Predicting Harvest Residue Moisture Content using Fire Indices

Courtney Amberger

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Supervised by Prof. Rien Visser

NZ School of Forestry, Christchurch, New Zealand

1 Executive Summary

This report investigates the relationship between the moisture content of harvest residue and the New Zealand Fire Danger Rating System (NZFDRS) index codes in the Nelson/Tasman Region. This relationship was utilized to forecast the energy content of harvest residue, aiding in a more accurate determination of projected biofuel availability.

New Zealand is currently attempting to move towards a low carbon future. To achieve this, the Carbon Neutral Government Program was launched by the Government in December 2020. The first immediate priority of this program is to phase out coal-fired boilers from the public sector. Harvest residue provides a realistic alternative fuel source for coal-fired boilers. Finding the most suitable alternative to coal requires an accurate estimation for the energy available in each source.

The study began by collecting weight data from 48 logs situated across two sites in the Nelson/Tasman region. There were two categories of logs: aged and green. The aged logs were harvest residues from 2021 while the green logs were harvest residues from 2022. The logs used had diameters between 10-25 cm and lengths of less than 1.5 m. The moisture content was inferred from the weight measurements by determining initial moisture content of individual logs. This was done using the gravimetric method from destructive testing on sections of each log. The moisture content was assumed to be consistent throughout the entire log.

After linear regression transformation, a very strong correlation of 0.95 between harvest residues aged one year, and the NZFDRS build-up index (BUI) was found. The correlation between green harvest residue and the BUI was only moderate at 0.63. The relationships can be modelled using the following equations:

$$Aged\ Moisture\ Content = \frac{1}{(0.29 * BUI + 6.24)^{\frac{1}{2}}}$$

$$Green\ Moisture\ Content = \frac{1}{0.04 * BUI + 2.60}$$

Applying these relationships to publicly available forest area data led to the conclusion that the Nelson/Tasman Region has sufficient harvest residue to replace coal currently. According to MBIE, coal energy consumption accounts for 1.1 PJ p.a., while the study estimated the energy availability of harvest residue to be 1.5 PJ p.a. for the next 5 years. The energy availability trend in the Nelson/Tasman region from harvest residues decreases slowly over the next 30 years. In 21 years, there will be insufficient volumes of harvest residue to replace coal.

The relationships both had limiting factors. The limitation of the aged relationship was not having an end point for the age of the residues. The accuracy of the green relationship was not strong enough to use as a base for regional scale predictions. Further research into the effects of decay on the moisture content of logs could be carried out to interpolate this value. This would also find the maximum time in which logs could be stored if excess amounts of residues are required to be carried over to meet future years energy demands.

2 Acknowledgements

This project would not have been possible without the assistance of David Robinson for his expertise and guidance throughout this project. I would like to thank Taylors Contracting Co Ltd. for providing the opportunity work in their company completing the data collection. I would also like to thank Prof. Rien Visser for his feedback and advice throughout the project.

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3 Introduction

New Zealand is currently moving towards a low carbon future. To achieve this, an initiative called the Carbon Neutral Government Program was launched by the Government in December 2020. The aim of this program is to ‘make a number of organisations within the public sector carbon neutral from 2025’ (MfE, 2023). The first immediate priority of this program is to phase out coal-fired boilers from the public sector. Harvest residues provide a realistic alternative biofuel for coal-fired boilers, potentially creating a large market for production forest harvest residue.

Production forest harvesting produces a large amount of unutilised harvest residue (Harvey & Visser, 2022). This residue could be utilised for biofuel purposes, producing a carbon-neutral alternative for coal-fired boilers. Utilising this component of harvested wood would not only increase revenue for forest companies, but also decrease environmental risk due to slash mobilisation in high intensity weather events.

Even with good practices in place for harvest residue (slash) management, it is still possible that residue will mobilise. This would potentially result in considerable environmental damage and safety risks. Best practices for slash management include slash traps across waterways, storing slash in a stable location or changing harvest practices. However, removing harvest residues is the only way to eliminate the environmental risk. Utilising residue for biofuel is a way this could be achieved. This is outlined in the section four guidelines of the best environmental practices in the New Zealand Forest Owners Association Environmental Code of Practice (NZFOA E-CoP). It states “where economic, hog residues (slash, slovens, and arisings) and consign to a biofuel plant” (NZFOA, 2007).

A major consideration for utilising these residues as biofuel is estimating supply and demand volumes. Current research in this area considers residue to have a constant calorific value year-round of 6.94 GJ/t (DETA, 2022). It is known that the moisture content in the residues changes seasonally, resulting in the calorific value in the residues changing too (Visser, Berkett, & Spinelli, 2014). To establish reliable supply to meet certain demands, it is important to know how the moisture content varies due to these seasonal factors. The National Institute of Water and Atmospheric Research (NIWA) and Fire and Emergency New Zealand (FENZ) provide current and historic Fire Danger Rating System values which provide data on fuel availability in forests for fire. Using these data, this study aims to find a relationship between residue moisture content and one or more of the fire danger indices to estimate the seasonal calorific values of harvest residue in the Nelson/Tasman region. This will improve uncertainties around the required volumes of residue for use as biofuel.

4 Literature Review

4.1 Waste Proportions in Pine Harvest

Currently harvest residues are stored either on a skid or in the cutover. Residues that are left on the skid are either moved to an unused skid or sometimes pushed back into the cutover. To minimise environmental risk, it is recommended in the ECOP that residues get transported to a different skid or hogged for biofuel (NZFOA, 2007).

4.1.1 Cutover Residue

Harvey and Visser (2022) recently estimated the total harvest residue found in cutover areas to be 88 m^3/ha. This total volume was divided into three components: merchantable residue, binwood residue and remaining residue, containing 11 m^3/ha, 19 m^3/ha and 58 m^3/ha respectively (Harvey & Visser, 2022).

Merchantable residues are logs that could have been used as a log product at time of harvest but have remained in the cutover due to processing errors or breakage during harvesting. These are logs with a small end diameter (SED) greater than 10 cm and a length greater than 4 m. This portion of the residue comes from the stem of the tree and will be of good quality e.g., minimal knots, little sweep (Harvey & Visser, 2022).

Binwood residue is considered to have potential for further biomass use, e.g., fuel for energy production or chipped for pulp feedstock. Any residue with a SED greater than 10 cm and a length greater than 0.8 m can be used for this. This portion of residue can be large branches, stem offcuts from felling breakage, or any logs with defects that were rejected during normal processing (Harvey & Visser, 2022).

The remaining residue is what is left after the binwood and merchantable wood is removed. Currently, this residue is too small to be used as fuel so only the merchantable and binwood residue volumes can be potentially utilized. The remaining residue comes from any small branches, needles, offcuts, or other tree biomass left from harvest (Harvey & Visser, 2022).

Another study was also conducted where residue volumes were analysed (Hall, 1998). Hall split the residues into different categories depending on where the trees were delimbed and depending on what type of residue was produced. The total cutover residue calculated was 77 m^3/ha if delimbing was carried out on the landing and 107 m^3/ha if delimbing was carried out at the stump. Of this, 25 m^3/ha or 49 m^3/ha was found to be stem residue from delimbing at landing or stump respectively. This is assumed to be similar to binwood and merchantable residue in Harvey and Visser's study. Smaller branches and residue from delimbing at the landing and stump were found to produce 52 m^3/ha and 58 m^3/ha respectively. This is assumed to be similar to the remaining residue in Harvey and Visser's study.

The results from the studies are compared in table 1 below:

Table 1: Cutover Residue Volumes

<table>
<tr><th></th><th>Merchantable (m^3/ha)</th><th>Binwood (m^3/ha)</th><th>Remaining (m^3/ha)</th></tr>
<tr><td>Harvey and Visser</td><td>11</td><td>19</td><td>58</td></tr>
<tr><td>Hall – Delimb Landing</td><td colspan="2">25</td><td>52</td></tr>
<tr><td>Hall – Delimb Stump</td><td colspan="2">49</td><td>58</td></tr>
</table>

4.1.2 Landing/Skid Residue

The residue left on the skid is any biomass remaining in piles after the processed logs have been transported to market. For residue accumulating on the skids, Harvey found a mean bulk volume of 170 m^3/ha in piles on skids (Harvey, 2022). This gross pile value can be approximately converted to a net wood volume using Hardy's method which uses packing ratios to scale down the bulk volume to account for the volume of air in the pile. These packing ratios depend on the type of residue in the pile. The first packing ratio is 0.25 which corresponds to 'highly compacted, clean piles with large logs (diameters > 25 cm), especially those built with a crane or loader'. The second option is a packing ratio of 0.2, corresponding to 'piles dominated by short-needled conifers with mean diameters <25 cm'. The final option is 0.1 which corresponds to 'piles dominated by long-needled conifers with mean diameters of large woody fuels < 25 cm' (Hardy, 1996).

Another study by Hall in 1998 found the total harvest residue on the landing was 5.5% of the total standing volume (TSV). These values are for whole tree harvesting only as this is usually the preferred option in the steeper New Zealand terrain (Hall, 1998). Using the average standing volume of New Zealand forests of 305 m^3/ha, as given in the Facts and Figures report 2021/22, Harvey and Halls studies can be compared (FOA, 2021/22). A packing ratio of 0.2 was used to convert Harvey's bulk volume to a net wood volume (see Table 2).

