Tasman Orchard Burn Experiments

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Report information sheet

Report title	Tasman Orchard Burn Experiments
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Client	Tasman District Council
Signed off by	Richard Parker
Date	August 2020
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Glossary

Aspect: Direction toward which a slope or topography predominately faces.

Combustion efficiency: A measure of how well the burning fuel is used during the combustion process

Fuel: Combustible material. For this case, this includes, vegetation, such as grass, leaves, ground litter, plants, shrubs and trees, and organic material in dirt.

Fuel Consumption: mass of fuel consumed per time unit

Fuel Moisture (Fuel Moisture Content): The quantity of moisture in fuel expressed as a percentage of the weight when thoroughly dried at 100 degrees Celsius.

Fuel Packet: Wood organised into a consistent volume ready for burning. Packets are standardized and documented for total weight, species ratio, log diameter, time since cutting, drying conditions and moisture content. Packets were standardized to ensure that each burn received the same fuel contents.

Fuel Type: An identifiable association of fuel elements of a plant species type (i.e. grass, shrub, forest), with similar form, size, arrangement, or other characteristics that will cause an indicative rate of fire spread or difficulty of wildfire control under specified weather conditions.

Fire Intensity: The rate of heat energy released by a fire, the energy released per unit time per unit area of actively burning fire. Closely linked to the amount of fuel available to burn and combustion efficiency.

Flammability: The ability of vegetation (in this case) to burn or ignite, causing fire or combustion.

Green wood: Recently cut wood that has not had an opportunity to dry. Green wood contains more moisture compared to dried (also known as seasoned wood)

Particulate matter (PM): Particulate matter this is the term for a mixture of solid particles and liquid droplets found in air. Particles range in size from visible to microscopic.

$PM_{2.5}$: Particulate matter with a diameter of 2.5 µm or less. Particles of this size are fine and inhalable and cause poor health effects.

Plume: A cohesive and continuous fluid (note: air is considered a fluid) of different properties compared to the surrounding fluid.

Plume height: Height of the plume. Different plume heights can result from vegetation fire resulting in different plume transport directions, spread and speed. Observed plume height for this case, it is the top of the visible plume near the fire.

Executive summary

Agricultural burning is a large contributor to particulate matter air pollution that exceeds the National Environmental Standards in the Tasman District. To improve understanding of the agricultural burning challenge, the Tasman District Council, working in partnership with Scion, undertook a field-based research trial to monitor the effectiveness of current best practice for outdoor wood burning. The results of this research are presented in this report. The research questions this study aims to answer are:

1. How does the fuel consumption (mass of fuel consumed per time unit) differ with methodology?
2. How does combustion efficiency, a measure of how effectively the energy content of a fuel is transferred into heat, differ with methodology?
3. How does smoke generation (measured as $PM_{2.5}$ and smoke plume height) differ with methodology?

Summary of results are:

- Consumption values, normalised to account for different amounts of fuel used and timing of the burns, show that Burn 3, new technique was the burn with the highest fuel consumption efficiency.
- Fire intensity values show that that Burn 3, new technique, was the hottest fire and held a high temperature throughout the burn period, consuming all available fuel by quarter 4.
- Plume rise was very high and at times almost invisible for Burn 3, new technique, due to the efficiency of the burn and the lack of particles in the plume. $PM_{2.5}$ concentrations were the lowest during quarters 1 and 2 of Burn 3, but also the highest during quarters 3 and 4. Indicating that with refined protocols the new technique could offer reduced emissions and a cleaner burn of recently removed orchard wood.

Recommendations based on the results of this research are as follows:

- To maximise fuel consumption and burn efficiency, a burn should be ignited with an ignition pile e.g. apple crate method and a large fuel pile (approximately 1 tonne) and fuels should be added incrementally, once the fire is burning hot. A fire created from a large pile, such as the standard practice burn practice, that is left burning without adding additional fuels will not consume fuels or combust as efficiently as a fire to which fuels are added over time.
- The new technique burning method with a fan blowing onto the fire shows significant potential to increase fuel consumption and burn efficiency, but this method needs further refinement as the force of air blown by the fan was found to entrain surface ash into the fire's plume leading to large spikes of $PM_{2.5}$ concentrations as observed during quarters 3 and 4 of Burn 3. There is likely an optimal ratio of wood pile size to fan size, and the amount of air blown through the trench, this is unknown at this time.
- When using the new technique, the use of a fan with a variable flow rate should be investigated so that the fan air output can be reduced as the fuels are consumed. Optimisation of the fan's output will help reduce the black carbon particle emissions, keeping the ash and soot on the ground. It is possible that the fan is only beneficial at the start of the burn and does not add additional benefit after the fire achieves a solid base of embers, but this should be tested with green wood before removing the fan.
- The new technique is suitable for when burning needs to happen as fast as possible in a limited amount of time, as when avoiding a morning and evening inversion, and it is possible to do it at midday, when atmospheric dispersion potential is at its highest
- It is recommended that the trench for the new technique is created parallel to the expected wind direction to maximise airflow through the pile.
- The apple crate ignition technique tested in this study showed significant potential and is recommended as a suggested protocol.

- Reshaping of burning piles with large machinery causes high $PM_{2.5}$ emissions and should be kept at a minimum. Management of the woodpile should limit collapse of the centre that would necessitate reshaping of the pile.
- Using the smallest heavy machine for the work has potential to help reduce $PM_{2.5}$ emissions during reshaping as this will allow for increased accuracy.
- The new technique offers the largest possibility of reducing particulate and pollutant gas emissions if refined to reduce emissions as smouldering sets in.

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1 Introduction

During clear winter nights the air at or near ground cools and becomes colder than the air in the layer above it. The cold air sits on the ground; cold air does not rise, and vertical air motion is non-existent unless an obstacle (i.e. hill) is encountered. This phenomenon is called an inversion. When there is an inversion the air temperature near the ground is colder than the air aloft (this is a skier's nightmare, finding out that the ski hill is above freezing, while in the town below it is experiencing freezing temperatures).

The lack of vertical motion in the atmosphere results in air pollution trapped near the ground and unable to dilute and disperse. Air pollution sources of fine particulate matter ($PM_{2.5}$, particles < 2.5 μm) that fill up the airshed include car exhaust, wood fires, industrial stacks, and smoke emissions from controlled burns. Inversions occur from late Autumn to early Spring in the Nelson-Richmond area.

In the Tasman District the combined effect of an inversion and polluting activities results in high particulate matter concentrations. Notably, there are a high number of days where air quality is compromised or even exceeds the National Environmental Standards for Air Quality (NESAQ) (Ministry for the Environment (MfE, 2004). When and where there is agricultural burning, it is often a large contributor to the particulate matter exceedance.

Burning of vegetation waste takes place in the Tasman district as part of agricultural programmes such as orchard replacement and land redevelopment. Within orchards, apple tree wood infected with European canker is particularly problematic for air quality as it requires immediate disposal for biosecurity purposes. If the disease is found, the biosecurity recommendation is to remove the entire orchard and burn it within seven days. This results in the burning of undried (green) wood.

The burning of moist (green) wood produces increased particles and increased release of gases that are likely to degrade air quality such as, poly aromatic hydrocarbons, methane, and ammonia (Tihay-Felicelli et al., 2017; Burling et al., 2011; Chomanee et al. 2009). Burn techniques that result in highly efficient combustion can mitigate release of these types of gases and particles, thus improving air quality. A highly efficient burn can also place the smoke plume higher in the atmosphere, taking it away from the ground and potentially outside the winter inversion zone.

The Tasman District Council (TDC) provides guidelines for best practice burning of this green wood. Any airshed can 'hold' a maximum number of particles before environmental standards are exceeded. Several pollutant sources compete for release into the Nelson airshed, all-contributing to the building up of particles and subsequent exceedance. There are some days when multiple green wood burns occur and TDC receives many complaints from the public and the Nelson airshed experiences breaches of the NESAQ.

The TDC, working in partnership with Scion, undertook field-based research to improve the understanding of smoke produced from three different types of apple green wood burning practices. Burn efficiency, measured through temperature and total fuel consumption, and smoke, measured through smoke colour and downwind $PM_{2.5}$ concentrations, were used to determine best ignition and burn practice for pile burning of green wood.

Best practice is an efficient (hot) burn that releases smoke as high as possible into the atmosphere so that the smoke can disperse either above the inversion layer or at least high above the ground where winds can help to dilute the plume. The best practice will also be the type of burn that is hot for a long duration, releasing gases from a more complete combustion (i.e. H_2O, CO_2, NO_2) and reduced particulates, rather than a practice that results in smouldering, as smouldering releases a high number of particulates and more gases that are prone to pollution problems (i.e., CO, NH_3).

This research project aimed to determine, for three different woodpile burning practices differences in fuel consumption, combustion efficiency, and smoke generation in the form of $PM_{2.5}$ concentrations and plume. The three woodpile burning practices tested were: Standard practice, current best practice and a new technique that involved digging a trench and running a fan to provide oxygen for the fire.

The following sections describe the methods used to collect and analyse the data and the results, followed by a discussion.

2 Materials and methods

2.1 Site location and Topography

The experimental site was a flat, fallow paddock located just outside the suburb of Richmond, in Nelson, New Zealand. The site is approximately 1.5 km from the town centre and 1.8 km from the ocean (red rectangle, Figure 1). Experimental burns were conducted between 14 and 19 May 2019.

This site was selected as it is within the TDC's region and within the area commonly reported to have air pollution issues from agricultural burns in winter. The time of year (May) was selected to best represent the likely time for apple orchard green wood burning. This time of year, the Nelson airshed often experiences morning inversions that hold air pollutants near the ground.

Figure 1: Experimental site location - Richmond, Nelson, New Zealand.

2.2 General Weather

To ensure comparability between experiments and individual burns, on-site weather conditions were recorded from an automatic weather station situated on a 5 m mast. The on-site weather station measured: temperature and relative humidity (Campbell Scientific EE81 Sensor, USA), wind speed and direction (Vector W200P Wind Vane & Vector A101M Anemometer), air pressure (Vaisala PTB110 Barometer), and rain (HyQuest Solutions TB3, Rain gauge). All data was recorded with a Campbell Scientific CR1000 data logger at 1-minute intervals. Weather observations are reported in Section 3.1.

2.3 Burn Practices

Burn efficiency and smoke production from three different burn practices were explored. The burn practices were: standard practice, current best practicing, and new technique. We describe these burn practices below.

Standard practice
The standard practice currently meets the minimum requirements of the Tasman Resource Management Plan for permitted outdoor burning. For this practice, wood is piled into a large heap and often contains a mixture of wood types green wood (moist wood), root balls and soil are commonly mixed into the pile.

Current best practice
This burn practice is recommended by TDC. For this practice, wood is piled into a small heap and can contain a mixture of wood types, as described above.
Different from standard practice, wood is added to the original small pile when needed to keep the fire burning efficiently, like stoking a wood stove.

New technique
This burn practice is a new technique designed to increase burn efficiency and create a hotter fire. For this practice a small pile of wood, of mixed wood types, is placed into a trench dug into the ground. At one end of the trench an air curtain or fan is placed to force air into the base of the fire (Figure 2). This provides oxygen to the fire. Oxygen is one of the three elements needed for combustion (the other two are fuel and heat).
Like Burn 2 (Current best practice), wood is added to the original small pile when needed to keep the fire burning efficiently and the pile is reshaped to keep the fire hot.

Figure 2: The setup for Burn 3 – New Technique. The burn pile was placed inside a trench and a fan, mounted on the back of a tractor, blew onto the fire. Note very little visual smoke emitted from the burn, indicating efficient combustion.

2.4 Experimental Design

To fully understand burn efficiency and smoke production two field experiments were designed:

1. The first, known as Experiment A., consisted of three individual burns over a period of three days (one burn per day). On each day different burn practices were followed (see below for further details).

2. The second, known as Experiment B., consisted of three burn piles lit simultaneously on a single day. This experiment was purposefully non-rigorous so that the consumption ability of each technique could be tested on green wood and stumps. Appendix A contains methods (where different from Experiment A described here) and results.

For these experiments naturally dried wood (seasoned) was used. Green wood was not used due to air pollution concerns of burning during a morning inversion. The difference in burn efficiency and smoke production between the burn practices will not change with different fuel moisture, dried (seasoned) versus green wood. Although we note the magnitudes of the results would change. A local contractor, Riverstone Balage Ltd, prepared the wood fuel, provided and operated all machinery and undertook all fire management duties for all three burns.

2.4.1 The Experiment

In this field trial we aimed to compare smoke production and burn efficiency differences between the three burn pile practices; these took place on three different days. On each burn day, ignition took place before the inversion layer lifted and the burn pile could burn for 5 hours, starting from ignition. This fixed time was put into place for practical safety purposes relative to daylight hours and post-burn work. For each burn pile, the same volume wood was prepared, however, not all burns used the same volume of wood due to this five-hour cease-burning time limit.

