adequately quantify in this study because it was not practicable to measure the moisture content of every piece of wood loaded onto the fire. Instead, an average moisture content of each household's wood pile was established using a

combination of wood moisture meters and samples sent to the ARL laboratory in Nelson for determination of moisture content using oven drying. Thus some of the variability in emissions that could occur as a result in variations in the moisture content (from the average of the wood pile) is not able to be quantified in the analysis.

The relationship between wood moisture content and emissions is typically parabolic with lower and higher wood moisture contents resulting in higher TSP emissions. This was observed in the Tokoroa older burners study (Wilton, et. al., 2005). In this study, however, low average wood moisture content did not result in high emissions (Figure 3.1). This was an unexpected result and the reason for this outcome is uncertain.

Figure 1:   Comparison of wood moisture content and emission rate (g/kg dry).
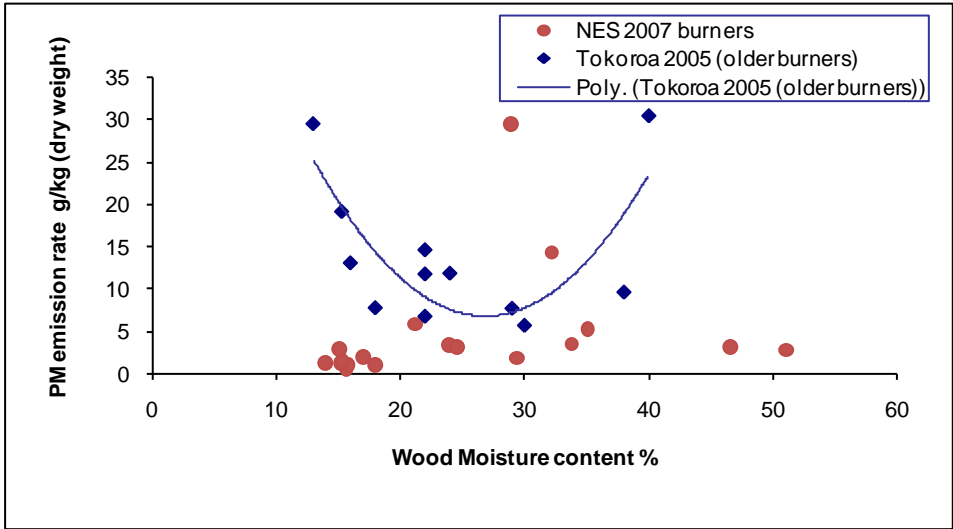
No.	Location	Make	Model	Emission (TSP) g/kg (dry)	Wood Moisture %	Burn Time minutes	Average Flue Temp C	Flue O2 %	Low setting % time %	Main wood type	Wood burnt per sample period kg	Wood burnt per day kg
1	Nelson	Ethos	FS100	0.9	18	574	232	17	87	P	13	14
2	Nelson	Logaire	Hestia, Bay Door, Clean Air	1.2	14	748	257	15	57	P	23	21
3	Nelson	Firenzo	Lady Kitchener 800, EF Dry	0.4	16	1363	183	14	80	O	34	36
4	Nelson	Ethos	FS100	1.0	16	531	290	15	44	P	12	13
5	Nelson	Metro	Eco Pioneer	1.1	15	1184	232	17	6	P	25	25
6	Nelson	Ethos	FS100 - bricks removed	5.8	21	637	238	15	53	O	13	13
7	Rotorua	Metro	Eco Pioneer	1.8	17	823	176	15	98	P	19	24
8	Rotorua	Kent	Firenze Max	1.4	15	851	224	15	95	O	17	16
9	Rotorua	Jayline	Classic FS	2.8	15	823	238	16	12	P	29	26
10	Rotorua	Metro	Eco Aspire	3.3	24	669	194	17	29	P	18	27
11	Rotorua	Metro	Eco Pioneer	3.0	47	608	237	14	0	O	22	22
12	Rotorua	Kent	Signature	3.4	34	409	212	16	49	P	14	15
13	Taumaranui	Metro	Eco Rad	2.7	51	712	203	15	33	O	37	48
14	Taumaranui	Woodsman	Matai ECR Mark 2	3.1	25	851	258	15	93	O	28	28
15	Taumaranui	Woodsman	Matai ECR Mark 2	14.3	32	453	219	15	.	O	.	83
16	Taumaranui	Metro	Eco Rad	29.5	29	68	249	15	22	O	6	30
17	Taumaranui	Woodsman	Matai ECR Mark 2	1.8	29	518	237	15	73	O	17	15
18	Taumaranui	Metro	Eco Wee Rad	5.2	35	350	243	15	64	O	21	26