Table 2: Skid Residue Volume

	Landing Residue Volume (m^3/ha)
Harvey	17
Hall	16.7

4.2 Heat Capacity

When being used as fuel, harvest residues will have a different energy content depending on the moisture content of the residues (Good Practice Guide, 2010). Standing tree moisture content varies with the age of wood and species, while the rate of change of harvested wood moisture content depends on the site conditions, e.g., wind, rain, temperature and relative humidity (Petterson, 2007). The following relationship between energy content and moisture content was derived by Koppejan and Van Loo to quantify this changing value (Koppejan & Van Loo, 2008):

$$Energy\ (GJ/t) = 18.9 - 0.213 \times MC_{wb}$$

4.3 New Zealand Fire Danger Rating System (NZFDRS)

Fire danger is defined as 'a general term used to express an assessment of both fixed and variable factors of the environment and that determine the ease of ignition, rate of spread, difficulty of control, and fire impact' (Merrill & Alexander, 1987). The Fire Danger Rating System presents these factors in a qualitative/numerical form. The New Zealand Fire Danger Rating System is governed by four components – Fire Weather Index, Fire Behaviour Prediction System, Accessory Fuel Moisture, and the Fire Occurrence Prediction System. Figure 1 below shows how these components work together to form the NZFDRS.

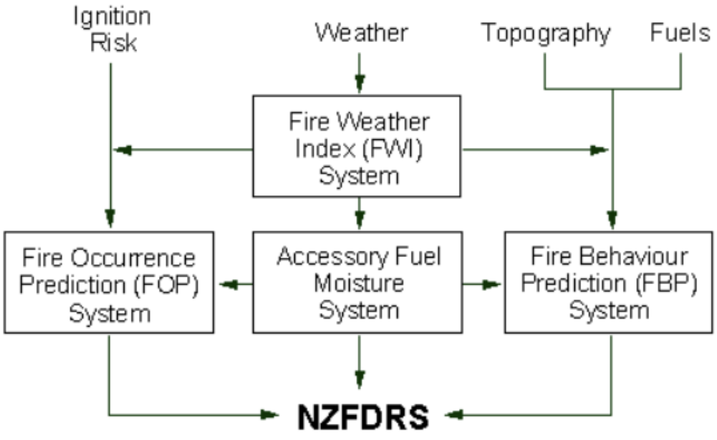

Figure 1: Components of the Fire Danger Rating System

4.3.1 Fire Weather Index (FWI)

The FWI system has an influence on all other components of the NZFDRS, making it a key component. It is made up of five indices: the build-up index (BUI), drought code (DC), duff moisture code (DMC), fine fuel moisture code (FFMC), and the initial spread index (ISI). The FFMC, DMC and DC are moisture codes representing different fuel layers while the ISI and BUI use these moisture codes to determine the spread risk of the fire and the available fuel respectively. Figure 2 shows how these indices work together to build the FWI.

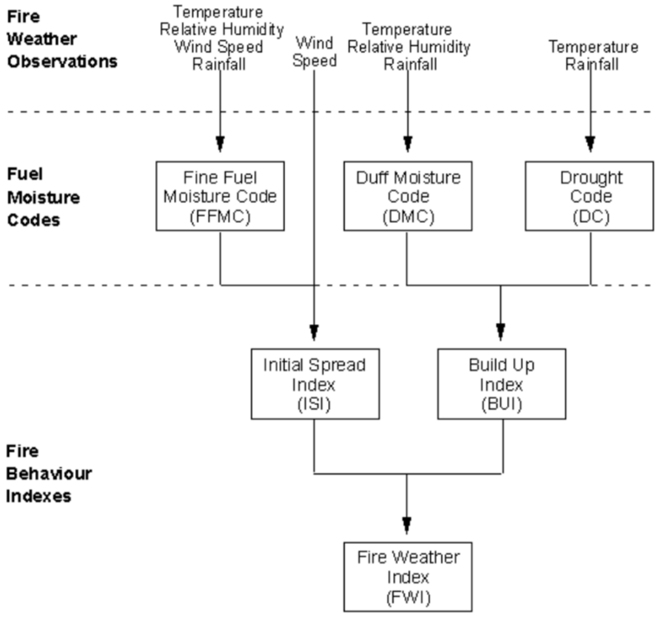

Figure 2: Components of the Fire Weather Index

The FWI represents the potential fire intensity of spreading fire for a mature pine stand on level terrain with wind speed measured 10 m above ground, 24-hour cumulative rainfall and indices calculated at 12pm (or 1pm for daylight savings) (FENZ). The equation used to calculate it is:

$$I = H \times w \times r$$

Where I is the fire intensity in kW/m (FWI), H is the fuel heat of combustion (constant ~18000 kJ/kg), w is the fuel consumed in the active flaming front, e.g., fuel available, in kg/m^2 (BUI), and r is the rate of fire spread in m/s (ISI) (Telford and Scion, 2012).

4.3.2 Fine Fuel Moisture Code (FFMC)

The FFMC is the first layer of the soil moisture codes. It represents the moisture content of the fine surface litter e.g., top layer of soil containing needles, grass etc. This provides the relative ease of ignition and the flammability of these fine fuels. Values for the FFMC range from 0 to 101 with higher values representing greater flammability. The lag time of 2-3 days is quite small meaning the response to weather input will be quick as it is most exposed to the elements. The rain threshold determining a response is small at 0.6 mm, meaning this code is variable (Telford and Scion, 2012).

4.3.3 Duff Moisture Code (DMC)

The DMC is the moisture code for the second layer of soil. It represents the moisture content of loosely compacted duff of moderate depth and smaller woody material e.g., small branches. It ranges between 0 to ~150 representing the extent a fire will burn these fuels. As this layer is slightly deeper than the FFMC, the lag time is around 15 days, with a rain threshold of 1.5 mm. This means that it takes more rain, and a longer period of time to respond to inputs (Telford and Scion, 2012).

4.3.4 Drought Code (DC)

The DC is the deepest layer of soil considered in the soil moisture codes. It numerically represents the difficulty of extinguishing the deep, compact organic matter and large woody fuels. This ranges from 0 to ~800 with a large lag time of 53 days and a rain threshold of 2.8

mm. This means it does not change as significantly and is not as responsive as the two upper soil layers. As it represents large woody fuels, it will also likely have stronger correlation to the moisture content of logs (Telford and Scion, 2012).

4.3.5 Build-up Index (BUI)

The BUI considers the total amount of forest fuel available for combustion. This is the DMC combined with the DC (FENZ). The values for BUI can range from approximately 0 to ~200. This is used to determine the 'w' component of the FWI equation (Telford and Scion, 2012).

4.3.6 Initial Spread Index (ISI)

The ISI combines the effect of wind speed at 10 m and FFMC to provide a numerical value for the expected rate of fire spread (r in the FWI equation). It does not take into consideration the effects of variable fuels. The values for the ISI can range from 1 to ~100 (Telford and Scion, 2012).

4.4 Previous Study

A study by DETA published in 2022 outlined the possible alternatives for replacing fossil fuels in the South Island. These alternatives included electricity, heat pumps, and biomass. For the Nelson/Tasman region, fossil fuels can be completely replaced by biomass fuel only if the biomass volumes were supplemented by expensive wood fibres. These results were based on assumptions of forest residue volumes being a total of 15% of total recoverable volume, and a consistent heat capacity of 6.94 GJ/t (DETA, 2022).

The overall conclusion for this study for the Nelson/Tasman region was that alternative fuels should be split between biomass and heat pump usage. This reduced the amount of biofuel needed so that smaller amounts of expensive wood fibre were needed to be used in conjunction with heat pumps offering a cheaper fuel unit price (DETA, 2022). This study was a first-time study looking to quantify the implications of removing fossil fuels from industrial heat processing in hopes of promoting a wider conversation around the possibility of using greener fuels (Pooch & Smit, 2022).

4.5 Moisture Content Changes

It is expected that the moisture content of the logs will decrease rapidly over summer then increase again over winter. The moisture gradient between wood and the ambient air is the exclusive cause for this change in moisture content (Visser et. al., 2014). This gradient is affected by ambient temperature, relative humidity, wind speed and precipitation. Yearly trends for these factors result in moisture content decreasing in summer and increasing in winter. This study also found that small logs (<35cm diameter) and logs that were split dried faster than larger logs (>35cm diameter). Figures 3 and 4 below show the moisture content trends found in the study (Visser et. al., 2014):

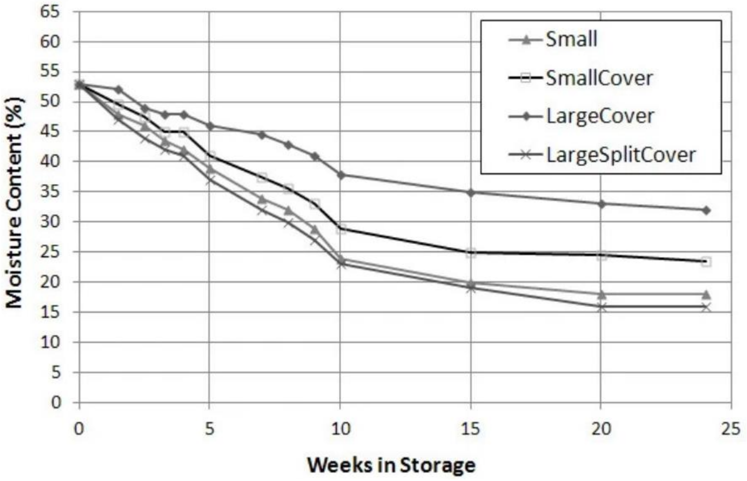

Figure 3: Moisture Content Relative to Weeks in Storage in Summer (from Visser et. al.)

