Fire Behaviour as a Determinant of Fire Effects in Tussock Grasslands

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Client Report No. 15029

Fire Behaviour as a Determinant of Fire Effects in Tussock Grasslands:

Comparison of fire behaviour associated with experimental burns conducted to assess fire effects

H. Grant Pearce, Stuart A.J. Anderson and Ian J. Payton

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Client:	Department of Conservation, and the Rural Fire Research Advisory Committee
Contract No:	DOC Investigation No. 3485 & 3290

EXECUTIVE SUMMARY

This report describes the fire behaviour associated with experimental burns undertaken from 2000 to 2006 as part of the Tussock Fire Ecology project. This project aimed to examine the impacts of fire on tall-tussock grasslands to provide information on the consequences of burning on the native flora and fauna, and for the fertility and longer term sustainability of pastoral production. It involved conducting experimental fires in different seasons at two sites in Otago – Deep Stream, near Dunedin; and Mt Benger, near Roxburgh.

The role of the Scion Rural Fire Research group in the experiments was to quantify fire behaviour to provide estimates of fire intensity and burn severity for use in describing fire disturbance effects. A secondary objective was also to collect data to model fire behaviour in tussock fuels. Information was collected on vegetation biomass and fuel consumption, weather and fire danger conditions, moisture contents of soil and vegetation, rates of fire spread, fire intensity and flame size, and in-fire temperatures. Changes in vegetation composition, plant biomass and nutrient pools and the effects of burning on soil invertebrates have been reported separately*.

Key results and conclusions regarding fire behaviour observed during the experiments included that:

- Both spring and summer burns at Mt Benger were conducted under cooler and damper conditions than the equivalent burns at Deep Stream, and had correspondingly lower Fire Weather Index (FWI) System codes and indices.
- As a result, there were few clear differences in the moisture contents of plant material or soil between the burns conducted at each site.
- However, the variance in weather and fire danger conditions, combined with differences in plant growth stage associated with the time of year, meant that contrasting fire impacts were obtained from burns conducted in different seasons.
- Fuel consumption was relatively consistent across the burn experiments, with the exception of the Mt Benger summer burns where it was significantly higher due to the occurrence of a tussock mast flowering season.
- Trends for fuel consumption were more apparent when considered on a percentage basis, and significant relationships were identified between biomass loss and soil moisture, and also with the Fine Fuel Moisture Code (FFMC) and Duff Moisture Code (DMC) components of the FWI System.

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* Payton, I.J.; Pearce, H.G. 2009. Fire-induced changes to the vegetation of tall-tussock (Chionochloa rigida) grassland ecosystems. Department of Conservation, Wellington. Science for Conservation 290. 42 p.

Barratt, B.I.P.; Ferguson, C.M.; Barton, D.M.; Johnstone, P.D. 2009. Impact of fire on tussock grassland invertebrate populations. Department of Conservation, Wellington. Science for Conservation 291. 75 p.

- Rates of fire spread varied widely, depending on wind speed and fuel dryness. However, wind speeds for the burn experiments were not as well correlated with spread rate as was the case for tussock burns conducted in other parts of the country.
- No moisture effect on spread rate could be readily identified.
- The burn data did not fit as well against the Initial Spread Index (ISI) from the FWI System (which integrates the effects of wind speed and fuel dryness) compared with other tussock fire data where fire spread rates are relatively well predicted by the Natural/Standing Grass (O-1b) model from the Canadian Fire Behaviour Prediction System (assuming 100% grass curing).
- The Mt Benger burns, with low ISI values (i.e. high moisture, lower wind speeds), were observed to spread faster than other tussock fires and the O-1b model predicts, whereas the Deep Stream burns with higher ISI values (lower moisture, higher wind speeds) spread slower than other tussock fires and predictions by the model.
- Fireline intensity for the burns varied considerably as a result of the variation in both fuel consumption and spread rates, and there was no consistent pattern with season of burning.
- The highest fire intensities were observed during the Deep Stream spring and Mt Benger summer burns (which had the highest spread rates), whereas the lowest intensities occurred during the Mt Benger spring burns (which had the least fuel consumption and slower spread rates).
- In comparison, flame lengths varied little between the burns, and the flame length-fire intensity relationship did not compare well with other tussock fires which more closely followed Byram's (1959) standard relationship.
- It is possible that the differences between results from these experiments and those from previous tussock burns arose due to the estimation of fire behaviour associated with short fire runs (<100 m). Under these conditions, fires may not have reached their equilibrium for the conditions. Wherever possible, future experiments should therefore look to collect observations from larger burn plots that enable longer fire runs.
- Further analysis, and likely additional data collection, is required before definitive models for predicting fire behaviour (rate of fire spread, fuel consumption) in tussock grassland fuels can be developed.