Table 3-1:   Summary household data.

3.3 Regression Tree Analysis

A number of transformations were made to the emissions data (g/kg TSP – dry) to minimise the skew in the data and therefore reduce the impact of extreme data on the regression tree. Transformation using $\log_{10}$ was found to be most effective in reducing the skew (non-transformed data skew of 4.7 to $\log_{10}$ of 0.4). The dry weight g/kg emission data were selected as the dependent variable to allow for the independent assessment of the impact of moisture and weight of fuel burnt.

A preliminary analysis of all variables was conducted with $\log_{10}$ TSP (g/kg dry emission data) as the dependent variable and each of the other variables listed in section 2.3. The regression tree was set to a minimum proportional reduction in error (PRE) of 0.05 which prevents a tree from forming a branch if a variable is unable to explain more than 5% of the variability in TSP. Other stopping criteria included a minimum of five data points at each node of the tree. The following variables were identified by the regression tree analysis as potentially contributing to more than 5% of the variability in TSP.

Moisture content (PRE - 0.42)

Duration (PRE - 0.33)

Maximum Temperature (PRE - 0.10)

Minimum Temperature (PRE - 0.13)

Oxygen (PRE - 0.20)

Oxygen Maximum (PRE - 0.16)
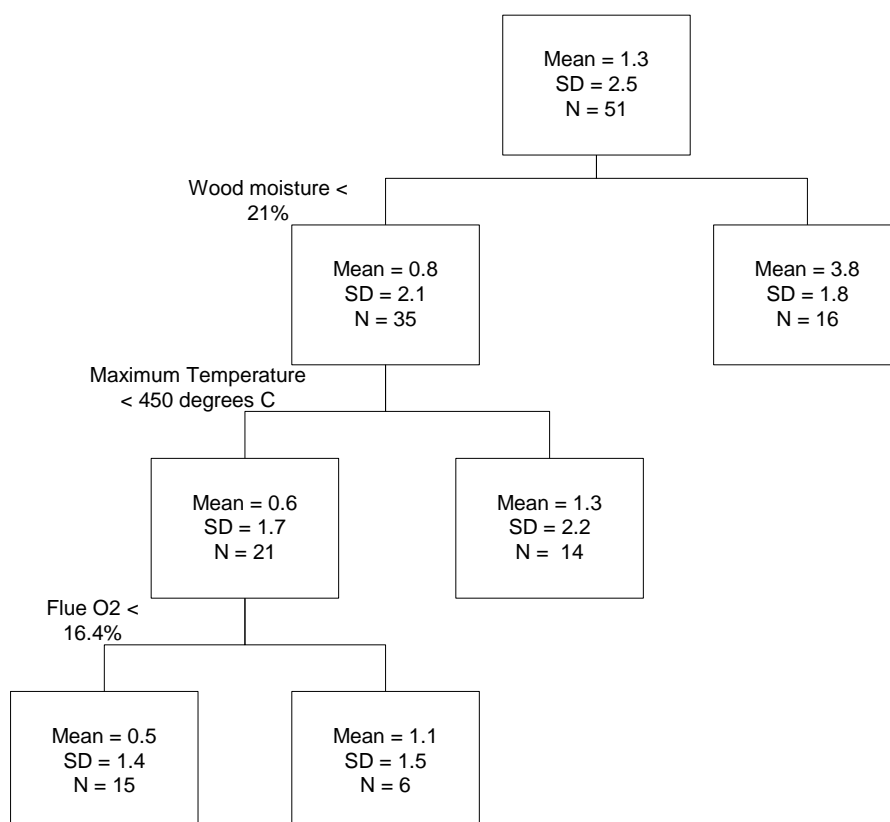
Oxygen Minimum (PRE - 0.22)