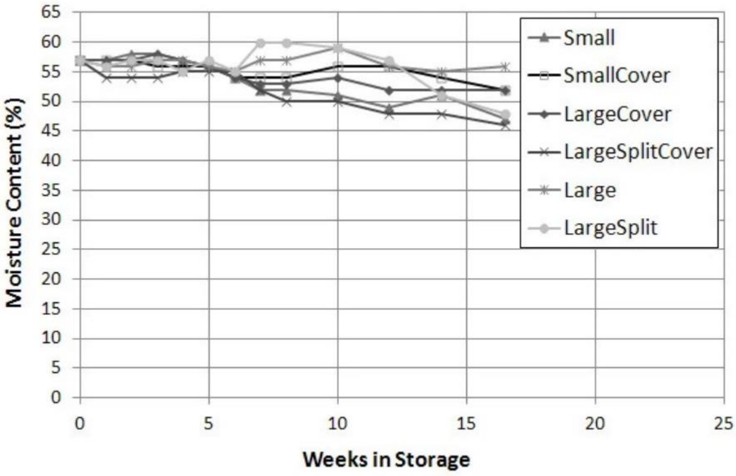

Figure 4: Moisture Content Relative to Weeks in Storage in Winter (from Visser et. al.)

Although this study aimed to determine the effects of storage on the moisture content of the wood, it can also be used to estimate approximate trends for moisture content through the year. This study can be compared with the average relative humidity and precipitation trends for New Zealand to justify why the moisture content is changing like this. Moisture content is directly proportional with relative humidity and precipitation. If relative humidity or precipitation increases, moisture content also increases. These factors change the moisture gradient between ambient air and wood, leading to a change in moisture content. World Data Info has relative humidity and precipitation information available by country. The data for New Zealand is shown in Figures 5 and 6 below (WDI, 2023):

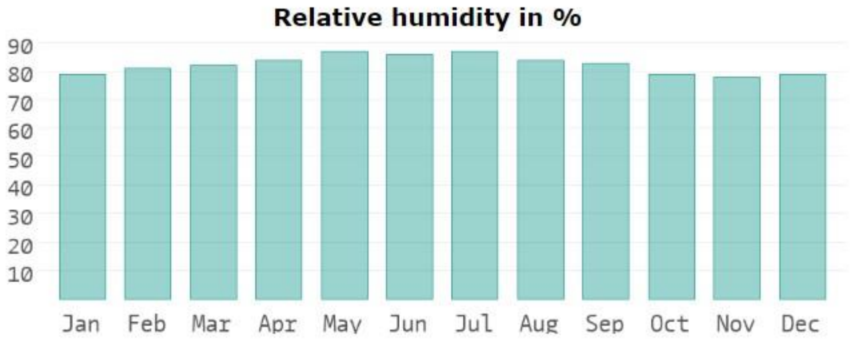

Figure 5: Relative Humidity Yearly Trend for New Zealand

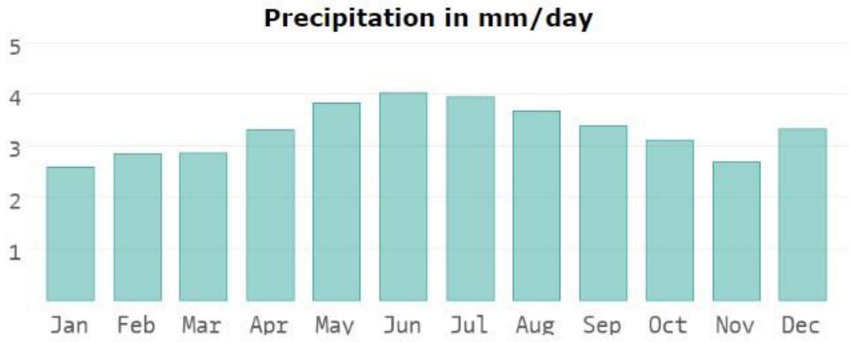

Figure 6: Precipitation Yearly Trend for New Zealand

Another study into the radial gradient of silver birch wood in different seasons found the same trend as Visser et. al. The study found that the lowest average moisture content could be found in summer and the highest in winter (Tomczak, Arkadiusz, Naskrent, & Jelonek, 2021). This shows an average trend for moisture content through the seasons; however, it does not allow for future predictions. The study was carried out on 50-year-old standing trees, so the size and material are not applicable to this study, but the trend is still relevant. The results for this study are shown below in Figure 7, where JW is juvenile wood, IMW is inner mature wood and OMW is outer mature wood:

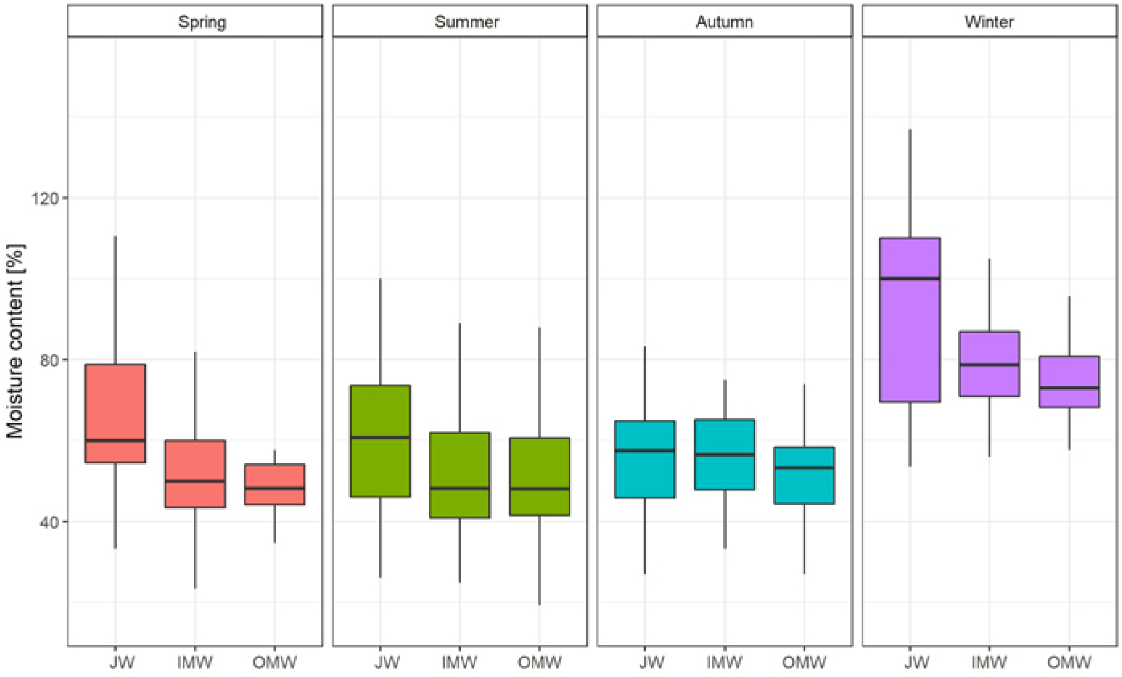

Figure 7: Moisture Content Changes on the Cross-Section of Silver Birch by Seasons

A third study into the changing moisture content of uncovered firewood in Southern Europe was carried out for 180 days starting in winter and ending at the end of summer. This study found the moisture content consistently dropped until a plateau was reached. As it began in summer, this meant that it was again proving the seasonal trend. It also found there was no relationship between diameter or position in the stack of the wood and moisture content. The study was conducted on poplar and black locust. The results for the 180 days of drying are shown in Figure 8 below:

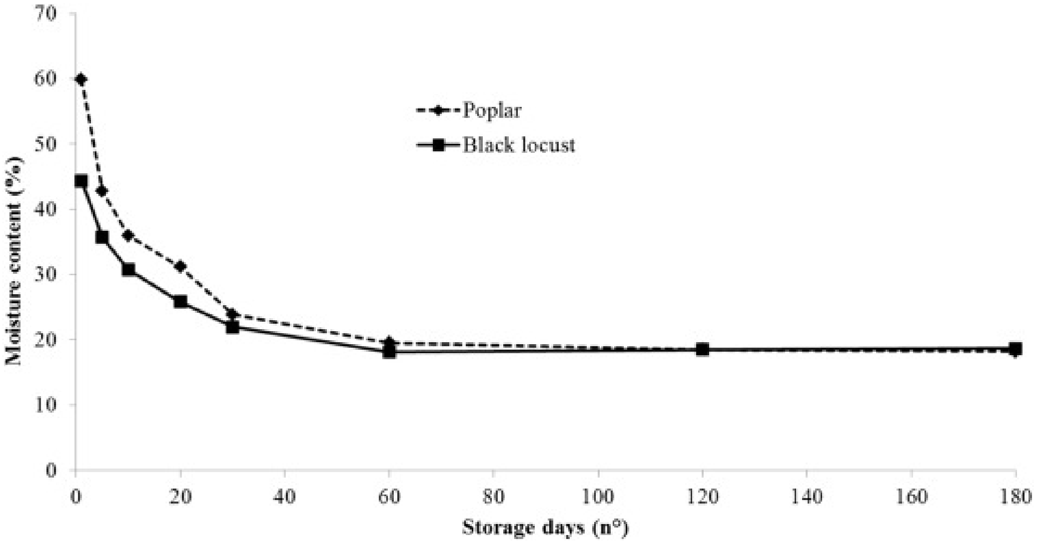

Figure 8: Moisture Content of Piles During the Six-Month Storage Period

5 Objective

The objective of this project is to develop a temporal estimate for energy content of stored production forest harvest residues. To do this, a relationship between moisture content of harvest residues and the NZFDRS will be identified. Historic NZFDRS trends will then be used to determine a model for the changes in moisture content of the residue throughout the year. This can be compared to the current coal consumption estimates given by MBIE to determine energy balances.

6 Methodology

6.1 Investigate Correlation Between Moisture Content and NZFDRS Indices

6.1.1 Sites

The initial portion of the study involved gathering the data for the changes in moisture content to compare to the NZFDRS indices. This was carried out by assessing 48 logs extracted from harvest residue piles. 24 logs were from a 2021 harvest and 24 were from a 2022 harvest to determine if there was a difference in the reaction to the fire indices with age and if so, when this difference was. These logs were cut to a length of 1.5 m or smaller, so they were short enough to be transported but still long enough to be representative of average harvest residue. All log diameters were within a range of 10-25 cm and weighed under 30 kg initially. This limitation was due to having to lift the logs by hand and the weighing scales having a maximum weight of 30 kg. The logs were situated across two forest sites in the Nelson region: Dovedale and Hira. Both sites have weather stations nearby, so fire index values were an accurate representation. The site locations and proximity to weather stations are shown below in Figures 9 and 10.

Figure 9: Dovedale Forest Sites

Figure 10: Hira Forest Sites

6.1.2 Moisture Content

The moisture content was calculated at the start of the trial using the gravimetric method. This was done by destructive testing involving the removal of two sections from each log and averaging their moisture content. To ensure the samples were representative of the whole log, one section was taken from only outerwood and one from both corewood and outerwood. There is relatively a larger proportion of outerwood to corewood in logs so this allowed the samples to be representative. These samples were taken to the university lab and dried at 105°C until the change in mass over 24 hours was less than 0.2% of the original weight (Mikulova, Vitazec, & Klucik, 2014). The samples used are shown in Figure 11 below. Moisture content was calculated on a wet basis so the moisture content could be used in the heat capacity equation. The formula used for moisture content was:

$$MC_{wb} = \frac{Water\ in\ Sample}{Total\ Weight} = \frac{Current\ Weight - Dry\ Weight}{Current\ Weight}$$

Figure 11: Initial Moisture Content Samples

To find the changing moisture content in the residues over time, the initial measurements of moisture content were used to calculate a total dry weight for each individual log. This was done by multiplying the percentage of wood content of the sample by the initial weight of the whole log:

$$W_{dry} = (100\% - MC_i) * W_i$$

The dry weight was used to estimate the moisture content on a wet basis in the samples over time by calculating the difference between the wet weight and dry weight, e.g., the amount of moisture in the log, and dividing it by the wet weight:

$$MC_{current} = \frac{W_{current} - W_{dry}}{W_{current}}$$

6.1.3 Measurement

The green logs and aged logs were stored on separate pallets for 14 weeks. They were weighed every Monday and Thursday recording the weights to calculate moisture content. The FDI's were also recorded every day the logs were weighed. The scales used had a sensitivity of 0.005 kg and were placed on levelled concrete pavers that were installed at each site. Pallets were used to avoid interference from ground conditions. Refer to Figure 12 and 13 for the in-situ setup.

Figure 12: Hira Site Set-Up

Figure 13: Dovedale Site Set-Up

6.1.4 Within Sample Variation

To ensure the samples selected were acceptable to use for accurate regression analysis, t tests were carried out. These t-tests investigated statistical differences in volume, density, length and moisture content. The moisture content t-tests were conducted as a whole population with all values, between green samples of different sites, between aged samples of different sites, and green and aged samples between sites. The t-test data was beneficial to determine if statistically significant results could be identified using the samples. Results could be analysed when the tests showed no significant statistical difference.

6.1.5 Data Analysis

Correlations were determined by comparing the recorded NZFDRS indices with the moisture content of the residues of individual logs. This meant that for each NZFDRS index value, there was a range of moisture content values from the logs. The NZFDRS codes used were: FFMC, DMC, DC, ISI, BUI, FWI, wind speed, and 24-hour rainfall. The moisture content values were analysed to find any points of potential incorrect data or outliers, then the values were averaged. This gave a single averaged moisture content value for each NZFDRS index value. To find statistical differences in the data, t-tests were used to compare sites against the indices to determine what populations were available for analysis. This means, if there were no statistical differences between these factors, the results could be considered a single population. The t-tests used depended on the variance of the sample. If the difference in samples variance was greater than a 1:4 ratio, a t-test assuming unequal variance was used and if less than 1:4, a t-test assuming equal variance was used.

The second point of difference in populations was the difference between green and aged log samples. To identify the juncture at which the aged residue reacted the same as the green residue, the difference between moisture contents of the two age classes were plotted and assessed.

Once populations were analysed, the raw data was grouped by indices to find the index with the strongest relationship to the moisture content. To ensure analysis was carried out on populations of sample sizes greater than 30 ($n > 30$), only populations with no statistical differences between sites were used. The correlations were tested using correlation data analysis in excel.

Once the strongest correlation was found, linear regression was carried out to determine the relationship between moisture content of the residues and the strongest code. The first step was to analyse different line transformations. Moisture content was transformed to a series of curves and plotted against the index code. The initial transformations were assessed using regression data analysis in excel to analyse the residual plot, determining potential further trends and transformations. The outcome of this linear regression gave a linear equation that could be transformed using the initial line transformation. This equation is the final relationship between the NZFDRS code and the moisture content of harvest residue.

To determine the temporal change in moisture content of harvest residues, the relationship had to be applied to the historic trends for the NZFDRS codes. The past data for the trends was applied to the relationship, along with confidence intervals. This resulted in a graph showing how the moisture content will change throughout yearly trends.

Finally, the temporal energy content was found using the equation derived by Koppejan and Van Loo (Koppejan et. al., 2008):

$$Energy\ (GJ/t) = 18.9 - 0.213 \times MC_{wb}$$

This equation was applied to the estimated moisture contents found by the NZFDRS codes trends to provide a temporal energy estimation.

6.2 Determine Possible Supply Volumes

To determine the supply volumes in the Nelson/Tasman region, global forest change data from EarthMap was analysed in ArcGIS. This found the total areas and approximate age of exotic production forestry in the region (EarthMap, 2023). The data ranged from 2001 to 2021 and could be analysed in 5-year groups. This analysis involved finding the differences between area polygons in the different age classes. The data was then exported to a spreadsheet and converted to volumes using Harvey's methods for estimating volumes of landing harvest residue (Harvey, 2022). Once polygons had volumes, a model of trucking distances to the Eves Valley mill could also be created to determine what volumes of residues were efficient to utilise. This distance was assumed to be 100 km as an initial range but depending on the region and sites, this distance could change.

7 Results and Discussion

7.1 Determining Populations

To find statistical populations for the collected data, the outliers and incorrect points had to be identified and removed. To do this, the individual moisture content values for the logs were graphed to examine how they compared to each other. Three logs were then removed from the raw data in each site, resulting in 21 logs per site. The individual log moisture content values for every measurement day were averaged out resulting in the moisture content trend shown in Figure 14.