The three-burn practise were set up and ignited in the following way:

Burn 1, using standard practice
We followed the standard practice for ignition and burning and ignited a large pile of known size (see below, Fuels). The ignition technique consists of drizzling the woodpile on the upwind side with a four-to-one, diesel-petrol mix (40 litres) and then lighting the pile with a fuel brick (Samba Natural Fire Lighters, Sims distributing company). Once the fire is ignited it is left to burn with minimal maintenance.

Burn 2, using current best practice
For this experiment we added wood packets when the pile had burned to 2/3 of its original height. In practice wood would be added when deemed visually necessary to keep the fire burning efficiently. The ignition technique for this practice uses “apple crate ignition”, where an apple crate is filled with cut and split dry wood and then placed at the centre of the burn pile, the burn pile is drizzled with a 4:1 diesel-petrol mix (40 L) and ignited with a fuel brick (Samba Natural Fire Lighters, Sims distributing company).

Burn 3, new technique
Like Burn 2, for this experiment, additional wood was added in stages, once the original pile reached 2/3 of its original height. The apple crate ignition technique described above to ignite the pile. It is also important to note how the fan was operated during this burn. The fan was operated with an in-duct velocity of 22 to 25 m/s and an air volume of 3.6 to 4.1 m^3/s. The fan was turned off when new packets were added and when the fire was reshaped.

2.5 Instrument layout

For each burn the same experimental design was used to measure burn efficiency and smoke production (Figure 3). An arc of 5 $PM_{2.5}$ air quality monitors (Dustmote, Airquality

Limited, New Zealand and E-Sampler, MetOne, USA), to measure particulate matter in the air near the ground were deployed downwind. An additional monitor was placed upwind to measure background $PM_{2.5}$ concentrations. Details of the sensors are below (section 2.5). All burns were recorded using four GoPro cameras (Hero5 camera, GoPro, USA), set up around pile in the four cardinal directions (Figure), recording two frames per second at narrow field of view and 1080p resolution. Cameras were located nine meters away from the burn pile edge. Height poles were used to visually observe the consumption of the fuel as the burn progressed (and the fuel pile was reduced). A Telops FAST series infrared camera (Telops L200 IR Camera, Telops, Canada) was used to measure fire intensity and for evaluating temperatures of the burn piles for the duration of combustion.

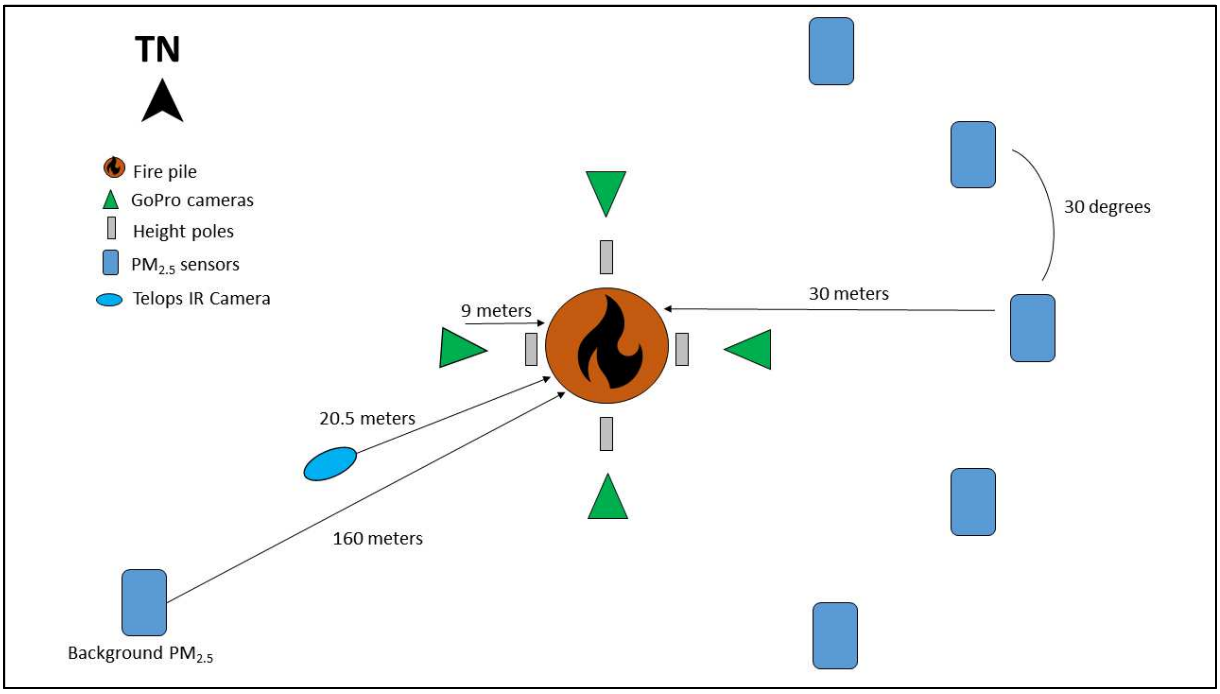


Figure 3: Example of experimental instrument setup.

2.6 Fuels

2.6.1 Fuel Types

In this experiment fuels were grouped into the following types: dried hardwood and softwood logs (*Populus* sp. and *Pinus radiata*) and split softwood ignition wood (*Pinus radiata*). Dried hardwood and softwood logs were used as the main fuel for all the burns while split softwood ignition wood was used in Burns 2 and 3 as part of the preferred ignition practices to encourage fast ignition and a hot burn.

2.6.2 Fuel Packets

To properly understand the effects of burning on fuel consumption and smoke production fuels were measured and made uniform across all burns. Uniformity and tracking of fuels to individual burns was managed by sorting hardwood and softwood logs into piles, referred to in this report as packets. These packets were then standardized and documented for total weight, species ratio, log diameter, time since cutting, drying conditions, and moisture content. Packets were standardized to ensure that each burn received the same fuel, since significant differences between packets would create a complexity in the results that would be difficult to parse out.

Hardwood and softwood log fuels were managed for moisture content and size by stacking as logs with limbs removed according to diameter for a period of seven months. Immediately prior to sorting they were cut to 1.5 m lengths. Following cutting, the logs were equally divided into 36 individual fuel packets for use in individual burns.

Description of Fuel Packet

Total packet weight, log diameters, and species of wood were sorted equally between packets. Equal packet weight, species composition and diameter were achieved by sorting and recording of logs during packet creation and weighing the hardwood and softwood logs using a Loadrite loader scale (Trimble Loadrite Auckland Ltd, Auckland, New Zealand) on a Komatsu WA320 loader (Komatsu Ltd., Tokyo, Japan). Packet weight, hardwood-softwood ratio, and log diameter were found to be the same with no significant differences across packets (pile weight $p = 0.6409$; species ratio $p = 0.2493$). Packets weighed 1729.167 ± 16.102 kg and were composed of 21.5 ± 0.43 % hardwood and 78.49 ±0.43 % softwood. Log diameter was measured by randomly sampling 10 logs per packet from 8 of 36 packets. While diameter of logs varied within each packet (239 ±86.1 mm), this range was common to all packets so there was no significant difference between packets for log diameter ($p = 0.9074$). Hardwood-softwood packet measurements were examined in base R analysis software (R Core Team, 2019), to determine if there was a statistically significant difference between fuel packets that might affect the burn efficiency or smoke production results.

Ignition wood (split softwood) was used in Burns 2 and 3 to encourage quick, hot ignition. Ignition wood was prepared from cut and split Radiata pine (*Pinus* radiata) and stacked in 1070 mm x 1600 mm x 620 mm wooden apple crates weighing 440kg each.

Since the main objective of Experiment A. was to assess the differences between burn practices, the time and amount of fuels added to the burn was controlled by both the burn practice type, and time limits to allow for the burns to be extinguished before dark each day. The total number of fuel packets used in the initial wood pile and then subsequently are outlined in Table 1.

Burn 1. Standard Practice was ignited with 5 hardwood-softwood fuel packets and no further packets added during the burn, simulating a standard large burn pile.

Burn 2. Current Best Practice was ignited with one hardwood-softwood packet and one crate of split ignition wood (ignition wood packet), with two more hardwood-softwood log packets added at intervals during the burn. This burn consumed two hardwood-softwood log packets during the 5-hour maximum time limit of the burn.

Burn 3. New technique was ignited with one hardwood-softwood log packet and one crate of split ignition wood (ignition wood packet), with four more hardwood-softwood log packets added at intervals during the burn. This burn received more packets as it was so efficient at consuming fuel, therefore, requiring more fuel packets to meet the 5hr maximum time limit of the burn.

Table 1: Number of fuel packets used during the experiment for Burn1: Standard practice, Burn 2: Current best practice, and Burn 3: New technique.

Packet Type	Burn 1	Burn 2	Burn 3
Ignition Wood Packets	0	1	1
Hardwood-softwood packets used for ignition	5	1	1
Hardwood-softwood packets added after ignition	0	2	4

Note – Burn 2 consumed 2 Hardwood-softwood packets after ignition before reaching 5hr time limit.

2.6.3 Fuel Moisture Content

The amount of moisture in a fuel has a significant effect on how much energy is needed to ignite and keep that fuel burning. High fuel moisture contents require more heat (energy) to dry the fuel out. It was therefore necessary to ensure that the fuels used in each of the burns had similar fuel moisture so that fuel moisture did not affect the experimental results.

To ensure consistent fuel moisture across wood packets we standardised the factors that affect fuel moisture content. These factors are wood diameter, species type and drying conditions. This standardisation allowed for any variation in fuel moisture to be experienced equally across all fuels used in the experiments.

Moisture content of fuels was measured each morning before ignition by randomly selecting logs from packets scheduled to burn that day. The method was to cut them in half, remove a thin disk from the middle section of the log and weigh this disc within 10 minutes of cutting. Wood disks were then stored and returned to the lab for drying.

Drying was performed in Contherm ovens at 105°C for 6 days, at which point samples showed no further moisture loss. They were then weighed for oven dry weight, and percent moisture content (mc) was calculated using Equation 1**.**

$$mc = \frac{m_w - m_d}{m_d} \times 100 \qquad \textbf{Equation 1}$$

Where m_w is the wet weight of the sampled fuel and m_d is the dry weight of the sampled fuel. All weights are in grams. Typical range of fuel moisture content is 0% (oven dried) to 300% (wet live vegetation).

Hardwood-softwood packet fuel moisture across all samples was 70.2 ±42.4%. This range in moisture content within fuels is acceptable as fuel moisture content differences between packets was not significantly different ($p=0.8986$) meaning that each fire received fuels that would behave similarly to the others and not interfere with the results.

2.6.4 Fuel consumption

Fuel consumption was calculated using video recordings of the burn piles for the duration of each burn. To calculate fuel consumption the first step was to use burn pile height to calculate pile weight (Equation 2). This calculation assumes the initial burn piles were half sphere shaped, and any time additional fuel packets were added they were built as half-spheres (half spheres are the standard practice for determining wood pile weight). Since the burn piles were constructed and reshaped throughout the burn to half-sphere shape, and each pile settled in the same manner across burn types, this process allows us to make effective comparisons of burn efficiency between burn types.

$$Mass_{observed} = Mass_{initial} \times Height_{observed}{}^{3} / Height_{initial}{}^{3}$$

Equation 2

Where $Mass_{observed}$ is calculated burn pile mass at the observed moment in time (kg); $Mass_{initial}$ is the initial mass of the burn pile (kg); $Height_{observed}$ is the burn pile height at the observed moment in time (cm); and $Height_{initial}$ is the initial pile height (cm).

After pile weight was determined, the rate of consumption (kg/min) was calculated using Equation 3.

$$\mathrm{Consumption_{observed}} = \mathrm{Mass_{previous}} - \mathrm{Mass_{current}} / \mathrm{Time_{elapsed}}$$

Equation 3

Where $Consumption_{observed}$ is the amount of fuel consumed over the observed time (kg/min); $Mass_{previous}$ is the burn pile mass at the start of the time period in question (kg); $Mass_{current}$ is the burn pile mass at the end of the time period in question (kg); and $Time_{elapsed}$ is the elapsed time (min). Therefore, subtracting current pile weight from the previous pile weight, then dividing by the time since the last measurement, provides a fuel consumption rate in kg/min for the period.

Because the total amount of fuel consumed varied across the three burns (8660 kg, 5640 kg and 9080 kg for Burn 1, Burn 2 and Burn 3 respectively), normalized consumption was also calculated by dividing fuel consumption by the total amount of fuel consumed during the burn. This allowed for a better comparison between the burns.

Since fuel packets were added to Burns 2 and 3 during their burn periods it was necessary to account for an increase rather than decrease in total burn pile mass at these times. To do this, burn pile mass was calculated immediately before a packet was added to the burn pile. This value was then added to new wood packet's weight for the new total burn pile mass. Once the fuel packet was added and burn pile reshaped, a new burn pile height was taken for Equation 2 and the consumption calculations continued.