Operation at high (PRE - 0.09)

Operation at low (PRE - 0.09)

Number of loads (PRE - 0.10)

These variables were included in a regression tree with $\log_{10}$ g/kg TSP as the dependent variable. The resulting tree is shown in Figure 3.2. Around 68% of the variability in TSP emissions was explained by the variables wood moisture (53%), maximum flue temperature (9%) and average flue oxygen (7%).

```
                          ┌─────────────┐
                          │  Mean = 1.3 │
                          │   SD = 2.5  │
                          │   N = 51    │
                          └─────────────┘
Wood moisture <
      21%
          ┌─────────────┐              ┌─────────────┐
          │  Mean = 0.8 │              │  Mean = 3.8 │
          │   SD = 2.1  │              │   SD = 1.8  │
          │   N = 35    │              │   N = 16    │
          └─────────────┘              └─────────────┘
Maximum Temperature
  < 450 degrees C
    ┌─────────────┐        ┌─────────────┐
    │  Mean = 0.6 │        │  Mean = 1.3 │
    │   SD = 1.7  │        │   SD = 2.2  │
    │   N = 21    │        │   N = 14    │
    └─────────────┘        └─────────────┘
Flue O2 <
  16.4%
 ┌─────────────┐  ┌─────────────┐
 │  Mean = 0.5 │  │  Mean = 1.1 │
 │   SD = 1.4  │  │   SD = 1.5  │
 │   N = 15    │  │   N = 6     │
 └─────────────┘  └─────────────┘
```
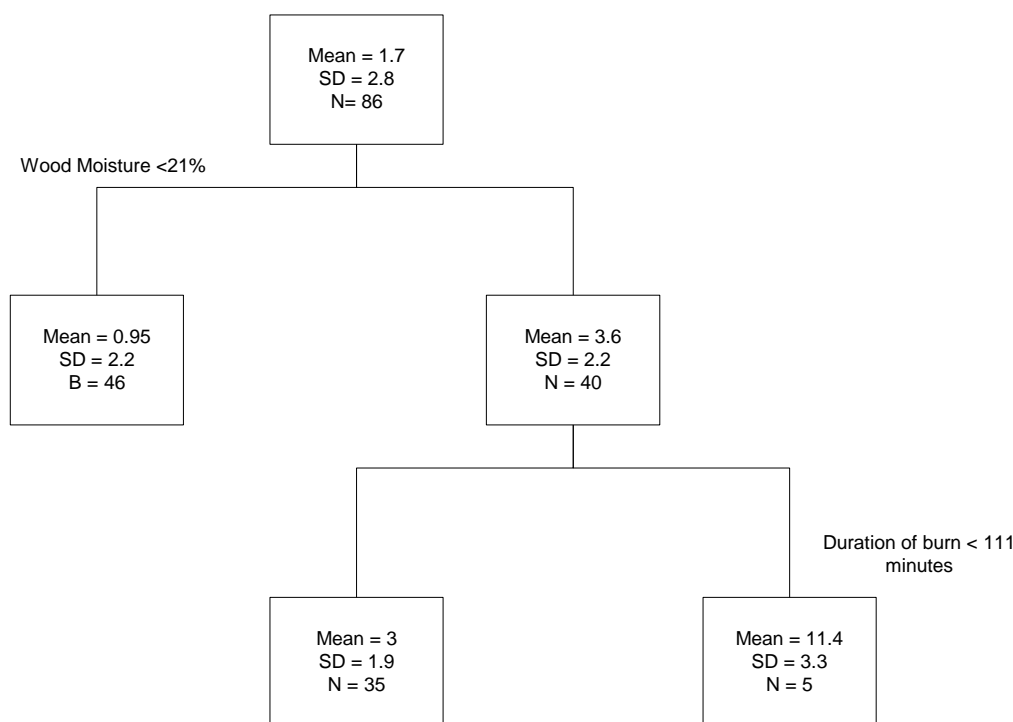
Figure 2:   Regression tree on all data. Data in boxes is $\log_{10}$ g/kg TSP emissions.