A further aim of the experiments was to determine whether fire behaviour predicted using fuel load, moisture contents, and onsite weather and fire danger conditions can be used to estimate potential burn severity and therefore subsequent fire effects. Results from the experiments, as well as other experimental fires in tussock vegetation, showed that tussock fire behaviour could to some extent be predicted based on onsite weather and fire danger information:

- The fuel moisture codes of the FWI System (in particular, the FFMC), were reasonable predictors of the actual moisture contents of soil, tussock bases and litter, and also of fuel consumption/biomass loss.
- Similarly, the ISI component (or wind speed) can be used to predict the rate of spread for tussock fires under some (generally drier) conditions;

however, the dependence of fire spread in tussock fuels on fuel moisture has yet to be properly determined.

- In combination, these predictions of fuel consumption and rate of spread can be used to estimate fire intensity which, in turn, can be used to estimate potential fire effects such as biomass loss.
- Fire temperatures, measured using both thermocouples and heat-sensitive paints, were not found to be a useful indicator of burn severity.
- Other fire behaviour characteristics such as depth of burn and flame residence time may provide more useful measures and require investigation in future experiments.
- However, relationships between these characteristics and predictors such as fireline intensity or flame length, still need to be derived for a range of fire effects before they can be considered as useful predictors of burn severity and fire impacts in tussock grasslands.
- This will require considerably more data and further modelling of fire behaviour relationships and associated fire effects, and it is recommended that similar experiments continue to be supported and conducted in tussock grasslands to achieve this.

TABLE OF CONTENTS

Information for Scion abstracting:

Contract number	DOC Investigation No. 3485 & 3290
Client Report No.	15029
Products investigated	Fire behaviour, Fire effects
Wood species worked on	
Other materials used	Tussock grasslands
Location	Dunedin City Council Water Catchment Area, Deep Stream; and Moa Hills Pastoral lease, Mt Benger, Roxburgh; Otago

Pearce, H.G.; Anderson, S.A.J; Payton, I.J. 2009. Fire behaviour as a determinant of fire effects in tussock grasslands: Comparison of fire behaviour associated with experimental burns conducted to assess fire effects. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No. 15029. 31 p. [Output No. 40469]

INTRODUCTION

This report describes the fire behaviour associated with experimental burns conducted in different seasons at two sites in Otago – Deep Stream, near Dunedin; and Mt Benger, near Roxburgh – undertaken as part of the Tussock Fire Ecology project (see Fig. 1). This project aimed to examine the impacts of fire on tall-tussock grasslands in the Otago high country and, in particular, to provide information on the consequences of burning those grasslands for the native flora and fauna, and for the fertility and longer term sustainability of pastoral production. The study attempted to answer three critical questions (after Payton 2002, Payton and Pearce 2009):

1. Does fire cause long-term damage to the native plant and animal populations and the fertility of snow tussock grasslands?
2. Are accidental summer fires more damaging than prescribed burns in late winter or early spring?
3. Can we predict fire behaviour, based on the amount of available fuel and the onsite weather and fire danger conditions?

The study was a collaborative venture between Landcare Research, the Department of Conservation, AgResearch and Scion. It was jointly funded by FRST, DOC, the National Rural Fire Authority (NRFA) and the Hellaby Indigenous Grasslands Research Trust.