Burn pile height was measured by analysing time-lapse videos recorded with GoPro cameras (Gopro Hero5, located 9m from the edge of the fire in the four cardinal directions) pointed at the burn piles with height poles in the frame. Initial burn pile height and weight were known from measurements taken prior to ignition. Percent reduction in height of the burn pile was tracked at 15-minute intervals using Adobe Premiere Pro video editing software (Adobe Premiere Pro, 2017).

2.7 Fire intensity

Combustion efficiency is defined as the ratio of heat released by the fire to the heat input by the fuel (Miller, 2011). The experimental design specified that the same type of fuels (vegetation type, fuel size and total mass) be used for each burn practice. This means there is the same input energy content for every burn pile. Which allowed for temperature, measured throughout the duration of each burn by infra-red imagery, recorded with a Telops FAST series infrared camera, to be used as a measure of combustion efficiency.

Using a pre-calibrated temperature detection range of 335°C to 2000°C (with a 13mm lens) at 1 Hz to capture much of flaming combustion, the camera was set up 20.5 m from the pile centre and 1.36 m above the ground to acquire a full image of the pile at a safe working distance. A temperature range of 335°C to 2000°C was chosen as that was the pre-calibrated range most appropriate to the expected observed temperatures, with lowest detectable temperature being 335°C and highest detectable temperature being 2000°C. Each frame was summarized to obtain the total number of active pixels (temperature ≥ 335°C), as well as the mean and maximum temperature across all active pixels, establishing metrics for total visible flaming area as well as associated average and maximum temperatures. Mean active pixels, representing total visible active pixels within the burn indicates the degree of fire activity, or involvement, across the burn pile with greater numbers of pixels indicating greater degree of flaming combustion occurring at the surface of the pile. We used mean active pixels to determine the volume of burning material and therefore the intensity of the fire.

2.8 Smoke

2.8.1 Smoke production: $PM_{2.5}$ concentrations

Smoke production was observed using $PM_{2.5}$ concentrations sampled near the burning burn pile and smoke plume rise observations. Five sensors were deployed to measure $PM_{2.5}$ concentrations above ground level (1.8-2m) near the burn piles:

- Four Dustmotes (Continuous Optical Particulate Monitors)
- One E-Sampler (Dual Ambient Monitor/Sampler).

Both types of sensors measured temperature, relative humidity, and wind speed and direction at each location. All data were recorded at one-second intervals, these were used to calculate 1-min averages. The five sensors were established in a semicircle, 30 m downwind from the burn pile and positioned 30 degrees apart from each other (Figure 3).

An additional E-Sampler was also deployed to measure background concentrations nearby and 160 m upwind from the wood burning piles (Figure 3). All $PM_{2.5}$ concentration data were adjusted to remove background concentrations.

During Burn 1 an $PM_{2.5}$ sensor malfunctioned and could not be replaced, which meant that only four sensors were operational for the duration of the burn, it is marked as faulty in results. During Burn 3, there was an unexpected wind direction shift from the south-west direction to north-east at 10 am in the morning, 2 hrs into the experiment. Because of this unexpected wind direction change, two air quality sensors were moved to new locations during the burn and previous data were disregarded.

We noted that within the data $PM_{2.5}$ concentrations increased during times of heavy machinery operations for burn pile reshaping and packet addition, due to this phenomenon data was adjusted to remove the “dirty” timeframes from the $PM_{2.5}$ data set.

2.8.2 Smoke Production: Plume Height

Plume height was assessed visually from a set distance, approximately every hour. A Suunto PM-5 clinometer (Suunto, Finland) was used to record the angle between the viewer's eye and the bottom of the smoke plume from a known horizontal distance to the plume (Figure 4). The angle and the horizontal distance were used to calculate the plume height (Equation 4):

$$\mathrm{Ph} = \mathrm{d\ x\ tan\ (a)} \qquad \textbf{Equation 4}$$

Where Ph is the plume height (m), d is the distance from the observer to the plume (m) and a is the clinometer angle reading (degrees).

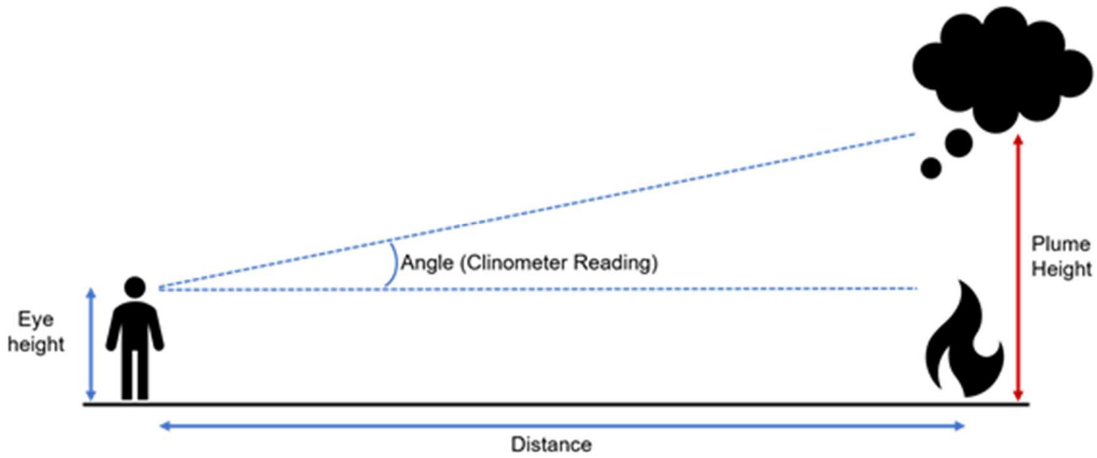


Figure 4: Plume height determination from a clinometer reading.

3 Results

3.1 General Weather

We conducted the burn pile experiment on three separate days with weather conditions as similar as possible for each burn (Table 2). Wind direction and speed were similar for Burns 1 and 2, however calmer and from the northeast for Burn 3 (Table 2, Figure 5). The difference in wind direction did not influence the results as the experimental design was flexible to change with wind direction. The wind speed influences the efficiency of the burn, however Burn 3 was the new technique burn practice, which takes place in a large trench, reducing the influence of wind speed on the fire efficiency. The air pushed by the fan provides air-flow far greater than the wind. Mean speed of the fan is 23 m/s and the mean wind speed on burn days was 3 m/s, therefore the fan speed is 7 times greater than local mean wind speed.

Table 2: Weather conditions for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New Technique.

Meteorological conditions (mean +/- standard deviation)	**Burn 1 14/05/2019**	**Burn 2 15/05/2019**	**Burn 3 17/05/2019**
Air Temperature (ºC)	12.3 ± 2.7	14.6 ±1.7	10.6 ± 1.5
Relative Humidity (%)	65.5 ± 12.4	63.7 ± 10.8	73.1 ± 5.3
Barometric Pressure (hPa)	1020.5 ± 1.3	1008.8 ± 1.2	1018.7 ± 0.5
Rain (mm)	0	0	0

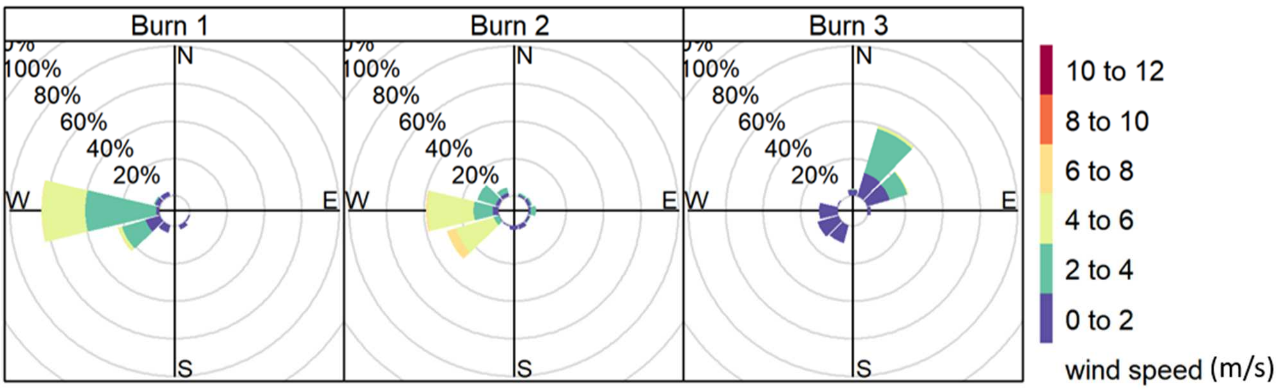


Figure 5: Mean frequency of counts for wind speed and direction for Burn1: Standard practice (left), Burn 2: Current best practice (middle), and Burn 3: New technique (right).

3.2 Fire

3.2.1 Fire intensity

Fire intensity is a measure of the rate of energy released by the fire, or how 'hot' the fire burned. A hotter fire increases the amount of fuel burned and emits a higher proportion of stable gases, such as carbon dioxide and water, lower number of particles, and sends the smoke plume high above the ground where it is more likely to experience dilution.

The hottest fire was determined using the mean count of infra-red pixels registering in the camera view (pixels above the lens threshold of 335 °C). The hottest fire was Burn 3: New Technique, with a mean pixel count of 1251 ± 715 pixels, followed by Burn 1:

Standard practice, with 1183 ± 868 pixels, and then Burn 2: Current best practice, with a mean pixel count of 769 ± 317 pixels (Table 3).

The mean number of pixels is high for Burn 1 because it started off with four times more fuel and this has influenced the mean pixel count. A steady trend of cooling, or less pixels above 335 °C, was observed as the Burn 1 fire progressed. Quarters 3 and 4 were cooler than Burns 2 and 3 (Figure 6). Burn 1 was weight comparable to the weight load at the start of Burns 2 and 3 at approximately the start of quarter 2.

When tracked over time, mean active pixel count provides additional information on fire behaviour as pixel count increases or decreases in time, with each burn showing a unique burn profile (Figure 6). Burn 1 showed an initial high pixel count, which rapidly declined, decreasing by approximately 50% every 1.25 hours. This burn never reached a steady state of burning. Burn 2 with its smaller initial mass took longer to fully ignite. Unlike Burn 1 the pile reached a steady state of burning (quarter 2) and this was maintained until cessation of fuel (quarter 4). Burn 3 quickly reached steady state and like Burn 2, only began to cool when fuel additions were halted (quarter 4).

Table 3: Mean, standard deviation and maximum number of pixels above the infra-red camera lens threshold of 335 °C for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New Technique. Showing fire intensity during each quarter of the burn period and the entire burn period (5 hours).

	Burn 1			**Burn 2**			**Burn 3**		
Quarter number	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**
1st	2435	410	3285	579	287	1257	1661	584	3232
2nd	1416	444	2595	1072	185	1531	1308	894	3587
3rd	704	152	1378	1001	192	1427	1311	669	3285
4th	267	86	525	548	141	979	880	465	2313
Entire burn (5hrs)	1206	868	3285	800	317	1531	1290	715	3587

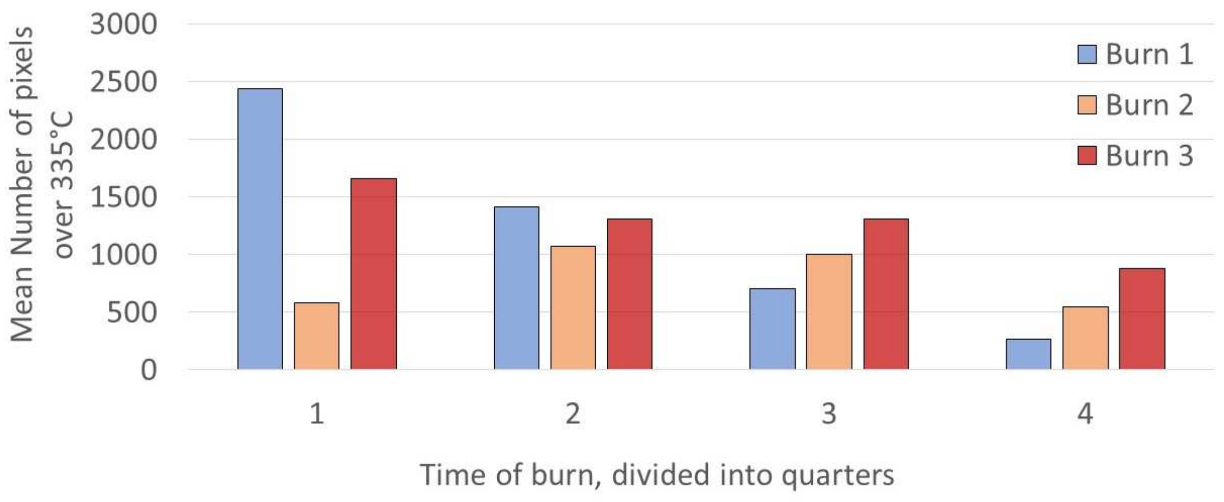


Figure 6: Mean number of pixels above the infra-red camera lens threshold of 335 °C for Burn 1: Standard practice (blue), Burn 2: Current best practice (orange), and Burn 3: New technique (red).