Factors influencing flue temperature and oxygen content were evaluated by conducting separate regression trees with each of these being the dependent variable. Burner setting (proportion of time on high), burn duration and wood moisture content had the greatest impact on flue temperature accounting for 38% of the variability in maximum flue temperature. Factors influencing average flue oxygen were wood moisture content and the burner setting (proportion of time on low) although these only accounted for 20% of the variability in average flue oxygen.

Approximately 40% of the available data including most of the highest TSP data were excluded from the analysis because of missing data for oxygen. To examine variability in the larger data set, oxygen was removed from the independent variables[1]. Figure 3.3 shows the resulting tree, which contained 86 data points. A smaller amount of variability in the results (50%) was able to be explained by the tree when the higher emissions runs were included (through the exclusion of oxygen). Wood moisture remained the most significant variable but in this dataset (which included the higher emission runs) it was only able to explain (41%) of the variability in the TSP data. Results suggest that the cause of the variability in emissions in the data excluded from the first tree (including the higher emission runs) is not as well explained by the input variables wood moisture and burn time as if could have been if the flue oxygen data had been available.

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[1] The regression tree excludes all data from the analysis if any one independent variable is missing.

```
                    ┌─────────────┐
                    │ Mean = 1.7  │
                    │ SD = 2.8    │
                    │ N= 86       │
                    └─────────────┘
Wood Moisture <21%
        ┌───────────────┴───────────────┐
┌─────────────┐                   ┌─────────────┐
│ Mean = 0.95 │                   │ Mean = 3.6  │
│ SD = 2.2    │                   │ SD = 2.2    │
│ B = 46      │                   │ N = 40      │
└─────────────┘                   └─────────────┘
                         ┌─────────────┴──────────────┐
                                          Duration of burn < 111
                                                 minutes
                  ┌─────────────┐            ┌─────────────┐
                  │ Mean = 3    │            │ Mean = 11.4 │
                  │ SD = 1.9    │            │ SD = 3.3    │
                  │ N = 35      │            │ N = 5       │
                  └─────────────┘            └─────────────┘
```

Figure 3:   Regression tree on larger data set when oxygen is excluded.

The above observation combined with knowledge of sampler operational issues with some of the Rotorua and Taumarunui results does lead to a reduced confidence in the reliability of the results for those households. To investigate this further, a regression tree was conducted on just households for which oxygen data were missing and this was compared with households for which oxygen data were available. In the oxygen data deficient dataset the amount of variability explained by the relationship determined in the tree was 32%. This compares with 67% for households for which the oxygen sampler was functioning. In summary, this finding suggests that the flue oxygen content data is an important predictive variable or alternatively the higher variability may be caused by an increase in sampling error associated with mis-functioning oxygen analyser.

3.4   Multiple Linear Regression

Multiple Linear Regression (MLR) was performed on the data with $\log_{10}$ TSP g/kg (dry) as the dependent variable. Results showed that 41% of the variability in the emissions could be explained by the model input variables, with wood moisture content having the greatest impact. Wood moisture content (p=0.006) and flue oxygen (p=0.005) were the only variables with p values less than 0.05.

3.5   Average fuel use

The average amount of wood burnt by householders in the study provides a useful comparison for those carrying out domestic heating surveys for emission inventory studies. In the latter surveys households are typically asked about their daily fuel consumption, often in terms of the average number of logs put on a fire per day. The information is then converted to an estimated daily fuel consumption based on an assumed average log weight.