Landcare Research staff are determining the changes to the vegetation composition, plant biomass and nutrient pools, while AgResearch are determining the effects of burning on soil invertebrates. While long-term monitoring of fire effects on some of these elements is continuing, results obtained to date have been reported separately (Barratt *et al*. 2009, Payton and Pearce 2009). The Department of Conservation (DOC) co-ordinated the operational aspects of the project, including fire suppression during the burn experiments, while the research project was co-ordinated by Landcare Research. Further information on the project, and the issues prompting the research, are contained in Payton and Pearce (2009).

The role of Scion's Rural Fire Research group was to measure the fire behaviour associated with each burn experiment, as the basis for comparison of "fire severity" for each burn and subsequent fire effects (Keeley 2009). This was done by collecting information on rate of fire spread and fuel consumption to estimate the intensity of the fires which, in conjunction with measurements of fuel moisture content and in-fire temperatures, was used to describe the severity of each experimental fire. This report outlines the results for these fire behaviour and fire severity characteristics and, as such, particularly addresses question 3 above.

In addition to supporting the studies on fire effects, fire behaviour observations collected during the burns will also be used by the Scion Rural Fire Research group to complement existing tussock fire behaviour data for the development of fire behaviour models for tussock grassland fuels.

METHODS

Experimental sites

The two experimental sites (Fig. 1) were located at Deep Stream inland from Dunedin (coastal site), and Mt Benger near Roxburgh (inland site) (Fig. 2). The Deep Stream site on the eastern end of the Lammerlaw Range is typical of lower altitude (640-700 m a.s.l.) tall-tussock grasslands that are coming under increasing pressure from pastoral development, whereas the Mt Benger site is representative of higher altitude (1100-1180 m a.s.l.) pastoral leasehold land that is progressively being retired from grazing and incorporated into the public lands managed by the Department of Conservation. The Deep Stream site is warmer and drier (mean annual temperature 6.8 °C, mean annual rainfall 993 mm) compared with Mt Benger (4.9 °C, 1264 mm). More detailed climate and site characteristics for the two study sites are described by Payton and Pearce (2009).

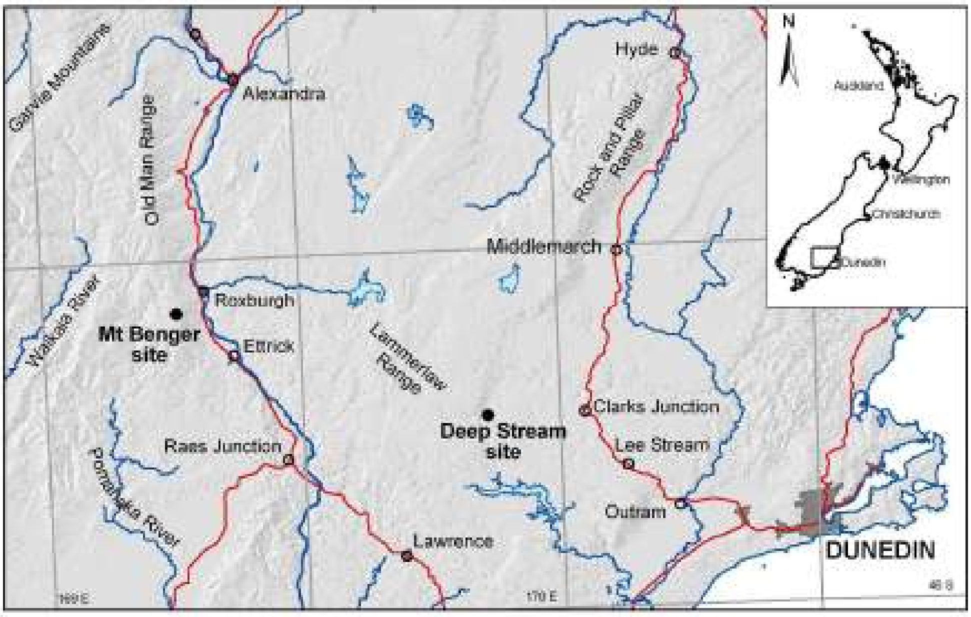

Figure 1. Map of the Tussock Fire Ecology project study sites at Deep Stream and Mt Benger [source: Payton and Pearce 2009].