3.2.2 *Combustion efficiency*

The temperature of the fire is used as a measure of combustion efficiency (Figure 7) as the same type of fuels are consumed by each burn therefore, the energy content of the fuels per mass unit is the same. The fire's maximum and mean temperatures at each point in time are used as indicators of combustion efficiency (Figure 8).

Burn 1 started out with a large fuel pile with no additional fuel added afterwards and reached its highest maximum temperature of 836 °C 17 minutes after ignition, which steadily declined after that (Figure 8). Burn 1 mean temperature was 434 °C and this was the lowest (Table 4).

Burn 2 took 1.3 hours to reach its highest temperature of 860 °C, but then retained a relatively constant maximum temperature at approximately 750 °C. The mean temperature of this fire also remained relatively constant over time at approximately 471 °C (Figure 8).

Burn 3 reached its maximum temperature of 986 °C 1 hour after ignition while the fan was operational. When the fan was not operating, the burn pile temperature maximum was 821 °C. It is evident that both the maximum and mean temperatures are higher when the fan is operational, 753 °C and 503 °C, respectively, as compared to when the fan is turned off, 645 °C and 442 °C, respectively (Figure 8). Burn 3 has a lower maximum and mean temperature while the fan is off because the burn pile was in a trench. The trench shields the burn from natural airflow that provides oxygen for combustion.

Table 4: Mean, standard deviation and maximum temperature (°C) for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New Technique. Showing fire combustion efficiency during each quarter of the burn period and the entire burn period (5 hours).

	Burn 1			Burn 2			Burn 3		
Quarter Number	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**
1st	484	11	528	456	51	545	517	41	628
2nd	445	21	507	495	14	549	470	37	558
3rd	421	10	464	478	10	504	480	41	541
4th	392	11	438	460	12	493	457	31	535
Entire burn (5hrs)	436	36	528	472	33	549	481	43	628

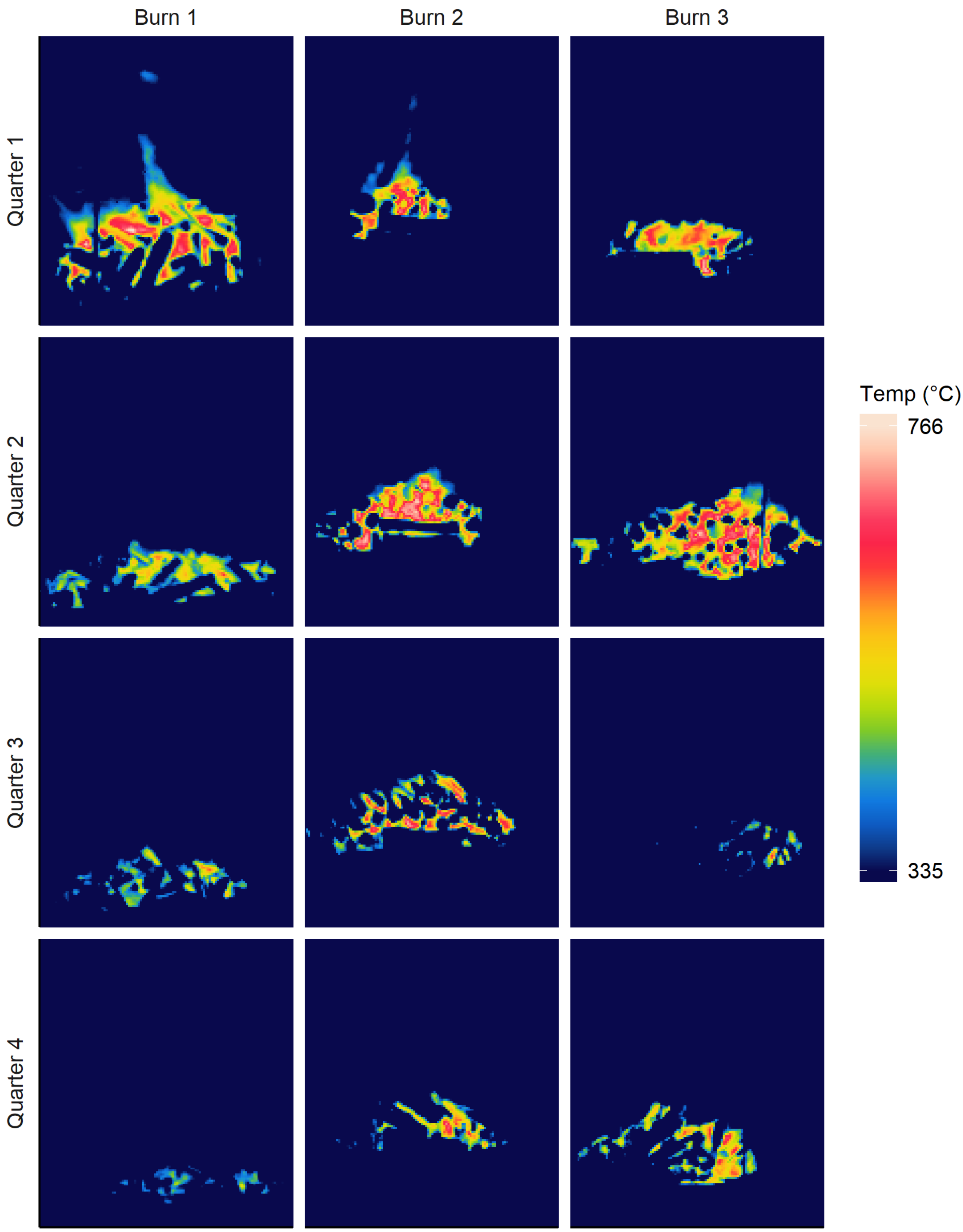


Figure 7: Infrared imagery (Telops IR camera) showing fire intensity (temperature (°C)) in the middle of each quarter of the burn period (middle of quarter = 75 minutes) for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New Technique. All images cover the same temperature scale using the same camera, distance and zoom.

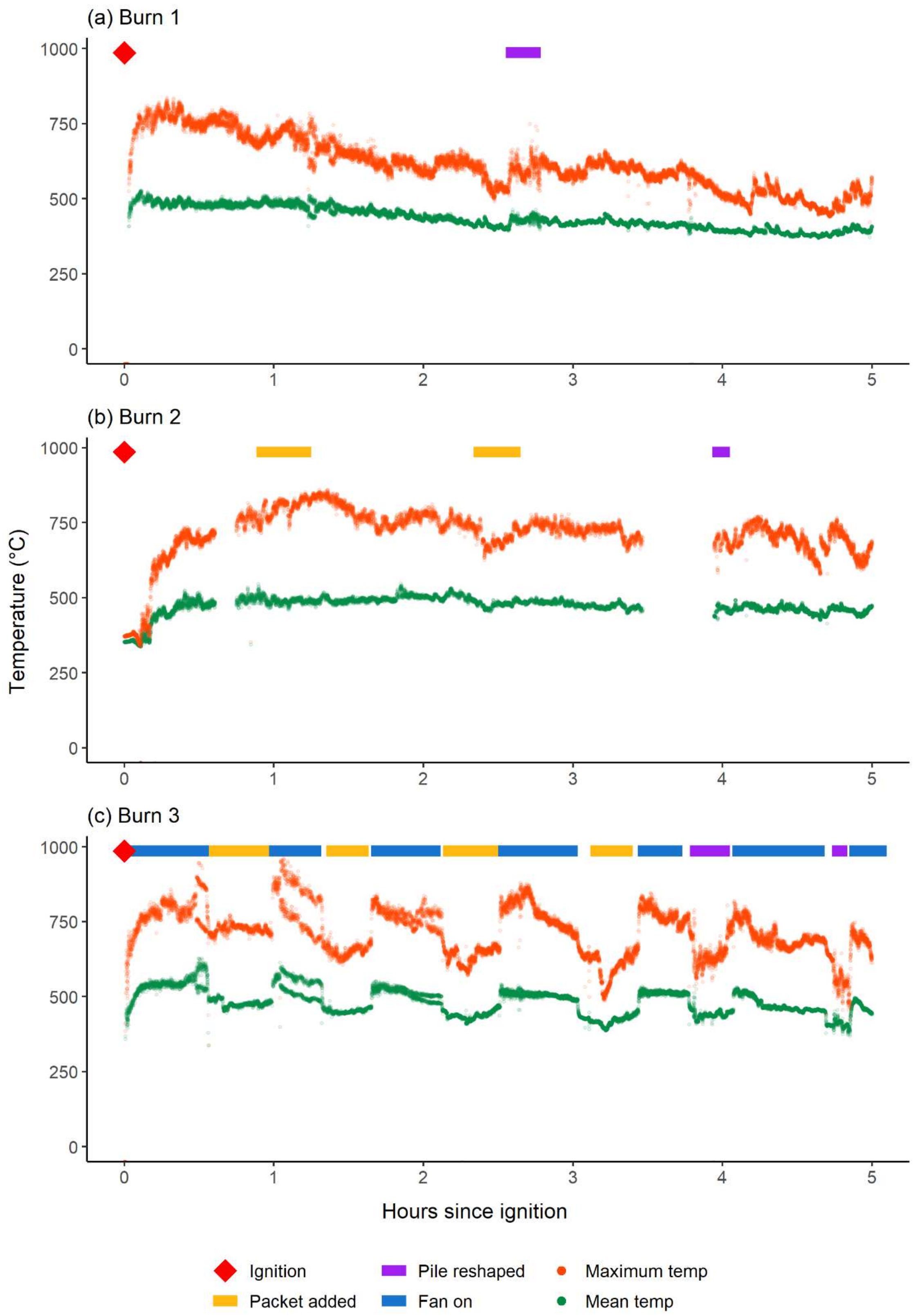


Figure 8: Mean (green) and maximum (orange) temperature (°C) observed per camera frame (1second intervals) showing fire intensity over the entire burn period (5 hours): (a) Burn 1: Standard practice, (b) Burn 2: Current best practice and (c) Burn 3: New Technique. The strip at the top of each graph represents the main events during the burn; ignition, burn pile reshaping, packet addition and fan operation.

3.2.3 Fuel consumption

Fuel consumption varied considerably between treatments and throughout the burn (Figure 9). Burn 1 followed the classical exponential decay (Figure 10) as the fuel was largely consumed during the first quarter while Burns 2 and 3 had more uniform consumption across quarters 1 to 3 with a drop-in consumption in quarter 4 when fuels were no longer added.

The fuels used in this experiment were relatively dry with moisture contents ranging from 27.8% to 112.6%. This level of fuel moisture content is considered dry, meaning once ignited the fuels readily burn and this was observed for Burn 1 in the infra-red pixels and temperature data (Tables 3 and 4) and in the fuel consumption data (Table 5). Burn 1 was one large wood pile with all packets of wood available for consumption and the low fuel moisture content allowed for all the fuels to readily burn shortly after ignition (Figure10). Fuel moisture content plays a large role in ease of ignition, fuel consumption, and smoke emissions and this is discussed further in Discussion (See section 4).

Average consumption rate (36 ± 38 kg/min) and maximum consumption (138 kg/min) were greatest in Burn 3 (Table 5). Interestingly, although Burn 2 reached steady state consumption and burned steadily, Burn 2 had the lowest average consumption (16 ± 16 kg/min) and lowest maximum consumption (60 kg/min). The difference in consumption rates between the different burns illustrates the increasing effect of a larger pile size (Burn1) and the usage of a fan (Burn 3) on fuel consumption.

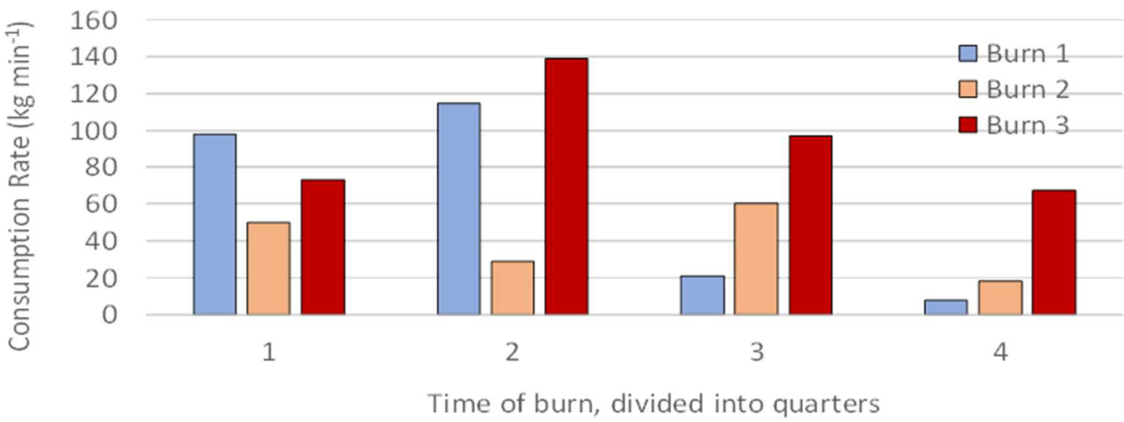


Figure 9: Fuel consumption for Burn 1: Standard practice (blue), Burn 2: Current best practice (orange), and Burn 3: New technique (red). Values shown are quarterly consumption rates normalised with total burn time per total fuel consumed.