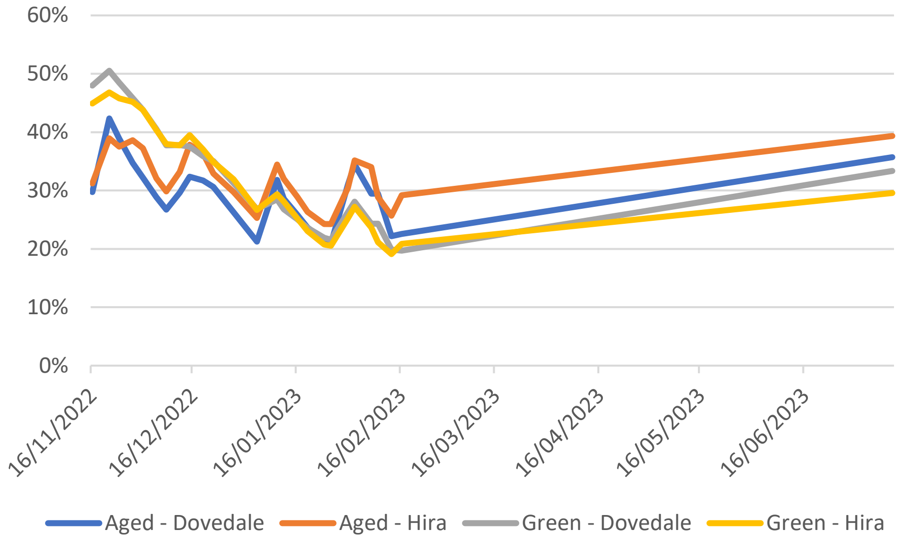

Figure 14: Collected Moisture Content Data

To determine if the two sites could be a combined population, t-tests were used to determine if there were any significant ($p < 0.05$) differences between the data at the sites. To carry out a t-test, the variation ratio had to be tested to find if the populations had equal or unequal variance. If the variance ratio was greater than 1:4, the population would have been tested for unequal variance but as the variance ratio was less than 1:4 for all ratios between sites, t-tests assuming equal variance were used. The variance ratios for the NZFDRS index values between sites are shown below in table 3.

Table 3: Individual Variance Ratio

Code	Ratio
FFMC	1.24
DMC	1.34
DC	3.30
ISI	2.55
BUI	1.67
FWI	3.02
Temp	1.00
Relative Humidity	1.56
Wind Speed	2.46
24 Hr Rainfall	2.06

The results of the t-tests determined that the DC and wind speed showed significant differences between sites. If analysed, the sites would have to be considered as two different populations. This means the sample size would be less than 30 and therefore should not be used to make statistical inference. The FFMC, DMC, ISI, BUI, FWI, temperature, relative humidity and 24-hour rainfall all showed no significant difference in a two-tailed test ($p > 0.05$) therefore, they were considered a single population. This meant a larger range of index codes and moisture content values so the certainty in the final equation could be higher due to a larger sample size.

The second potential difference in populations was the age of the log samples. To identify the juncture at which the age of the residue no longer influenced moisture content, the difference between moisture contents of the two age classes were plotted. This gives a time value to define which of the final equations should be used for moisture content predictions. The difference was negligible (0% - 1%) from 12th December 2022 - 4th January 2023, however the response to rainfall after this period resulted in the age classes differing again. Green logs were not as responsive to rainfall after this period, resulting in a negative difference in moisture content after 4th January 2023. Due to this, the difference in moisture content after the study was still too great to consider the age of the residue a single population at any point. For the remainder of the analysis, they have been considered as different populations. The difference between average moisture contents of the green and aged residues are shown below in Figure 15.

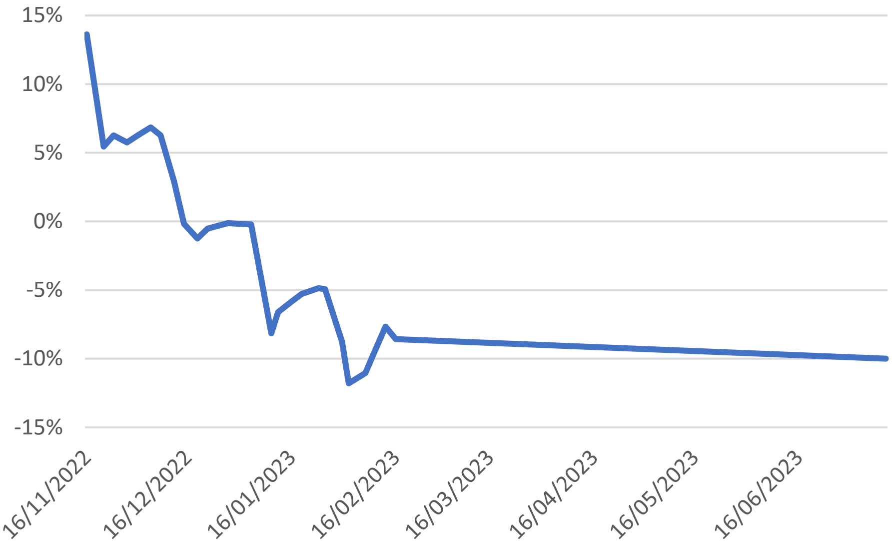

Figure 15: Moisture Content Difference Between Aged and Green Harvest Residues

Though no junction between the different age classes could be found from this study, the aged residue was known to be one year old, and the green residue was one month old initially. This means that the aged relationship can be used for residues that have been stored for at least one year and the green relationship can be used for residues that have been stored for up to one year.

7.2 Correlations

As aged and green samples were determined to be different populations, the moisture contents were tested individually against the NZFDRS indices to find the correlation strength. For both aged and green wood, the BUI had the strongest relationship with moisture content. Table 4 shows the correlations for the codes assessed.

Table 4: Correlations

	Aged	**Green**
FFMC	0.68	0.40
DMC	0.89	0.57
ISI	0.74	0.43
BUI	0.92	0.60
FWI	0.80	0.48
Temperature	0.55	0.51
RH	0.34	0.21
24Hr Rain	0.33	0.07

7.3 Linear Regression

The initial transformations assessed were:

- $\frac{1}{MC}$
- $\frac{1}{MC^2}$
- $\frac{1}{\sqrt{MC}}$
- $\frac{1}{\ln MC}$
- $\log \frac{1}{MC}$

The strength of the correlation with the transformed moisture content was tested against the NZFDRS indices. The green logs showed the strongest correlation with $\frac{1}{MC}$ while the aged logs showed the strongest correlation with $\frac{1}{MC^2}$. These were the transformations used for the linear regression. Using excels data analysis regression function, the following residual plots shown in Figures 16 and 17 were found:

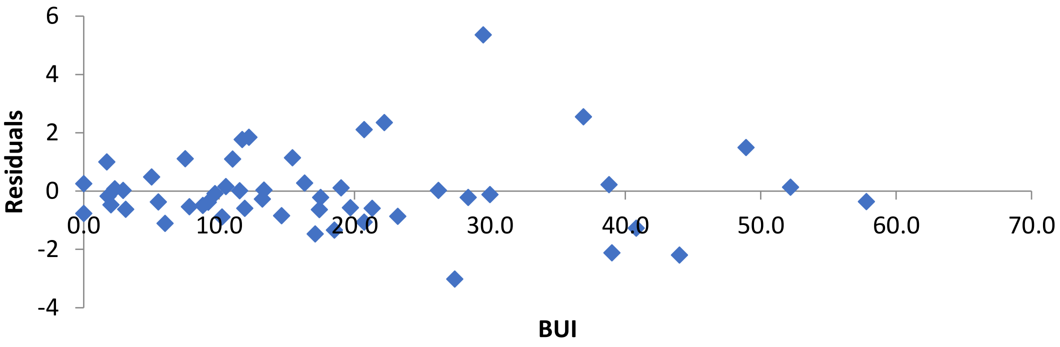

Figure 16: Linear Regression for Aged Samples

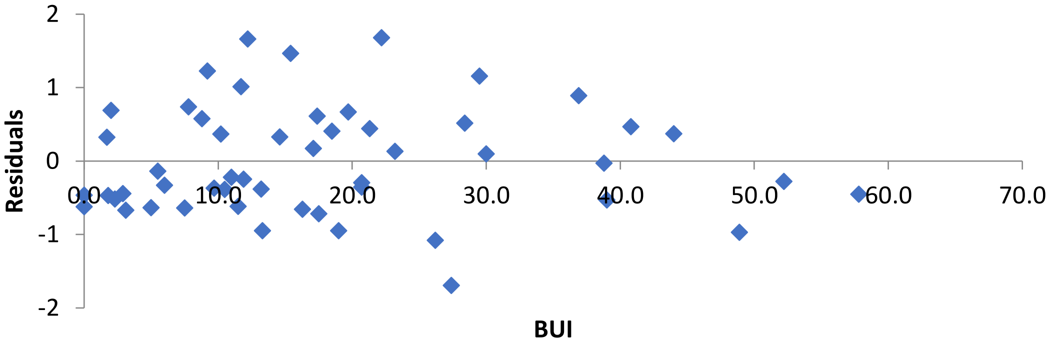

Figure 17: Linear Regression for Green Samples

As the spread of these residual graphs does not show any of the trends for linear transformations, these are the final linear transformations that will be used. If the residuals followed any of the trends discussed by Zar, further transformations would have been made to get a stronger correlation (Zar, 2010). However, further transformations made the correlation weaker, so the initial transformations were applied. The line fit plots for the resulting relationship are shown in Figure 18 and 19 below.