Each of the experimental sites comprised nine 1-hectare (100 m x 100 m) plots that were subjectively located on gently sloping terrain (Fig. 2), to which experimental treatments were randomly allocated. At each site, three of the plots remained unburned, three were burned under winter-spring conditions (to simulate the current farming practice of early season burns), and three plots were burned in summer or autumn (to simulate accidental wildfires under drier conditions). All plots were surrounded by a 2-5 m wide mineral earth fire-break, and each site was equipped (courtesy of the NRFA) with an automated fire weather station (see Fig. 2). Each plot was subdivided into 25 x 0.04 ha (20 m x 20 m) subplots, and randomly selected subplots were allocated to destructive plant biomass harvests, non-destructive plant measurements (see Payton and Pearce 2009), invertebrate sampling (see Barratt *et al*. 2009), and in-fire temperature measurements.

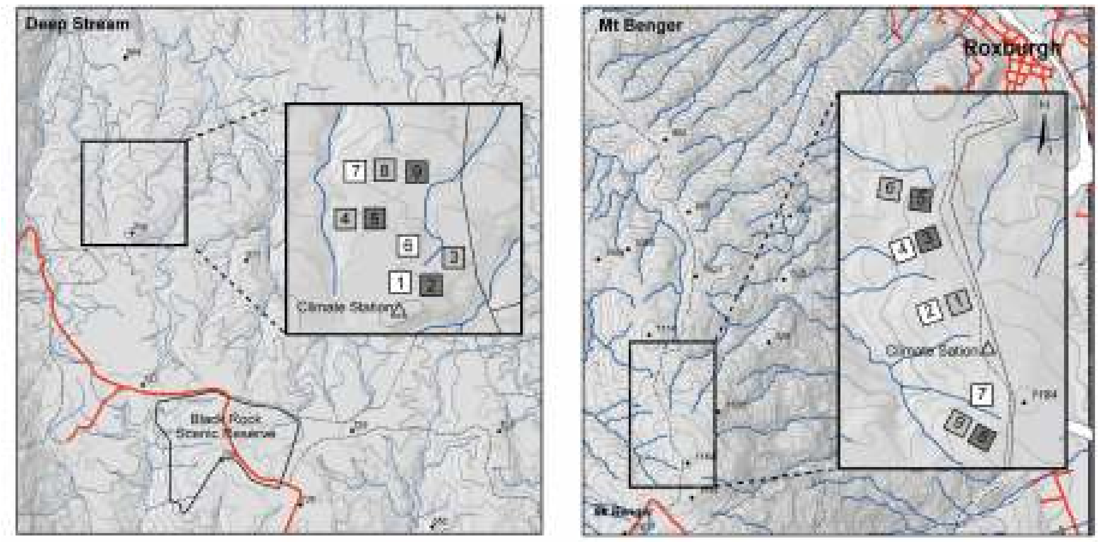

Figure 2. Layout of experimental plots at the Deep Stream (left) and Mt Benger (right) study sites. The colour of the squares denotes the burning treatment – white (unburned), light grey (burned in spring), dark grey (burned in summer) [source: Payton and Pearce 2009].

The principal role of the Scion Rural Fire Research group in the project was to quantify the fire behaviour for each burn to provide estimates of fire intensity and burn severity, for use in describing fire disturbance effects in tall tussock ecosystems. A secondary objective was to collect data for use in modelling fire behaviour in tussock fuels. Information was therefore collected on:

- vegetation biomass, grass curing, fuel loads and consumption;
- weather and fire danger readings prior to and on the day of burning;
- fuel moisture at the time of burning;
- fire behaviour (rate of fire spread, flame size); and
- in-fire temperatures.

Biomass/fuel consumption

Plant biomass harvest subplots (0.04 ha) were divided into 400 (1 × 1 m) squares, five of which were randomly chosen for each biomass harvest within each burn plot. The corners of each harvested square were permanently marked with aluminium pegs to ensure that squares were not inadvertently resampled at a later date. Biomass samples were collected prior to burning, and then again immediately following burning (Fig. 3), with the difference between these pre- and post-burn samples used to estimate fuel consumption.[1]

Within each square, a sharp spade was used to remove all above-ground plant material to the level of the mineral soil (see Fig. 3). All plant material was bagged and returned to the laboratory, where it was separated by species or species-group (e.g. minor forbs, mosses), and into live and dead material. Plant samples were dried to a constant weight in a forced-draft oven (70 °C).