Table 5: Mean fuel consumption rate (kg/min) and standard deviation (SD) for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New Technique. Showing fire combustion efficiency during each quarter of the burn period and the entire burn period (5 hours).

	Burn 1			Burn 2			Burn 3		
Quarter Number	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**
1st	76	19	98	26	20	50	46	22	73
2nd	38	44	115	25	4	29	71	48	139
3rd	6	9	21	33	18	60	36	42	97
4th	4	3	8	6	6	18	17	25	67
Entire burn (5hrs)	29	37	115	21	16	60	40	39	139

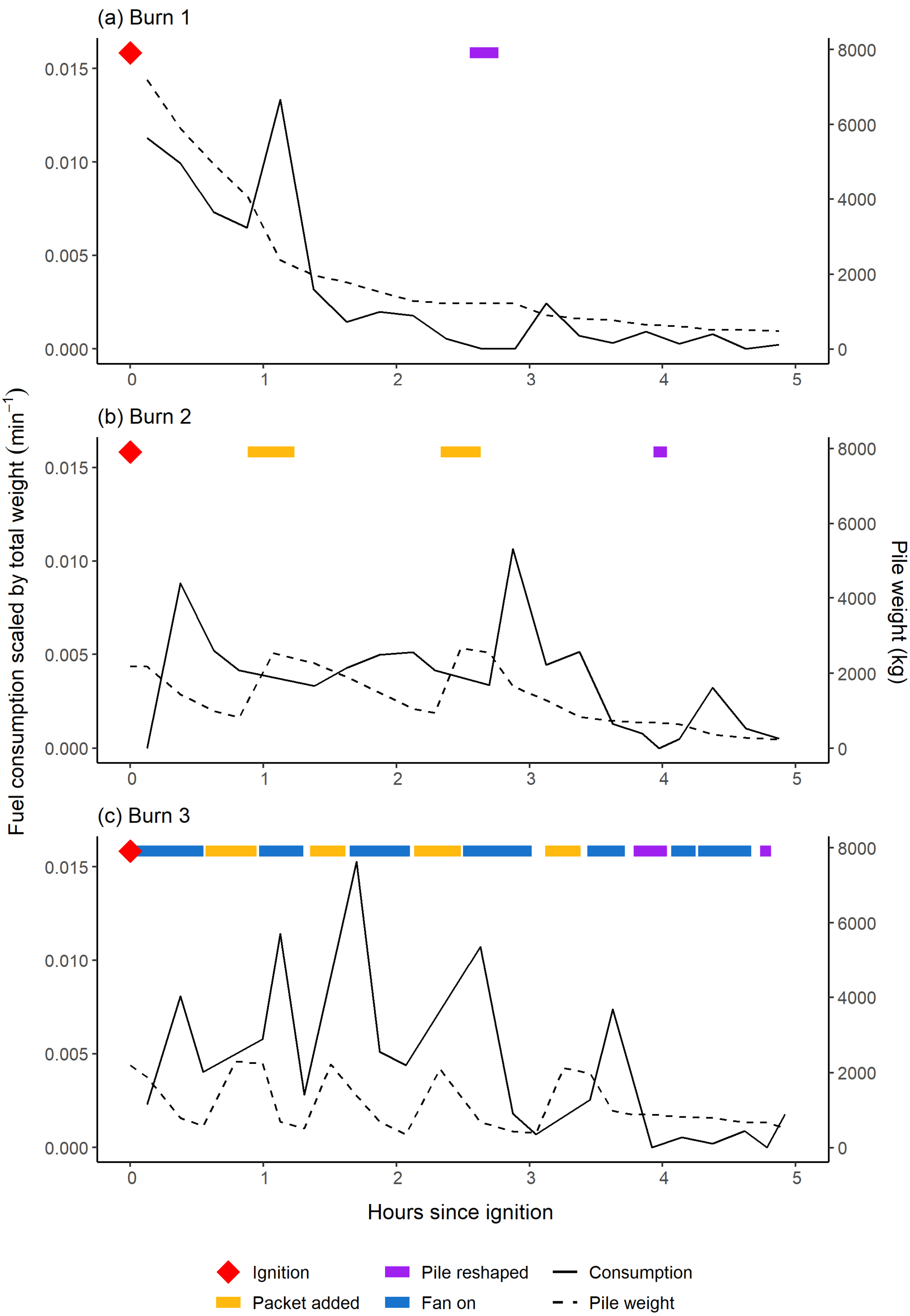


Figure 10: Fuel consumption (kg/min) and pile weight (kg) for (a) Burn 1: Standard practice, (b) Burn 2: Current best practice and (c) Burn 3: New Technique. The strip at the top of each graph represents the main events during the burn, ignition, pile reshaping, packet addition and fan on (Burn 3 only).

3.3 Smoke

3.3.1 Smoke Production: $Pm_{2.5}$ concentrations

The placement of the air quality sensors made it possible to measure $PM_{2.5}$ concentrations at the plume centre and fringes, with favourable wind conditions (Figure 11). The $PM_{2.5}$ plume centre and fringes were captured in Burns 1 and 2, and only the centreline for Burn 3, due to a wind direction change.

Overall Smoke evaluation – taking the practice as a whole
$PM_{2.5}$ concentrations associated with Burn 2 were the lowest of the three burns, with a mean value of 2.50 µg m^{-3}, and a maximum of 45.10 µg m^{-3} (Table 6, Figure 12). Burn 2 also had the lowest peak to mean ratio, indicating that the mean is representative of the downwind concentrations.

The second lowest smoke concentrations were associated with Burn 1, with a mean value of 3.01 µg m^{-3} and maximum of 199 µg m^{-3} (Table 6, Figure 12). The highest concentrations were observed during Burn 3, with a mean of 7.11 µg m^{-3} and maximum of 646.40 µg m^{-3} (Table 6, Figure 12). The highest concentrations for all three burns occurred when the combustion reached the smouldering phase. For Burn 3 the concentrations were exceptionally high when the digger pushed burning material together to reshape the fire as seen in $PM_{2.5}$ data (Figure 12). Burn 3 had the highest peak to mean ratio indicating sharp $PM_{2.5}$ concentration peaks relative to the mean value and these peaks are dominating the mean value.

Burn 3: New technique – a closer look
Burn 3 requires further examination of the data, as the practice is not refined to fully reduce particulate emissions. It was noted with visual observation that the highest emissions of particulates and smoke occurred when the digger pushed the burning material together and when the fan began to blow soot from the smouldering pile in quarters 3 and 4.

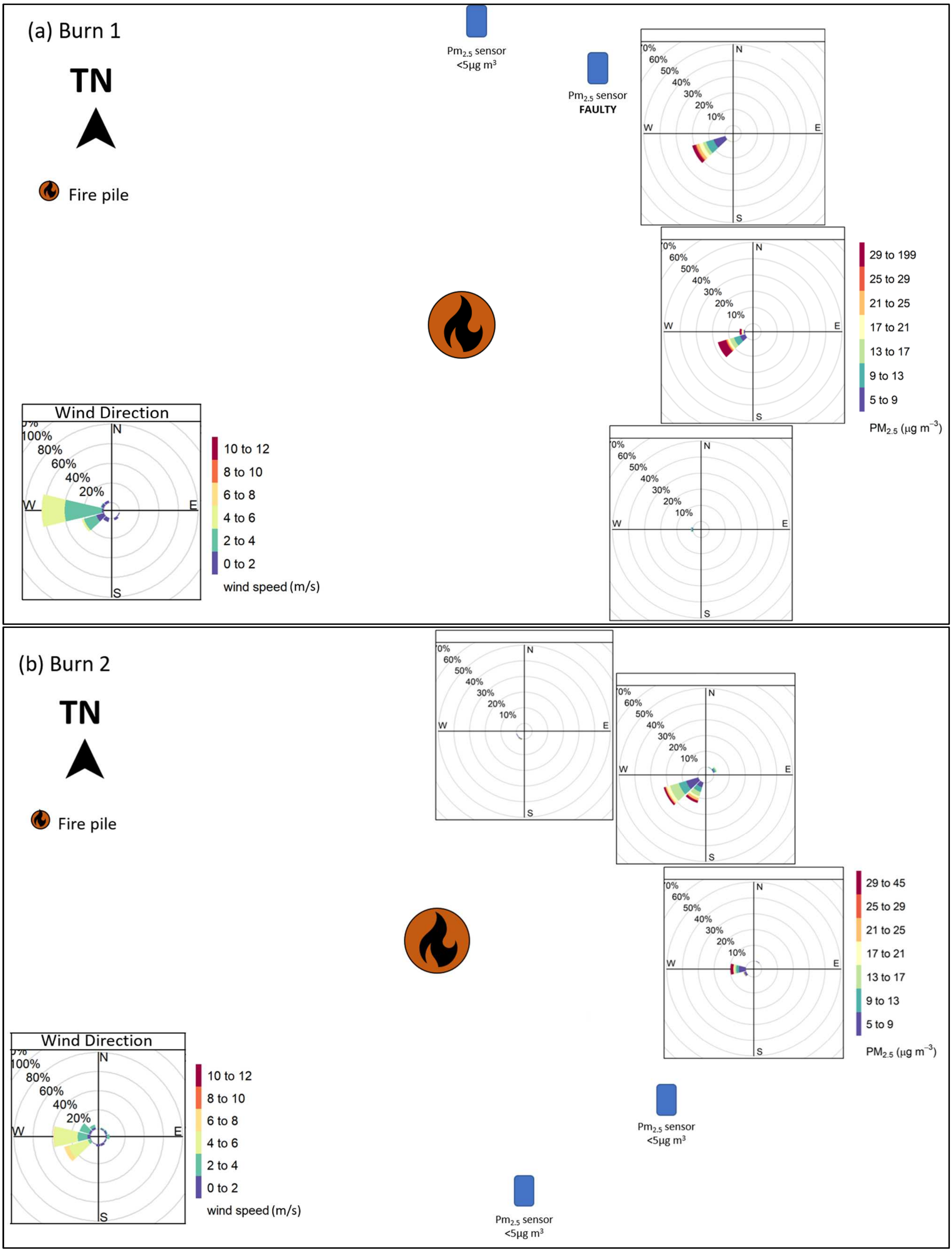
If smoke concentrations are examined during a time when reshaping and smouldering are not occurring, such as quarters 1 and 2 (see Figure 12) then Burn 3 has the lowest mean values of $PM_{2.5}$ concentrations with 1.04 and 0.65 µg m^{-3} for quarters 1 and 2, respectively (Table 6). In addition, the peak to mean values from Burn 3 are very low for quarters 1 and 2 indicating that even the peak values were low and that the low mean values represent the concentrations observed.

During Burn 3, smoke concentrations remained low for approximately 2 hours and 40 minutes after ignition, but then started to increase significantly when the fire became smaller, towards the end of the burn. Field observations suggest that the fan air speed was too high for the size of the fire and that the air blown onto the fire started to blow surface ash into the air that was then entrained by the buoyant plume. This was evident from the increase in particulate matter and the lack of ash on the ground surface and logs closest to the fan.

This lends to an interesting result, taken as an entire practice without modification, Burn 3, new technique, proved to be quite dirty. However, results from quarters 1 and 2 lend themselves towards a very clean burn with low particulates. The new technique offers the largest possibility of reducing particulate and pollutant gas emissions if refined to reduce emissions in quarters 3 and 4.

Table 6: Mean $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) per burn – total and broken up by quarters. Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New technique. Data are adjusted to remove the time when heavy machinery was in operation, burn pile was getting reshaped and when a packet was added.