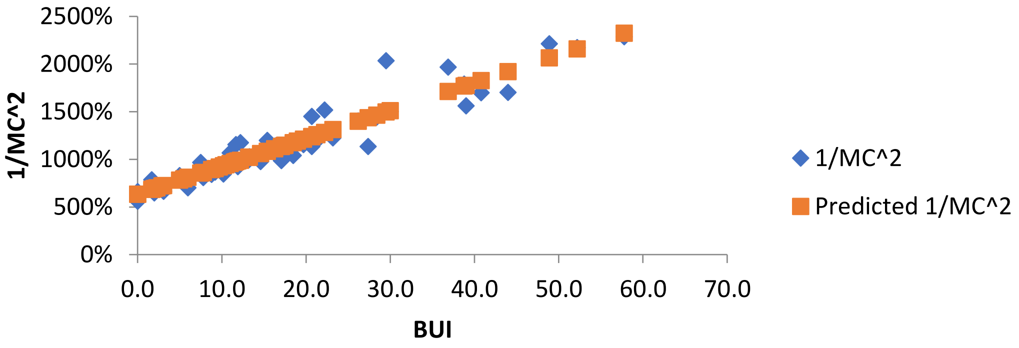

Figure 18: Aged Regression Line Fit Plot

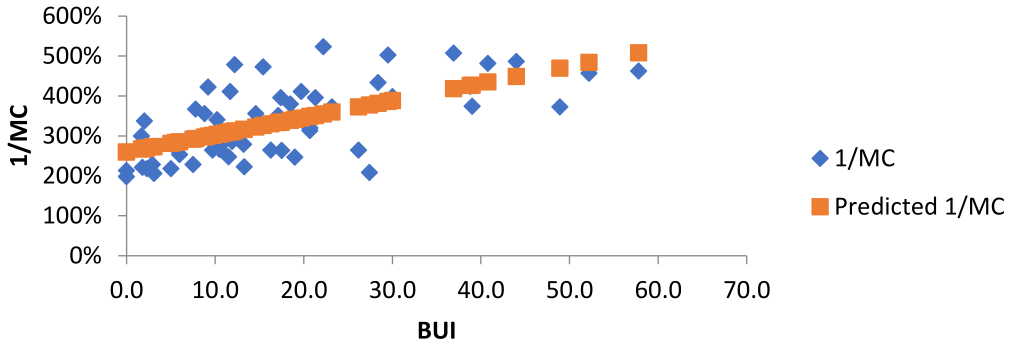

Figure 19: Green Regression Line Fit Plot

The resulting graphs for the relationship between moisture content and BUI are shown in Figures 20 and 21 using the linear equation and transformation from the regression analysis. The upper and lower limits are using the upper and lower 95% intervals from the regression analysis.

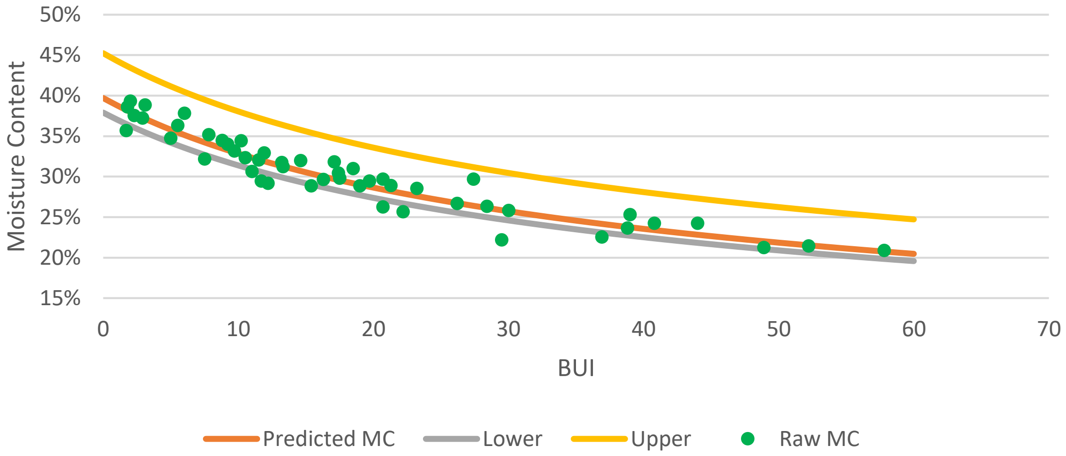

Figure 20: Final Aged Relationship

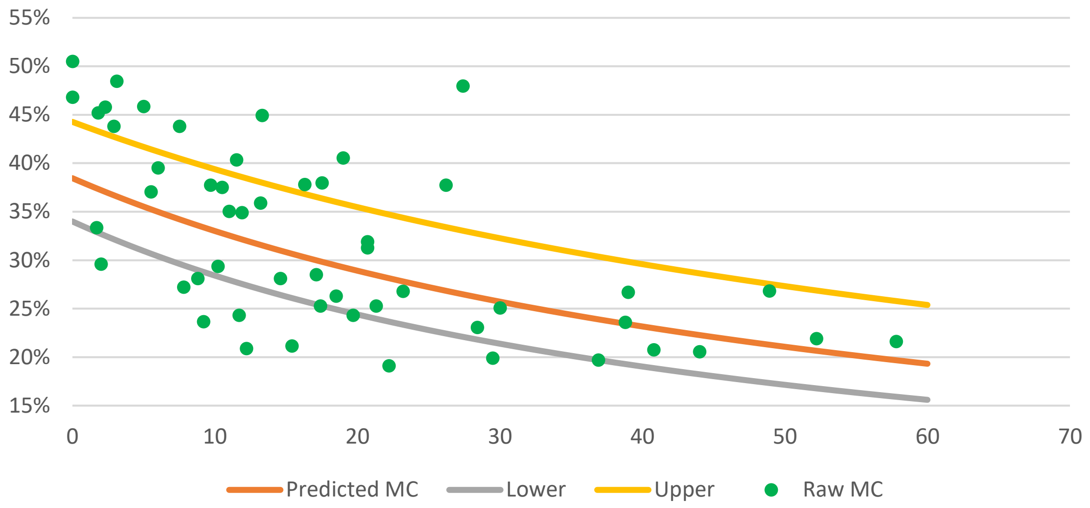

Figure 21: Final Green Relationship

The correlation for the aged logs was significantly stronger at 0.95 than the green logs at 0.63. The final equations for each of the lines are:

Aged, predicted moisture content: $$MC = \frac{1}{(0.29 * BUI + 6.24)^{\frac{1}{2}}}$$

Aged, lower bound: $$MC = \frac{1}{(0.32 * BUI + 6.96)^{\frac{1}{2}}}$$

Aged, upper bound: $$MC = \frac{1}{(0.27 * BUI + 5.73)^{\frac{1}{2}}}$$

Green, predicted moisture content: $$MC = \frac{1}{0.04 * BUI + 2.60}$$

Green, lower bound: $$MC = \frac{1}{0.06 * BUI + 2.94}$$

Green, upper bound: $$MC = \frac{1}{0.03 * BUI + 2.26}$$

The buildup index is therefore identified as the best indicator for moisture content for the samples used in this study. This showed the strongest correlation for both green and aged log samples, however the correlation for the aged logs was a lot stronger at 0.95 than the green logs at 0.63. The strength of the green relationship is considered moderate, but as the aged relationship was very strong, it would provide far greater accuracy in the assumption of energy content. Due to this, only the aged relationship was used for further supply analysis to reduce uncertainty of the result. The temporal moisture content analysis used the green relationship alongside the aged as a comparison.

7.4 Temporal Moisture Content

The relationship between the BUI and the moisture content of harvest residues can be applied to the historic trends for the BUI by averaging the daily BUI data from 1993-2021 retrieved from the FENZ website (FENZ, 2023). This data gives the average yearly trend for the BUI which is then used with the relationships developed above to estimate the temporal moisture content. The BUI trend is shown below in Figure 22.

Figure 22: Average BUI Trend

From this trend, the relationship between BUI and moisture content was applied resulting in the temporal moisture content models in Figures 23 and 24 below.