In this study wood weights were reported by ARS for the period of operation of the sampler. On several occasions the sampler malfunctioned and prematurely ceased working. ARS supplied data for these runs but the emissions and wood weights were not representative of the time for which the householder actually operated the fire. In addition, the sampler was often changed either late morning or afternoon giving a variable sample period.

The actual average daily fuel use by householders in the study was obtained by extracting fuel use records from the daily field sheets. Table 3.1 shows the average daily wood use in kilograms by each household in the study for the period midnight to midnight and for the period as reported by the householder.

Results suggest that around 27 kilograms of wood were used per day on average by households in the 2007 NES authorised wood burner emissions study. This is comparable with average fuel use estimated by households in surveys carried out for emission inventory purposes in New Zealand which are typically around 20-25 kilograms (e.g., Wilton, 2006).

3.6   Temperature data

A comparison of daily fuel use and average daily temperature for households in the study is shown in Figure 3.4. The purpose of this was to evaluate if householders used more fuel on colder nights to maintain a consistent household temperature.

The relationship was examined using linear regression between actual daily fuel use as recorded by households[2] and daily average temperature (from midnight to midnight). The relationship was examined across all study areas, for each town individually and on an individual householder basis.

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[2] Note this differs from the fuel weights in "wood burnt per sample period" because it includes all fuel burnt during the day rather than just that consumed during the period the sampler was operating.

Figure 4: Daily fuel use and average daily temperature for all households.
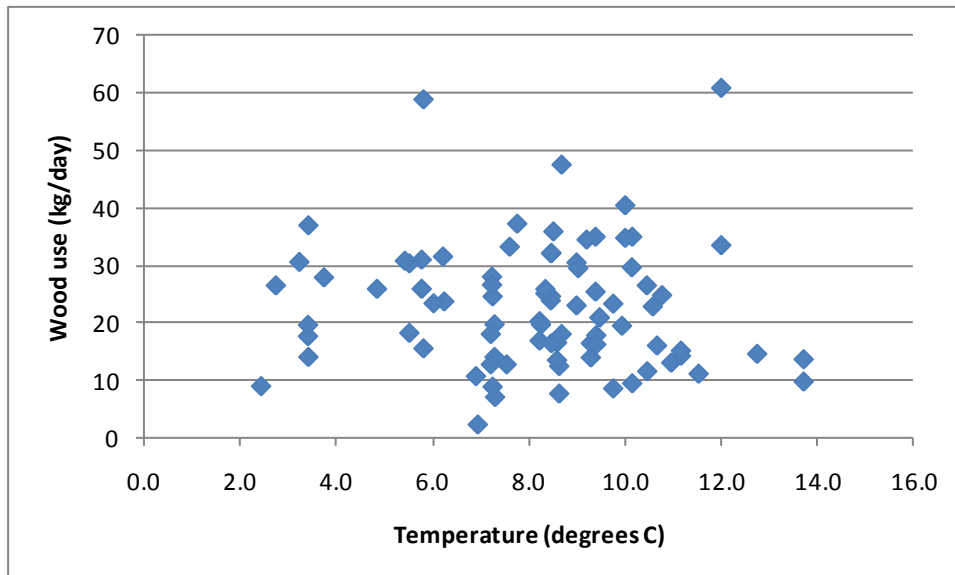
Results indicted no relationship between wood use and temperature across all study areas ($R^2 = 0.01$) or for each town (Nelson $R^2 = 0.07$, Rotorua $R^2 = 0.05$, Taumarunui $R^2 = 0.1$). At an individual household level, six of the 18 households showed some indication of households using more fuel on colder days. Of these four were from Nelson and two from Rotorua. The R^2 values were 0.94[3], 0.2, 0.96, 0.2 (Nelson) and 0.46 and 0.47 (Rotorua). A negative relationship (decrease in wood use with decrease in temperature) was also observed with one Rotorua household ($r^2 = 0.36$).

A large proportion of the variability in the relationship observed with the collated data is likely to be associated with householder variability in fuel use occurring as a result of other factors such as different sized appliances and heat requirements or behavioural aspects such as the habit of lighting and loading a fire irrespective of temperature.