	Burn 1				Burn 2				Burn 3			
Quarter Number	**Mean**	**SD**	**Max**	**Peak/Mean Ratio**	**Mean**	**SD**	**Max**	**Peak/Mean Ratio**	**Mean**	**SD**	**Max**	**Peak/Mean Ratio**
1st	1.39	1.28	13.50	9.73	1.55	2.04	13.20	8.51	1.86	2.03	10.30	5.55
2nd	3.99	11.68	103.30	25.90	0.88	1.66	17	19.34	1.43	1.19	4.30	3.02
3rd	1.81	6.42	75.10	41.46	2.84	5.38	32.70	11.51	13.81	52.97	465.10	33.67
4th	4.78	14.79	199	41.64	4.53	8	45.10	9.96	13.79	57.80	652.40	47.32
Entire burn (5hrs)	2.99	10.09	199	66.50	2.45	5.29	45.1	18.41	7.72	41.48	652.4	84.48



(a) Burn 1
TN
Fire pile
Pm2.5 sensor
<5μg m3
Pm2.5 sensor
FAULTY
Wind Direction
10 to 12
8 to 10
6 to 8
4 to 6
2 to 4
0 to 2
wind speed (m/s)
29 to 199
25 to 29
21 to 25
17 to 21
13 to 17
9 to 13
5 to 9
PM2.5 (μg m-3)
(b) Burn 2
TN
Fire pile
Wind Direction
10 to 12
8 to 10
6 to 8
4 to 6
2 to 4
0 to 2
wind speed (m/s)
29 to 45
25 to 29
21 to 25
17 to 21
13 to 17
9 to 13
5 to 9
PM2.5 (μg m-3)
Pm2.5 sensor
<5μg m3
Pm2.5 sensor
<5μg m3

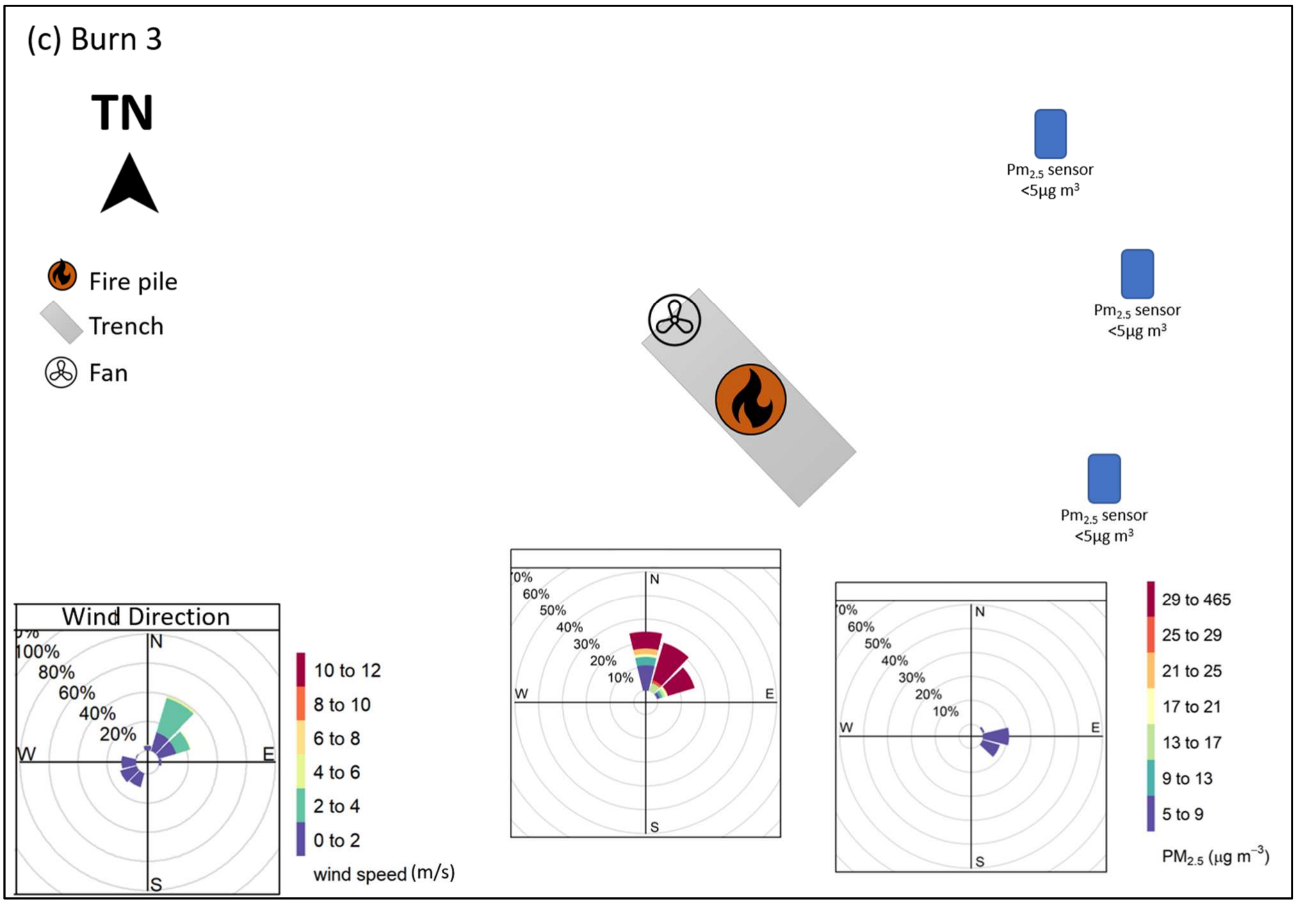


Figure 11: Frequency count of PM2.5 concentrations associated with wind direction for each air quality monitor (shown as they were positioned in the field for (a) Burn 1: Standard practice, (b) Burn 2: Current best practice and (c) Burn 3: New technique) for the duration of each burn (5 hours). Sensors with PM2.5 concentrations lower than 5 µg m³ were removed and shown as blue rectangles. Data adjusted to remove time periods from heavy machinery operation, burn pile reshaping and packet addition to show true particulate matter levels for the burn period.

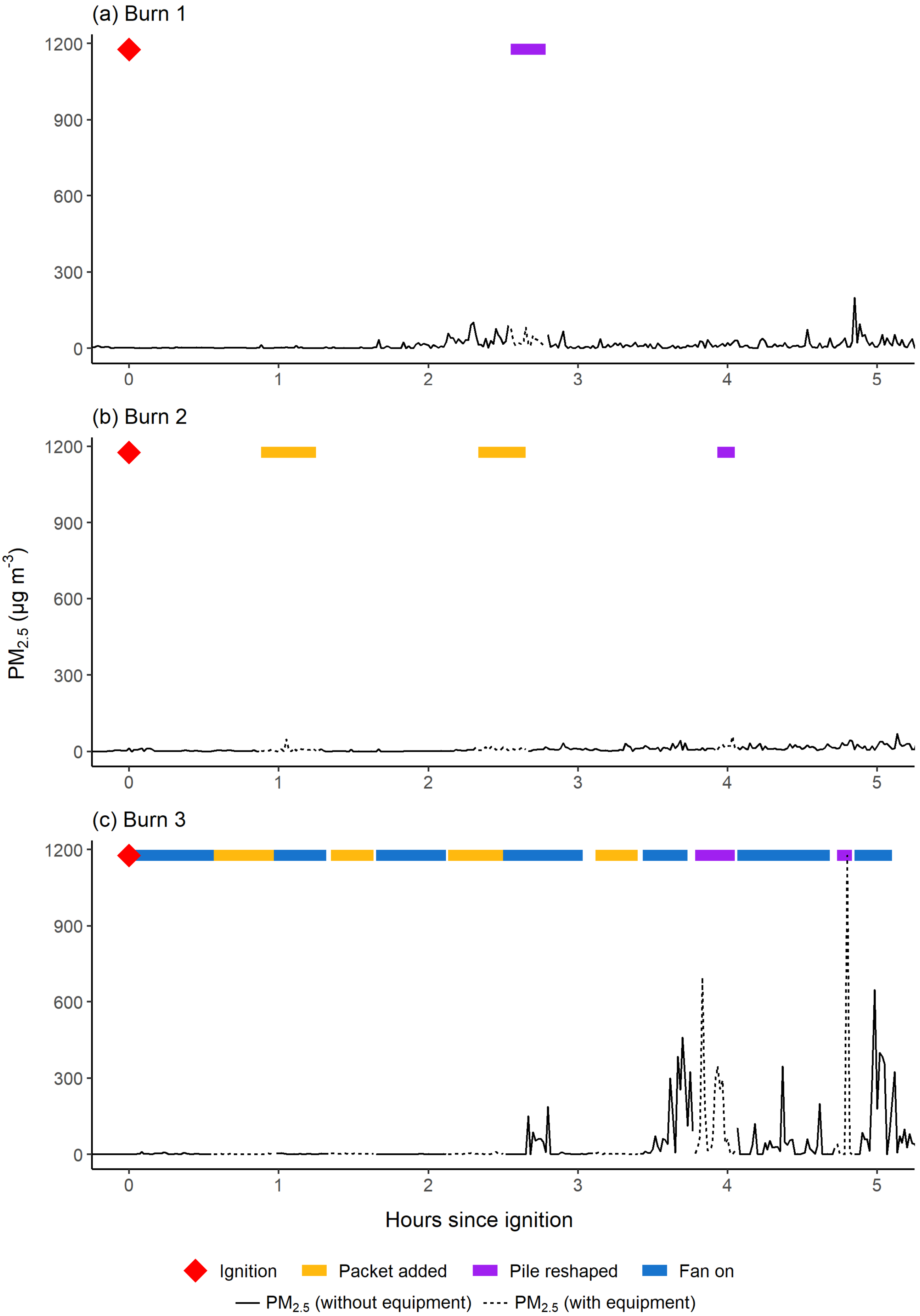


Figure 12: $PM_{2.5}$ concentration (µg m^{-3}) time series for (a) Burn 1: Standard practice, (b) Burn 2: Current best practice and (c) Burn 3: New technique. Showing $PM_{2.5}$ concentration (µg m^{-3}) data with and without heavy machinery operation. The strip at the top of each graph represents the main events during the burn, ignition, pile reshaping, packet addition and fan on (Burn 3 only).

Figure 13: Visual imagery (GoPro camera) of smoke and particle production in the middle of each quarter of the burn period (middle of quarter = 75 minutes) for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New technique. All images use the same camera, distance and zoom.

3.3.2 Smoke Production: Plume Height

The smoke plume height was recorded for the burn experiments. In calm wind conditions, smoke plume height is dependent on the amount of heat emitted by the fire, the more heat emitted, the more buoyant the plume and the higher the smoke will rise. When wind speeds are higher, the smoke plume will bend over, and the top of the plume may not represent the buoyancy of the fire. During calm wind conditions, the higher the smoke plume is lifted into the air, the better it is for ground-level air quality as the smoke is transported away from ground-level receptors such as people and diluted higher in the atmosphere.

While there was not a large difference between the mean plume heights reached during Burns 1 and 2, the mean smoke plume height during Burn 3 was much higher during all four quartiles (Table 7). The same trend was visible in the maximum plume heights. The wind conditions were relatively calm during Burns 1 and 3 but higher speeds prevailed during Burn 2 (Figure 5). The smoke plume during Burn 2 was bent over by the wind at times and this reduced the plume height. The high plume rise observed during Burn 3 was due to a combination of higher fire temperatures (Table 3) and lower wind speeds.

Table 7: Mean, standard deviation and maximum smoke plume heights for Burn 1: Standard practice, Burn 2: Current best practice and Burn 3: New technique. Showing plume height during each quarter of the burn period and the entire burn period (5 hours). A higher plume rise is desired as this increases the chance for plume dilution.

	Burn 1			**Burn 2**			**Burn 3**		
Quarter number	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**
1st	7	6	14	5	4	7	14	11	29
2nd	5	2	6	5	1	6	136	145	238
3rd	5	0	5	5	1	5	45	61	115
4th	5	0	5	6	1	8	16	2	18
Entire burn (5hrs)	5.5	3	14	5	2	8	53	66	238

4 Discussion and recommendations for optimisation of the new technique

Fire behaviour is dependent on fuels, weather, and terrain. Terrain was negligible for this experiment as all burns were on flat terrain. Fuels were controlled to be constant for all burns. There was no significant difference between burns for fuel types and fuel moisture contents. The influence of weather, not a controllable factor, was reduced by choosing to burn under similar weather conditions, and this was achieved for temperature and relative humidity, however, winds were calm during Burn 3 as compared to wind speeds during Burns 1 and 2. Fortunately, the practice used for Burn 3 involved the woodpile burning in a deep trench with a high-speed fan directing oxygen into the burn pile, thus reducing the influence of wind on combustion. Mean speed of the fan is 23 m/s and the maximum wind speeds during Burns 1 and 2 did not go over 12 m/s. Essentially the fan would have been the main driver for Burn 3 no matter what day it was conducted on.

If fuels are held constant, as they were, and weather was similar, as it was, then what remains as an influencer on the results is ignition technique and management of the burn. We are confident the difference in results described above are primarily due to the burn practice.

For this experiment, we used dry wood due to smoke emission concerns from green wood (or recently cut wood). The assumption made for this experiment was that the relative differences between the burn techniques will remain the same with dry or wet wood. The magnitude of the values reported, however would change with the use of wet wood verses dry wood.