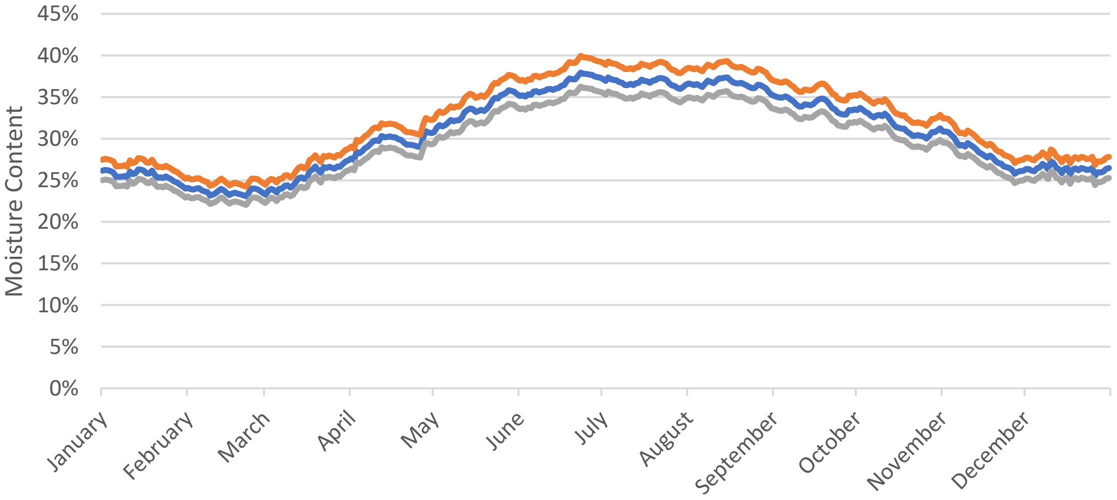

Figure 23: Temporal Moisture Content for Aged Residues

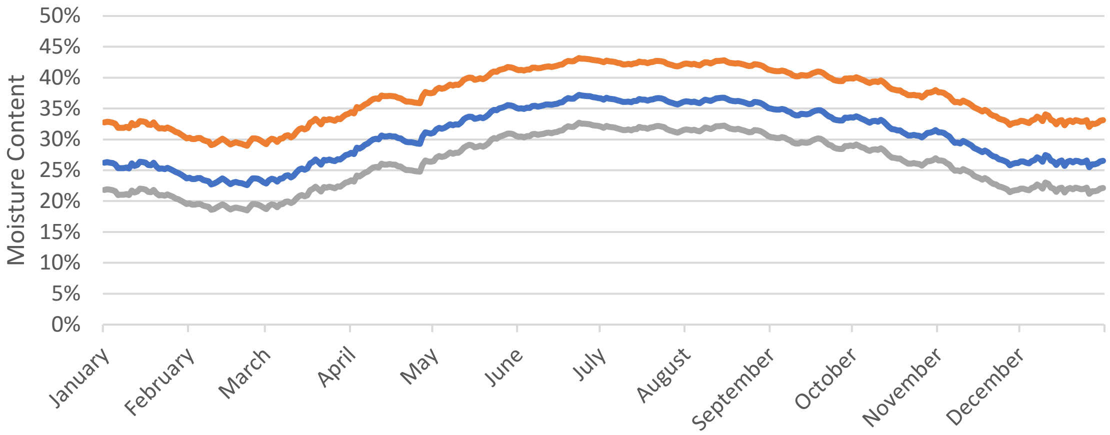

Figure 24: Temporal Moisture Content for Green Residues

7.5 Temporal Energy Estimation

The final step in using the moisture content data is to relate it to the energy content in residues by applying the following relationship to the models in Figures 23 and 24:

$$Energy\ (GJ/t) = 18.9 - 0.213 \times MC_{wb}$$

The resulting energy content trends are shown in Figures 25 and 26.

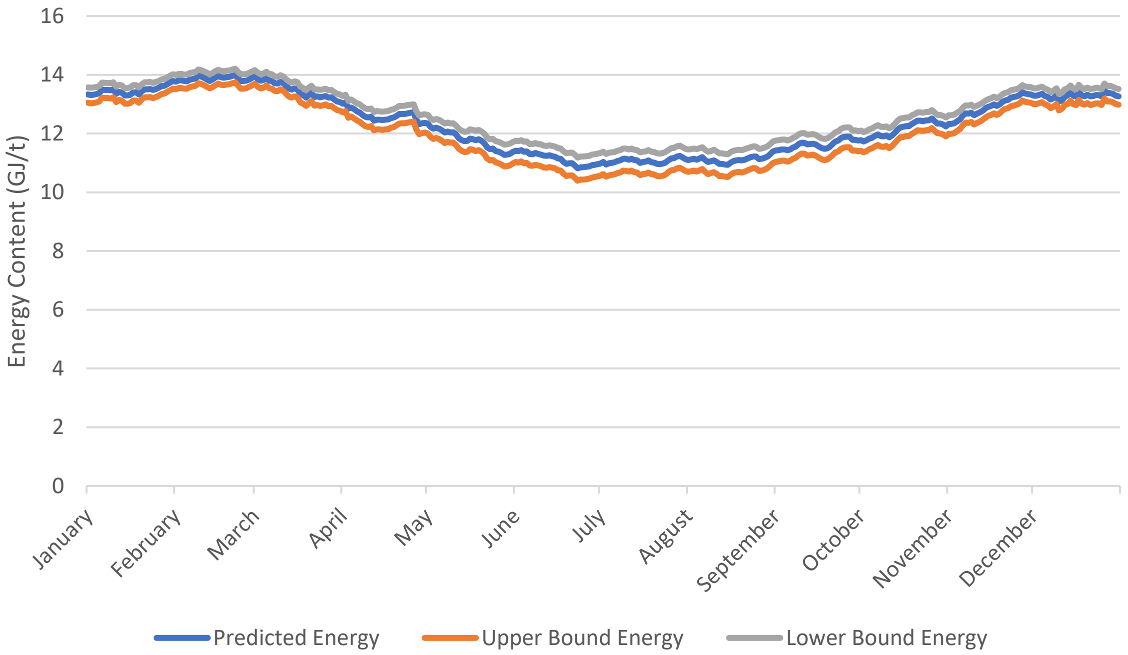

Figure 25: Aged Residue Energy Content

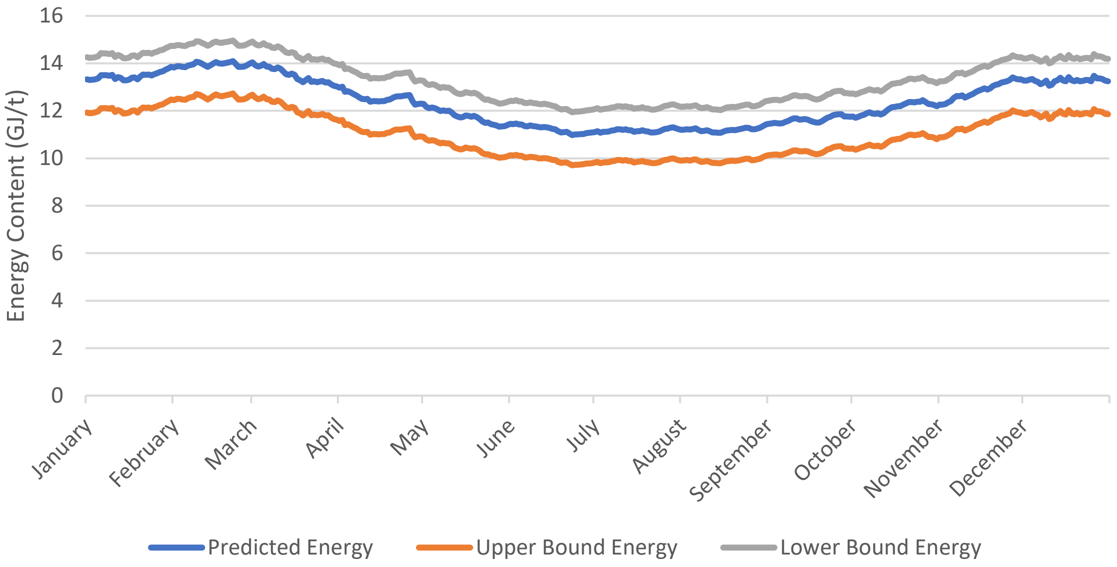

Figure 26: Green Residue Energy Content

7.6 Supply Volumes

In order to utilise the above relationships, the volumes of wood available in the Nelson/Tasman region were considered. The net stocked area of plantation forests in the Nelson/Tasman region is 92,313 ha with a standing volume of 26,439,000 m^3 (EarthMap, 2023). The age class distribution of this forest area is largely centred around ages 16 to 20, so in approximately the 11 to 15-year forecast, the harvest area is expected to be at its largest. This is shown in Figure 27. However, this is not considering the harvest of the over mature stands in the first 5 years so the largest harvest area is shown to be expected in the first 5 years, shown in Figure 28. Any Radiata stands older than 35 years and Douglas stands older than 60 years are considered non-commercial and were not included in the planned harvest of overmature stands.

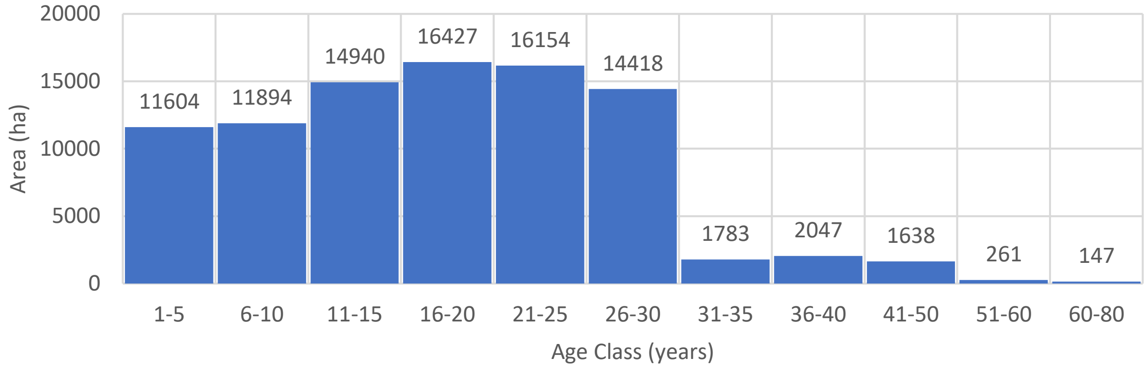

Figure 27: Age Class Distribution for All Plantation Forests in the Nelson/Tasman Region