[1] Additional biomass samples have also been collected at intervals after burning (currently up to 5 years), for use in assessing post-fire vegetation recovery (Payton and Pearce 2001, 2009).

Figure 3. Collection of pre- (left) and post-burn (right) biomass samples in tussock fuels.

Prior to the burning of each plot, smaller grab samples were also collected at random from within each burn plot to determine the degree of curing of the fuels at the time the burns were conducted. Describing the proportion of dead material within the fuel complex (Gates 1987), the degree of curing is a key factor in determining the rate of spread and intensity of fires in grassland fuels (Cheney and Sullivan 1997). Samples were collected from elevated tussock and, where present, understorey grass vegetation. These were sorted into dead and live components, oven-dried (at 100 °C) and weighed to determine the percentage (%) of dead and live plant material.

Fire weather conditions

Weather conditions (temperature, rainfall, humidity, wind speed and direction) at each site were monitored using an automated climate station that formed part of the National Rural Fire Authority's (NRFA) network of fire weather stations. This was supplemented by portable weather stations that were used to gather more detailed fire weather data from individual plots in the lead-up to and during the burns.

Data from the fire weather stations, which provide numerical ratings for the Fire Weather Index (FWI) subsystem of the New Zealand Fire Danger Rating System (Anderson 2005), enabled changes in fuel moisture codes and fire behaviour indices (see Appendix 1 for details) to be tracked on a daily basis throughout the year. Fuel moisture codes (Fine Fuel Moisture Code, FFMC; Duff Moisture Code, DMC; Drought Code, DC) provide a measure of the dryness of available fuels and soil organic layers, based on the cumulative effects of temperature, humidity and rainfall. Fire behaviour indices combine these codes with information on wind speed to provide numerical ratings of the expected rate of fire spread (Initial Spread Index, ISI), fuel availability for combustion (Buildup Index, BUI) and fire intensity (Fire Weather Index, FWI).

Target ranges (based on long-term fire weather records) for each of these indices were set to reflect average conditions experienced in the region during spring (when early season burns are normally conducted) and summer (when accidental dry season wildfires are likely to occur). In conjunction with the time of year (season), these were used to determine when the experimental burns should be conducted. These target ranges for the FWI System components and associated weather conditions were:

	Spring	Summer
Temperature (ºC)	5 - 25	10 - 35
Relative Humidity (%)	20 - 95	15 - 90
Wind speed (km/h)	0 - 20	0 - 20
DSR[2] >1.5 mm	2 - 5	>5
FFMC	70 – 90	75 - 95
DMC	0 – 20	10 - 30
DC	30 – 200	200 - 500
ISI	0.5 - 12.0	1.0 - 24.0
BUI	10 – 30	20 - 50
FWI	0 – 19	1 - 40

Fuel moisture content

Samples were collected from each of the main vegetation and soil layers immediately prior to and following burning to determine moisture contents (Fig. 4). The components sampled included elevated live and dead tussock tillers, tussock litter, tussock bases, and soil layers of 0-5 cm and 5-10 cm depth. Where present, samples were also collected from understorey vegetation (grasses)[3]. Five samples of each component were collected prior to the ignition of each burn plot, and then again following the completion of the final burn from adjacent (unburned) vegetation. Samples were placed in sealed containers for return to the laboratory, where they were oven-dried (at 105 °C) to a constant weight. Moisture content was expressed as a percentage of the dry weight of each sample.

Figure 4. Collection of moisture content samples in tussock fuels.

[2] Days Since (Significant) Rain. A value of 1.5 mm was used as this is the amount of daily rainfall required to impact on the FWI System's Duff Moisture Code (DMC), which is an indicator of the moisture content of shallow soil organic layers.