Exceptionally dry fuel is considered to range between 2% and 30% in moisture content, while live fuel fuels can range from 30% to 300% depending on the vegetation and season. Moisture contents for this experiment were similar across burns (no significance difference) and ranged from 28% to 113%. In this range fires are readily ignitable and exhibit high fire behaviour, at the 113% content, to advanced fire behaviour, at the 28% content (Pollet & Brown, 2007). The ignitability, sustained consumption, and fire intensity observed during all three burns were all influenced by this fuel moisture content. All burns, including Burn 1, standard practice, burned well with good consumption values due to the low fuel moisture contents (dry wood).

Fuel moisture content of orchard wood burned within seven days of removal would be very high (likely over 180%). At this moisture content, ignition is difficult and maintaining sustained consumption is problematic. Therefore, when looking at these results the key factors to focus on are: (1) consumption and (2) plume rise and (3) $PM_{2.5}$ concentrations.

Consumption values, normalised to account for different amounts of fuel used and timing of the burns, show that Burn 3, new technique was a highly efficient burn with mean normalised consumption of 0.35 followed by Burn 2 (0.30), and then Burn 1 (0.26). Plume rise was very high for Burn 3 and while this was influenced by the lack of wind the observers also noted that at times the plume was almost invisible (in quarters 1 and 2) due to the efficiency of the burn and the lack of particles in the plume. $PM_{2.5}$ concentrations were the lowest during quarters 1 and 2 of Burn 3, but also the highest during quarters 3 and 4 of Burn 3 (i.e., Figure 15). Indicating that with refined protocols the new technique could offer reduced emissions and a cleaner burn of recently removed orchard wood.

Recommendations for reducing particulate emissions of the new technique

- When using the new technique, the use of a fan with a variable flow rate should be investigated so that the fan air output can be reduced as the fuels are consumed. Lowering the fan's output will help keep the ash and soot on the ground, rather than kicking it up as observed during quarters 3 and 4 of Burn 3. It is possible that the fan is only beneficial at the start of the burn and does not add additional benefit after the fire achieves a solid base of embers, but this should be tested with green wood before removing the fan.

- It is recommended that the trench is created parallel to the expected wind direction to maximise airflow through the pile.

- There is likely an optimal ratio of wood pile size to fan size, and the amount of air blown through the trench, this is unknown at this time. Optimisation will help reduce the black carbon particle emissions.

- Reshaping of burning piles with heavy machinery causes high $PM_{2.5}$ emissions and should be kept at a minimum. Management of the woodpile should limit collapse of the centre that would necessitate reshaping of the pile.

- Using the smallest heavy machine for the work has potential to help reduce $PM_{2.5}$ emissions during reshaping as this will allow for increased accuracy.

The new technique, with modifications as recommended, offers the best potential to reduce pollutant gases and particle emissions during green wood burning in the winter months. A set of protocols that help to reduce the emissions during quarters 3 and 4 should be tested, adjusting the fan to a lower speed and/or turning it off.

Figure 15: Soot particles (circled in yellow) lofted into the air by the fan used during Burn 3.

Appendix A. – Experiment B.

1 Introduction

The TDC, working in partnership with Scion, undertook field-based research to improve the understanding of smoke produced from three different types of apple green wood burning practices. Burn efficiency, measured through temperature and total fuel consumption, and smoke, measured through smoke plume height observations, were used to determine burn practice for pile burning of green wood.

Best practice is an efficient (hot) burn that releases smoke as high as possible into the atmosphere so that the smoke can disperse either above the inversion layer or at least high above the ground where winds can help to dilute the plume. The best practice will also be the type of burn that is hot for a long duration, releasing gases from a more complete combustion (i.e. H2O, CO2, NO2) and reduced particulates, rather than a practice that results in smouldering, as smouldering releases a high number of particulates and more gases that are prone to pollution problems (i.e., CO, NH3).

This research project aimed to determine, for different pile burning practices:

1. How will fuel consumption differ?
2. How does combustion efficiency, an indicator for plume rise as more heat equates to a higher plume rise, differ?
3. How does smoke generation differ?

The following sections describe the methods used to qualitatively assess each burn practice using infra-red and visual techniques. This experiment afforded the TDC team a bit of a play to better understand consumption of different types of wood, such as green wood, stumps, etc. It is a qualitative demonstration of consumption power of each of the three burn practices.

2 Materials and methods

2.1 Experimental Design

This experiment consisted of three burn piles ignited simultaneously on a single day. For each burn a different wood pile burning practice was used to accomplish the burn. The purpose of this experiment was to add a real-life component to the methods of burning and to test the consumptive power of each burning practice when under the same atmospheric conditions with the addition of green wood (moist wood) to the fuel source.

For these experiments naturally dried (seasoned) wood was used as with the primary experiment described above. Unlike the experiment described above the consumption power of the burn practices was tested by adding green wood (moist wood) and recently cut mixed wood and stumps (Table B). A local contractor, Riverstone Balage Ltd, prepared the wood fuel, provided and operated all machinery and undertook all fire management duties for all three burns.

This experiment (experimental setup depicted in Figure A) was designed to simultaneously compare the burning of three piles using three different practices (standard practice, current best practice, and new technique). A simultaneous burn eliminates weather as a potential confounding factor influencing the results. Due to practicality of running the experiment a more intensive sampling design (as done with the individual burns described above) was not possible.

The contractor managing the three burn piles was given the brief of “manage the fires as you would out in the field” to ensure the experiment had real life application. This meant that the contractor added packets of wood to each burn pile based on visual observation that the fire had burned down sufficiently to add more wood. The same person monitored all three burns and added packets of wood when visually perceived it was time.

Burn A, using standard practice
We followed the standard practice for ignition and burning and ignited a large pile of known size (see below, Fuels). The ignition technique consists of drizzling the woodpile on the upwind side with a four-to-one, diesel-petrol mix (50 litres) and then lighting the pile with a fuel brick (Samba Natural Fire Lighters, Sims distributing company). Once the fire is ignited it is left to burn with minimal maintenance.

Burn B, using current best practice
For this experiment we added wood packets when the observer noted the pile had burned down sufficiently and deemed visually necessary to keep the fire burning efficiently. The ignition technique for this practice uses “apple crate ignition”, where an apple crate is filled with cut and split dry wood and then placed at the centre of the burn pile, the burn pile is drizzled with a 4:1 diesel-petrol mix (5 L) and ignited with a fuel brick (Samba Natural Fire Lighters, Sims distributing company).

Burn C, new technique
Like Burn 2, for this experiment, additional wood was added in stages based on visual observation, as described above. The apple crate ignition technique described above to ignite the pile. It is also important to note how the fan was operated during this burn. The fan was operated with an in-duct velocity of 22 to 25 m/s and an air volume of 3.6 to 4.1 m/s. The fan was turned off when new packets were added and when the fire was reshaped.

Burn piles were laid out length wise down the site, with pile centres 65 m to 70 m apart. The piles were ignited at the same time using the same type of wood, although the size of the piles and when additional wood was added depended on the burn method.
The differences from Experiment A. are as follows:

- Each burn pile had an instrument setup of two GoPro cameras, at the north and west cardinal directions (Figure A), recording two frames per second at narrow field of view and 1080p resolution. Cameras were located nine meters away from the pile edge. Height poles were used to visually observe the burn.
- A Telops FAST series infrared camera and a FLIR A615 IR camera (FLIR A615 IR Camera, FLIR, Oregon, USA) were used to measure fire intensity and for evaluating temperatures of the burn piles for the duration of combustion (as outlined in Figure A).
- Table A. outlines the ignition technique for each Burn practice.

Table A: Experiment B. ignition mythology for Burn A: Standard practice, Burn B: Current best practice, and Burn C: New technique.

	Burn A	**Burn B**	**Burn C**
Method	Standard burning practice	Current best practice	New technique
Ignition	control ignition – with 50L diesel/petrol	apple crate ignition – with 5L diesel/petrol	apple crate ignition – with 5L diesel/petrol
Note: reduction of ignition fluid due to excess in first experiment			

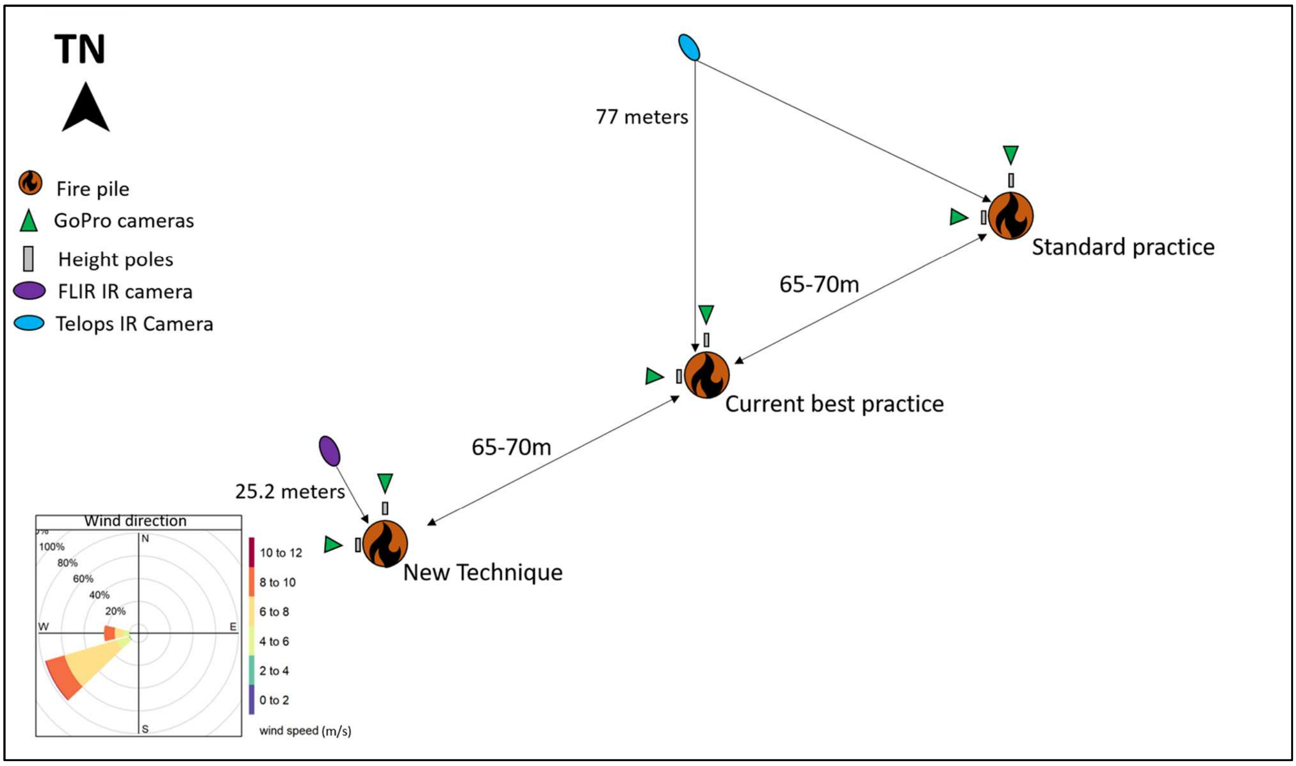


Figure A: Experiment B experimental setup, 19th May 2019 showing Burn A: Standard practice, Burn B: Current best practice, and Burn C: New Technique.

2.2 Fuels

2.2.1 Fuel Types

As in Experiment A., fuels were grouped into the following types: dried hardwood and softwood logs (*Populus* sp. And *Pinus radiata*) and split softwood ignition wood (*Pinus radiata*). Dried hardwood and softwood logs were used as the main fuel for all the burns while split softwood ignition wood was used in Burns B and C as part of the preferred ignition practices to encourage a quick ignition and hot burn. Hardwood stumps and recently cut mixed woods were used to make the burns as close to a real burn as possible.

2.2.2 Fuel Packets

Fuel packets were prepared and standardized in the same manner as in Experiment A. All burns received 5 hardwood-softwood packets at ignition. The total number of fuel packets and the packet type is additionally outlined in Table B. The experiment ran for a maximum time of 3 hours.

Burn A was ignited with 5 hardwood-softwood log packets and, as well as 4 green wood packets. No stumps or other additional packets were added during the burn, due to reaching maximum time limits. The pile fuels were mixed with the excavator to simulate a normal agricultural burn in which fuels are not carefully laid out and stacked.

Burn B was ignited with 5 hardwood-softwood packets and 1 ignition wood packet (crate of split ignition wood). Four packets of recently cut wood were added when the contractor deemed it was fully ignited and would be suitable to receive the additional fuels. Six stump packets (12 stumps total) were added after the recently cut wood packets had been added and the pile had burned successfully to receive the additional fuels (approximately to 2/3 of its original height).

Burn C was ignited with 5 hardwood-softwood log packets and 1 ignition wood packet (crate of split ignition wood). Four packets of recently cut wood were added when the contractor deemed it was fully ignited and would be suitable to receive the additional fuels. A further 3 recently cut wood packets were added when the fire was found to be burning successfully enough to receive further fuel. Six stump packets (12 stumps total) were added after the recently cut wood packets had been added.