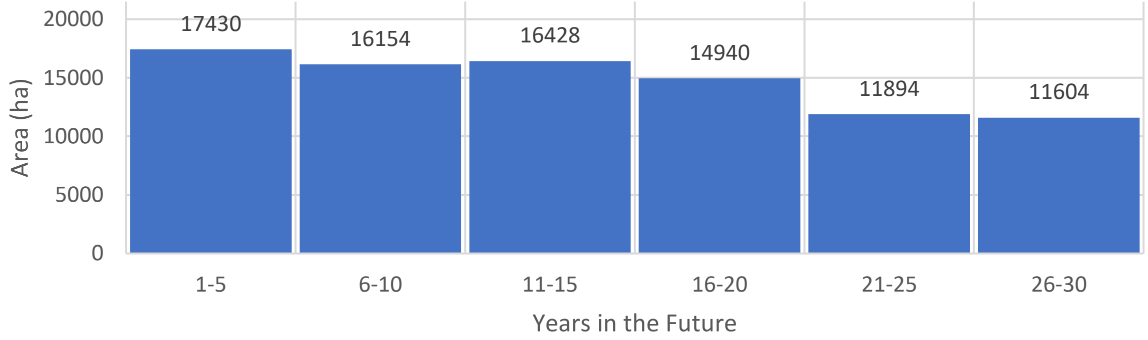

Figure 28: Forecast Harvest Areas for Plantation Forests in the Nelson/Tasman Region

From these forecasts, the volume of predicted landing residue can be calculated using the estimated 17 m^3/ha from Harvey's study (Harvey, 2022). This results in the expected supply volumes for the Nelson/Tasman region shown in Figure 29. This gives the total volume expected in each 5-year interval rather than individual years.

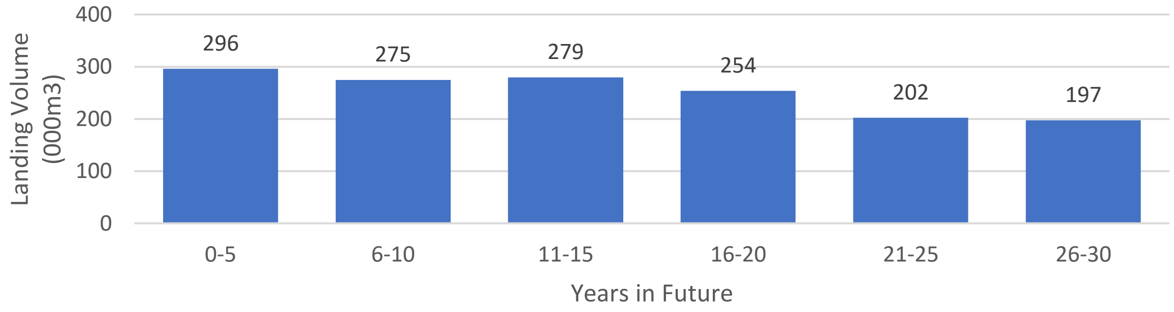

Figure 29: Expected Landing Residue Volumes

Assuming that the harvest volumes are spread equally across the year, the values in Figure 29 can be split into each year, then each month. Finally, the average monthly temporal energy estimation can be used to determine the approximate monthly energy content in one-year old harvest residue in the Nelson/Tasman Region. Table 5 below shows the energy content available in PJ/month for each of the 5-year groups.

Table 5: Available Energy in PJ Per Month for 5-Year Groups

	0-5	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**
January	0.13	0.12	0.13	0.11	0.09	0.09
February	0.14	0.13	0.13	0.12	0.09	0.09
March	0.13	0.12	0.13	0.11	0.09	0.09
April	0.12	0.12	0.12	0.11	0.09	0.08
May	0.12	0.11	0.11	0.10	0.08	0.08
June	0.11	0.10	0.10	0.09	0.08	0.07
July	0.11	0.10	0.10	0.09	0.07	0.07
August	0.11	0.10	0.10	0.09	0.07	0.07
September	0.11	0.11	0.11	0.10	0.08	0.08
October	0.12	0.11	0.11	0.10	0.08	0.08
November	0.13	0.12	0.12	0.11	0.09	0.08
December	0.13	0.12	0.12	0.11	0.09	0.09
Yearly Total	**1.5**	**1.4**	**1.4**	**1.3**	**1.0**	**1.0**

As the purpose of this report is to reach a more accurate conclusion about the potential of harvest residues to replace coal boilers, these values must be compared to the current coal demand. The value for this was retrieved from the MBIE website as 1.1PJ p.a. for the Nelson/Tasman Region (MBIE, 2019). This means that following the estimation for moisture content based on the BUI, for the next 20 years, the region produces more than enough harvest residue to replace coal as an energy source for the region. After 21 years, the region does not produce enough harvest residue from the landings alone, however, the cutover volumes have not been considered in this study. The excess residues from the next 20 years could also be used to meet the difference between the required energy and the available for the remaining 10 years.

8 Further Research

Further research in this area could involve other areas that need a more detailed analysis. This could include other areas in the published MBIE report similar to the Nelson/Tasman Region where the current forecast harvest residue energy content is lower than the current coal consumption. This report only investigated the relationship between moisture content and BUI in the Nelson/Tasman Region, and may, therefore, not be applicable to the rest of the country. If the results in the current MBIE study show that the residual biomass supply is larger than the coal demand in the region, e.g., Marlborough, Otago, or Bay of Plenty Regions, repeating the study may not be justified. For the other regions where this will make a difference, it may be worth repeating.

Another further research area could be around storage of the residues, as the excess yearly residue may need to be stored for use in later years. There would be many solutions for where the residues could be stored but the effects of decay on the wood after storage for over one year may need to be investigated. At the end of this trial, there was a significant presence of insects, bugs, and fungi on the residue. This could affect how the residues react to external weather factors, therefore making the relationship inapplicable. This would determine the end of the age range that the aged relationship could be applied to.

Knowing the energy content of the total harvest residue, further research could be done into maximizing this energy content. This could be in the form of biochar, palletization, gasification. How the products could be used to maximize the energy content while minimizing wastage would also be beneficial.

The reason for the Carbon Neutral Government Program is to move towards a lower carbon future. Therefore, a future study could assess the effects of transportation on the net carbon in using harvest residue as a biofuel. This could compare the effects of transporting green or aged residues on fuel consumption along with volumes of residue able to be transported.

A final further research area could be determining if it is possible for the harvest residue to meet increasing energy consumption trends. This would investigate the forecast energy consumption, then project moisture content relationships to determine if harvest residue biomass is still a viable option to replace coal.

9 Conclusion

The objective of this project was to determine whether landing harvest residue can be used to replace coal energy in boilers. To determine this, a relationship was found between moisture content and an external factor that had sufficient historical data: the New Zealand Fire Danger Rating System (NZFDRS) fire weather index codes. The moisture content of both green and aged logs had the strongest correlation with the buildup index (BUI). This code indicates the total amount of forest fuel available for combustion.

The relationship between moisture content in aged logs and BUI was the strongest at a correlation of 0.95 for while the correlation for green logs was only 0.63. Green residue was considered aged once it reached one year old. The aged relationship was used for further energy estimations due to the higher correlations resulting in lower uncertainties. The relationships for both age classes are given below:

Aged, predicted moisture content: $MC = \frac{1}{(0.29*BUI+6.24)^{\frac{1}{2}}}$

Aged, lower bound: $MC = \frac{1}{(0.32*BUI+6.96)^{\frac{1}{2}}}$

Aged, upper bound: $MC = \frac{1}{(0.27*BUI+5.73)^{\frac{1}{2}}}$

Green, predicted moisture content: $MC = \frac{1}{0.04*BUI+2.60}$

Green, lower bound: $MC = \frac{1}{0.06*BUI+2.94}$

Green, upper bound: $MC = \frac{1}{0.03*BUI+2.26}$

The historical trends for the daily BUI were recorded from the FENZ website from 1993 to 2021, then values from each day were averaged to find the yearly trends. The moisture content through the year could be estimated based on the yearly trends and therefore, the energy content could also be estimated. This resulted in a moisture content range between 23% to 40%, depending on the time of year. The calorific equation was then applied to the estimated daily moisture content resulting in an energy content range between 13.98 GJ/t to 10.81 GJ/t for aged wood. This is significantly higher than the usual 6-7 GJ/t expected from green wood in previous studies.

The final step was to assess the amount of forest area in the Nelson/Tasman region and apply the estimated energy content values to this area. The total area was 92313 ha of varying ages which resulted in a total possibility of 1.5 PJ p.a. for the next 5 years of harvest. The total coal usage was given to be 1.1 PJ p.a. by MBIE and therefore, the harvest residue from the next 5 years should be able to replace coal.

The issues with this prediction were that this included harvesting overmature stands so in reality, the energy content would be lower due to a lower volume of harvest. It also does not account for the need to store residue for one year before it is usable and therefore, there will be no aged residue available for the first year. The actual harvest could also be different to the assumed volumes due to the assumption based on only mapping forest loss.

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