[3] Moisture samples were collected separately by both Scion and Landcare Research. With the exception of soil moisture samples which were collected by Landcare, all other fuel moisture contents reported here are based on the samples collected by Scion. Values may therefore differ slightly from those reported elsewhere (e.g. Payton and Pearce 2001, 2009), due to the subjectivity involved in collecting samples from the various fuel elements and minor differences in sample processing methods (e.g. Landcare oven-drying temperature of 70 °C).

Fire behaviour observations

Observations of the location of the spreading fire front and flame size for each experimental fire were documented to determine the rate of fire spread and fireline intensity. The rate of fire spread was estimated by timing the movement of the forward-most part of the fire front as it reached each of the 20 m reference markers (fencing standards or 'waratahs') used to demarcate the 20 × 20 m subplots within each burn plot (Fig. 5). Flame front characteristics (i.e., flame height, length and angle) were also estimated using the height of these reference markers, and observations made during the burns were later validated using still and video photography recorded of each burn.

In conjunction with estimates of fuel consumption obtained from pre-and post-burn biomass sampling, rates of fire spread were used to estimate the fireline intensity for each experimental fire (after Byram 1959a, Burrows 1984). Flame lengths, which are a visual indicator of fire intensity, were used to validate these estimates (using Byram's 1959b relationship). Fireline intensity was the principle fire behaviour characteristic used to describe the severity of burns for use in comparing fire effects (Keeley 2009).

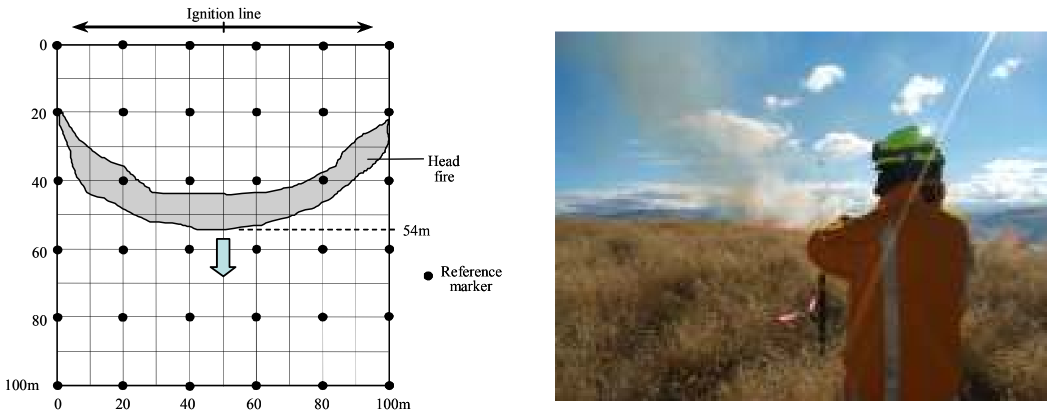

Figure 5. Layout of the reference grid used to monitoring progress of the fire front across a burning plot (left), and an example of the timing of the fire front as it reaches a reference marker (right).

In-fire temperatures

As a further means of describing the fire severity of each experimental burn, fire temperatures were measured using thermocouple sensors (spring burns at Deep Stream only) and heatplates (all burns) marked with temperature-indicating paints (Hobbs *et al*. 1984; Gill & Knight 1991; Tolhurst 1995).

Thermocouple sensors were placed 1 m above the ground and at ground level, near the centre of the plot. The resulting temperature traces provided a continuous record of in-fire temperatures during the experimental fire. Where possible, thermocouples were located adjacent to heatplate measurements (Fig. 6)