Table B: Number of Fuel Packets used in Experiment B. by burn type, Burn A: Standard practice, Burn B: Current best practice, and Burn C: New Technique.

Packet Type	Burn A	Burn B	Burn C
Hardwood-softwood packets	5	5	5
Ignition Wood Packets	1	1	1
Green wood Packets	4	4	7
Stump Packets (2 stumps/packet)	0	6	6

3 Results

3.1 General Weather

We conducted this experiment on 19th May 2019, over a 3 hour period between of 8 am and 11 am. The day was clear, with strengthening winds between 4-10 m/s, wind direction was consistent from the southwest (Table C, Figure B).

Table C: Weather conditions during Experiment B. for Burn A: Standard practice, Burn B: Current best practice and Burn C: New Technique.

Meteorological conditions (mean +/- standard deviation)	**Burn A, B, C 19/05/2019**
Air Temperature (ºC)	14.6 ± 0.7
Relative Humidity (%)	54.6 ± 3.1
Barometric Pressure (hPa)	1009.7 ± 0.8
Rain (mm)	0

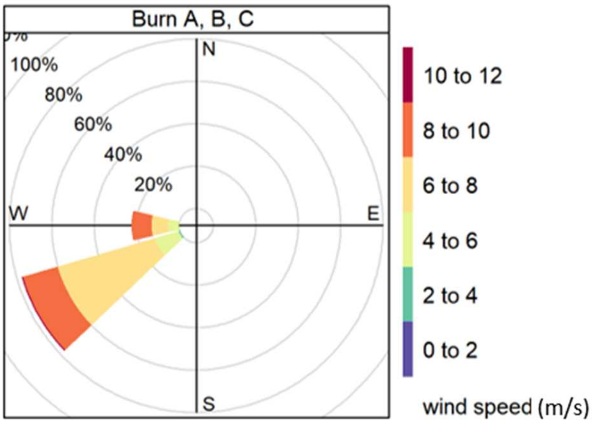


Figure B: Mean frequency of counts for wind speed and direction during Experiment B. for Burn A: Standard practice, Burn B: Current best practice and Burn C: New technique.

3.2 Fire Intensity

3.2.1 Combustion efficiency

Combustion efficiency is defined as the ratio of heat released by the fire to the heat input by the fuel (Miller, 2011). The experimental design specified that the same type of fuels (vegetation type, fuel size and total mass) be used for each burn pile. This means the same input energy content, fuels, was similar for every burn pile. This allows for temperature measured by infra-red imagery to be used as a measure of combustion efficiency.

The temperature of the fire can be used as a measure of combustion efficiency and this along with the knowledge of the types of fuels added and why we can draw some conclusions.

Burn A started out with a large fuel pile and failed to reach a maximum temperature visible on the infra-red camera, never rising above 100°C (Figure C). The pile had to be relit multiple times and only smouldered for the entire experiment. This was due to the green wood packets added for a more realistic outlook. The pile was dismantled in quarter 4, after 2 hr 45min, as compared to Burns B and C, which consumed most or all of the available fuel and burn out by the end of the experiment at 3 hours.

Burn B started well and reached a maximum burn temperature of 825°C in quarter 2, after the temperature dropped in quarters 3 and 4.

Burn C reached the highest temperature of 881.3°C, this occurred in quarter 1. After reaching the maximum the burn pile cooled slightly but otherwise maintained a constant temperature throughout the burn period of 3 hrs (Figure C). It is interesting that Burn C remained so hot because it is the burn practice that consumed the highest quantity of green fuels, therefore containing the most moisture which would be considered a dampener to a fire. Burn C consumed 4 packets of green wood during Q1, and an additional 3 packets of green wood and 6 packets of stumps during Q2, whereas Burns A and B only burned 4 packets of green wood in total over 3 hours, all added in Q1.

Burn C was able to reach ignition temperatures hot enough to consume a greater quantity of green wood and stumps compared to the other two burn techniques.

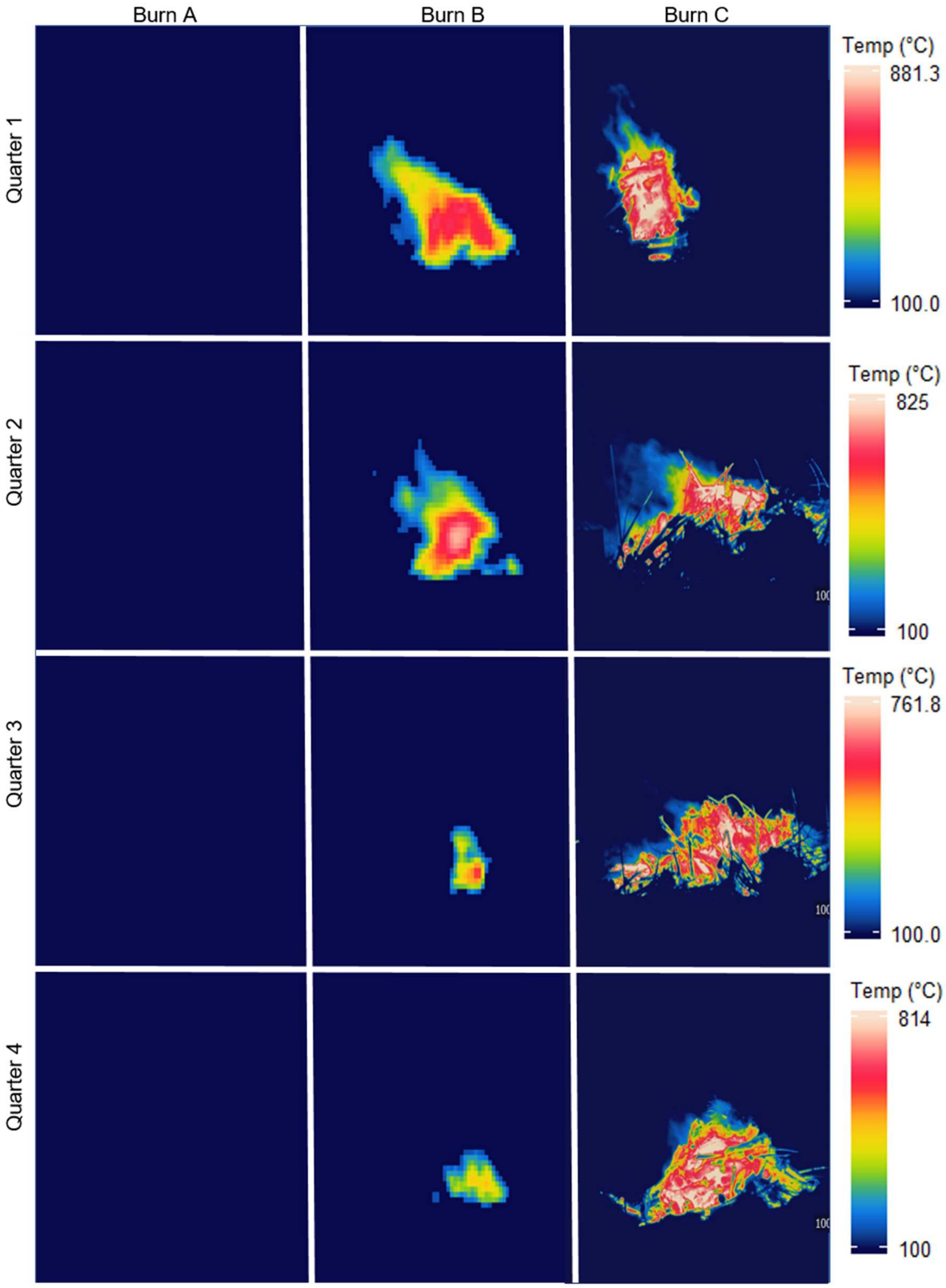


Figure C: Infrared imagery in the middle of each quarter of the burn period (middle of quarter = 42 minutes) for Experiment B., Burn A: Standard practice (Telops IR camera), Burn B: Current best practice (Telops IR camera) and Burn C: New technique (FLIR IR camera). Burn A never reached a temperature of 335°C or above, therefore did not register on the Telops IR camera.

3.3 Smoke Production: Plume Height

While there was little difference between the observed maximum and mean plume heights reached during Burns B and C. The smoke plume height during Burn A was far lower (Table D). The wind conditions were relatively strong with higher speeds prevailing (Figure B). The smoke plume for all three burns was bent over by the wind and this reduced the observed plume heights for all burns (Figure D).

Table D: Experiment B. mean, standard deviation and maximum smoke plume heights for Burn A: Standard practice, Burn B: Current best practice and Burn C: New technique. Showing plume height during each quarter of the burn period and the entire burn period (3 hours).

	Burn A			Burn B			Burn C		
	Mean	**SD**	**Max**	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**
Entire burn (3hrs)	3	0.44	3.5	5	1.46	6	6	2	8.5

Figure D: Visual imagery in the middle of each quarter of the burn period (middle of quarter = 42 minutes) for Experiment B., Burn A: Standard practice, Burn B: Current best practice and Burn C: New technique.

4 Discussion

Fire behaviour is dependent on fuels, weather, and terrain. Terrain was negligible for this experiment as all burns were on flat terrain. Burning on the same day at the same time of day reduced the influence of weather, not a controllable factor.

Burn practice was the controlling factor in this burn experiment. The contractor managing the three burn piles was given the brief of "manage the fires as you would out in the field" to ensure the experiment had real life application. This meant that the contractor added packets of wood to each burn pile based on visual observation that the fire had burned down sufficiently to add more wood. This meant that the faster the fire consumed fuel the more fuel packets it received and, in the end, only one out of the three burns consumed the total amount of available fuel.

Exceptionally dry fuel is considered to range between 2% and 30% in moisture content, while live fuel fuels can range from 30% to 300% depending on the vegetation and season. Moisture contents for this experiment were similar across burns (no significance difference) and ranged from 28% to 113%. In this range, fires are readily ignitable and exhibit high fire behaviour, at the 113% content, to advanced fire behaviour, at the 28% content (Pollet & Brown, 2007). The ignitability sustained consumption, and fire intensity observed during all three burns were all influenced by this fuel moisture content.

When looking at these results the key factors to focus on are (1) combustion efficiency and (2) plume rise.

Burn A, standard practice failed to achieve a solid ignition and did not burn with good intensity, suggesting that the ignition technique and the overall fuel moisture was influencing the burning practice, as the pile was built out of the total available fuel resources, seasoned dry wood and green wood. The fuel moisture content of green or recently cut orchard wood, burned within seven days of removal, would be very high (likely over 180%). At this moisture content, ignition is difficult and maintaining sustained consumption is problematic. This was seen in Burn A, which failed to reach a maximum temperature visible on IR, only smouldering and never actually reached flaming stage before having to be put out when the smoke production reached levels that caused concern to TDC.

Burns B, current best practice ignited well, with good fire intensity, reaching a maximum burn temperature of 825°C before the temperature dropped off. The burn consumed the initial available dry wood and greenwood mix before the addition of stumps to the pile. The burn pile cooled over the remaining ¾ of the burn period as more fuel, stumps (6packets) and green wood (4 packets) were added, decreasing fuel temperature and therefore consumption, consuming a total of 16 fuel packets.

Burn C, new technique, consumed the highest quantity of fuel over the same amount of time as Burn B,19 packets, which included 6 stump packets and 7 green wood packets. Showing that the new technique was a highly efficient burn which can handle increased fuel moisture without compromising fuel consumption. Burn C reach its highest temperature of all burns, 881°C, maintained high temperatures throughout the rest of the burn periods 3 hrs, receiving 3 more green wood packets of fuel than Burn B. Showing that Burn C has the highest combustion efficiency.

Plume rise was overall very low due to strong wind on the day of the experiment, the highest was observed in Burn C, the observers also noted that it had the lowest percentage of a visible plume, this was due to the efficiency of the burn and the lack of particles in the plume. Indicating that with refined protocols the new technique could offer a faster burn with reduced emissions and a cleaner burn of recently removed orchard wood.

Recommendations

The new technique, with modifications as recommended in Experiment A., offers the best potential to reduce pollutant gases and particle emissions during green wood burning in the winter months. A set of protocols that help to reduce the black carbon emissions observed during quarters 3 and 4 as the burn winds down should be tested, adjusting the fan to a lower speed and/or turning it off is also an option.

It is important to note that the new technique allows for a very fast burn. This is useful for burning at midday, when atmospheric dispersion potential is at its highest - the advanced burning method is ideal as consumption is very rapid.

Acknowledgements

The authors acknowledge Jane Stuart and Diana Worthy from the Tasman District Council, Aaron Baigent from Riverstone Balage Ltd for the great work preparing, sorting and weighing fuels and heavy machinery operation during burn management and Woody Pattinson from Mote for the preparation and supply of sensors. Thank you to all for their significant contributions to this study.

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