The two variables most likely to influence the relationship between wood consumption and outdoor temperature are the heat output of the burner (relative to the space heating requirements) and the skill of the operator. An unskilled or inattentive operator will use the burner in much the same way on any day irrespective of amount of heat the room requires.

If an appliance has been appropriately sized and an operator is competent and attentive in the use of the burner then an increase in fuel consumption could be expected to maintain the living area of the home at a constant temperature on colder nights. However, if an appliance has been inappropriately sized it is probable that the householder will not be able to operate it in an efficient manner and outdoor temperature will have little impact on fuel consumption. For example, an undersized wood burner is likely to be operated at a maximum fuel burning rate for a large proportion of the time and is likely to result in a colder indoor temperature on

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[3] Strong leverage provided by one data point.

days when the outdoor temperature is colder. For oversized wood burners (those that deliver more heat than the living area requires), householders are likely to operate burners at a lower fuel burning rate and may often over heat a room or living area on average temperature nights; the extent of overheating may be reduced on colder nights. Anecdotally, the installation of oversized wood burners is more common than undersized burners, mainly due to the pitch of people selling the appliances.

Overall results suggest that outdoor temperature does not influence fuel consumption for most householders (72% of households in this study). It is uncertain whether inappropriate burner sizing or operator skill/ attentiveness is the reason for this.

3.7   Comparison of laboratory test data to real life emissions

The relationship between NZS 4013 emission rate for the make and model of burner and the average real life emissions measured in this study are shown in Figure 3.5. The poor relationship observed is consistent with the results of previous sections which suggest that operational factors account for most of the variability in emissions within this group of appliances. Notwithstanding this, as a group these burners emit considerably less particulate than the older burner category evaluated in Wilton et. al., 2006.

Figure 5:   Real life particulate emissions and laboratory test (NZS 4013) results.
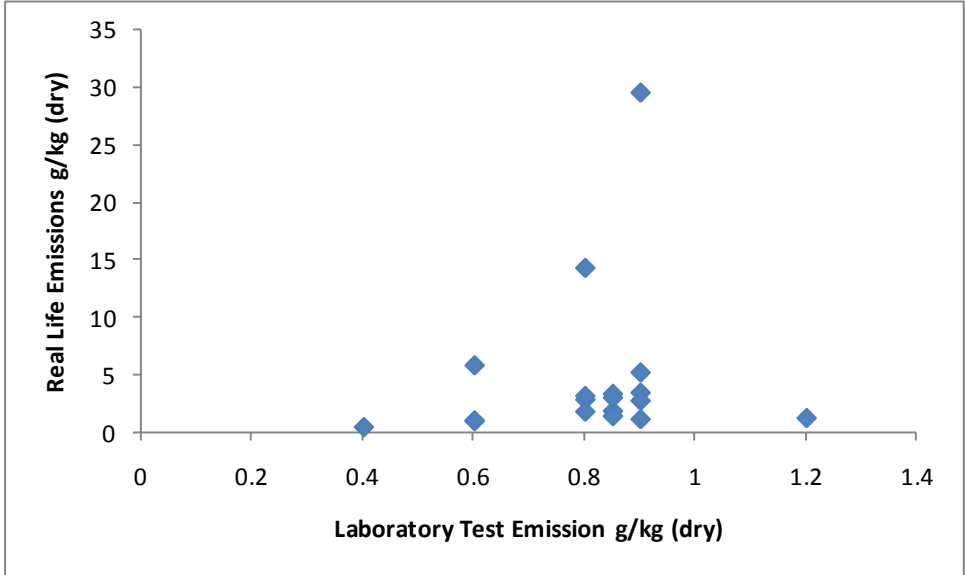
3.8   Location differences

Of the three locations included in the study, average particulate emissions were lowest in Nelson (1.4 g/kg wet weight), followed by Rotorua (1.9 g/kg wet weight). In Taumarunui the average wet weight emission was 6.5 g/kg although this was strongly influenced by one household with short duration sample runs which did not reflect emissions from the total burn

cycle. Excluding emissions from this household gave an average wet weight emission of 3.6 g/kg for Taumaranui.

To determine if there was some aspect of the location or location based bias in the sampling programme that was influencing emissions the location of each household was included as a categorical variable in the Regression Tree. The resulting tree analysis (section 3.3) shows that the differences in emissions occur as a result of operational parameters (e.g., moisture content) rather than a non operational location related variable.

The lower emissions in Nelson and associated variable data suggest that the Nelson households tended to operate their burners better and use better quality (dryer) fuel. The average moisture content of the wood used in Nelson was 17% compared with 25% in Rotorua and 33% in Taumarunui. Results of the comparison of daily wood use to temperature also suggest that households in Nelson either had more appropriately sized appliances or were better operators of wood burners (or both). A reason for the lower wood moisture content and better sizing and operation performance in Nelson may be the implementation of the "good wood" scheme, energy audits associated with the "clean heat warm homes" incentives programme and possibly education campaigns.

4   Conclusion

This study evaluates of the causes of variability in TSP emissions in NES authorised wood burners operated in "real life" by householders. Prior work looking at causes in variability in TSP emissions used a similar method but focused on older wood burners (Wilton, et al, 2006).

This study found the greatest factor influencing variability in the NES authorised wood burners was wood moisture content. This accounted for around 43% of the variability in TSP emissions in the whole data set, increasing to 53% for households for which the sampling equipment had no known problems. Other factors influencing variability included maximum flue temperature and oxygen content. Maximum flue temperature was most influenced by fire setting (proportion of time on high), duration of burn and wood moisture content all of which could explain 38% of the variability in maximum flue temperature. Around 20% of the variability in flue oxygen content was explained by fire setting (proportion of time on low) and wood moisture content.

In comparison, the study on variability in older wood burners found household, kilograms of wood burnt, flue temperature and flue oxygen to be the main factors influencing variability. The prevalence of the household factor as a key cause of variability indicated some element of inter household variability that was not adequately quantified in the variables collected. A regression tree on household average emission data found that wood moisture and fire setting (proportion of time on low) were the main factors accounting for variability.

The results found in this study are an improvement from the previous study in that the variability can be explained largely by tangible factors (as opposed to the household output from the Tokoroa 2005 study).This is an important finding as it may provide helpful clues on how to better manage particulate emissions from domestic woodburners.

The average daily fuel use for a wood burner across the 18 households included in the study was around 25 kilograms (wet weight). This is comparable to estimates made from emission inventory studies in which households are required to estimate the number of logs placed on a fire per day which typically range from around 18 kg/day (e.g., Masterton (Wilton & Baynes, 2008) to 25 kilograms per day (e.g., Nelson (Wilton, 2006)).

Households in the Nelson area may select and operate burners more appropriately than in other areas. Measures undertaken by the Nelson City Council including the good wood scheme, energy audits through the incentives programme and education measures may be effective in reducing particulate emissions from NES authorised burners.

5 Recommendations

- The limited data set collected in this study will facilitate the refinement of emissions factors used in emission inventories and help explain the reasons for high house-to-house and night-to-night variability in emissions. Both these issues are vital pieces of information that will allow Regional Councils to understand and manage particulate emissions from woodburners. Given the importance of these issues and the limited data base available to date, it is recommended that further work be done on NES authorised wood burners and factors influencing variability.

- In this study, malfunction of the sampling equipment resulted in poorer quality data for around a third of the samples. Investigations into methods for minimising sampling equipment malfunctions are recommended before further studies are undertaken.

- Investigations into real life emissions and factors influencing variability for other burner types are also required. In particular little is known about emission from coal burners in New Zealand and factors influencing variability in these.

- Councils give consideration to measures to improve the quality of wood burnt, specifically the moisture content (e.g., good wood scheme for Nelson), and options for ensuring appropriately sized wood burners are installed and operated well.

6   References

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7   Acknowledgements