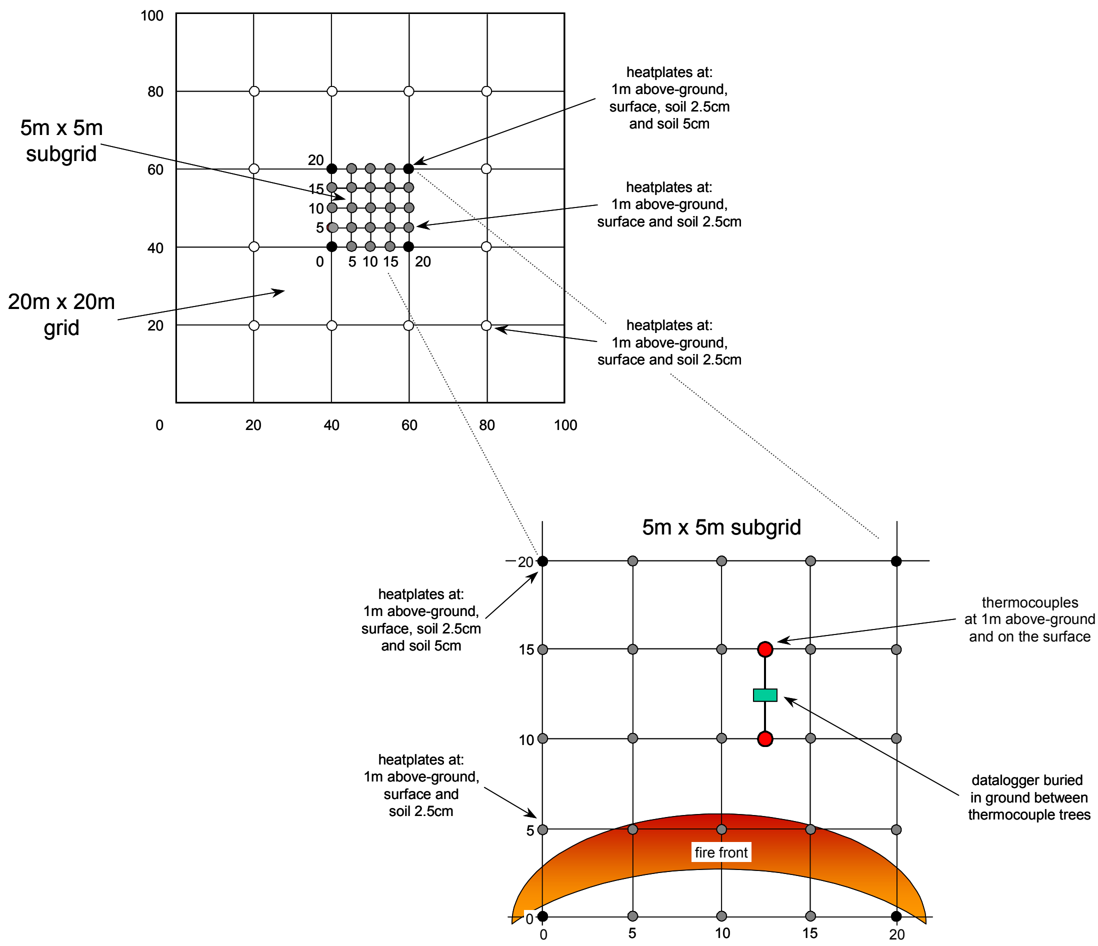

Figure 6. Grid layout for in-fire temperature measurement using heatplates and thermocouples.

Heatplates were positioned 1 m above the ground, at ground level, and at soil depths of 2.5 cm and 5.0 cm, on a 5 × 5-m grid on the central 20 × 20-m subplot, and on a 20 × 20-m grid over the remainder of the 1-ha plot. Each heatplate consisted of a strip of copper folded back on itself with a row of temperature-indicating paint strips on the inside surface (Fig. 7). The choice of paint temperature ranges related to expected fire temperatures and the effects of heating on plant tissue (Moore *et al*. 1995), and different ranges were used for above-ground versus below-ground heatplates:

- 1 m above-ground (above tussock foliage): temperatures 121°, 316°, 593°, 774° and 1010°C;
- surface (tussock base): temperatures 121°, 316°, 593°, 774° and 1010°C;
- below-ground (soil): temperatures 69° and 121°C.

The heatplate measurements had the disadvantage of only recording the maximum temperature reached within a range, and gave no indication of actual temperature or duration. However, multiple observations were obtained easily and cost-effectively from the grid of heatplates spread across each burn plot.

Figure 7. Examples of thermocouple and above-ground heatplate (left) and soil heatplates (right) used to measure fire temperatures.

Fire ignition

Each set of experimental fires was conducted on a single day, with burns carried out between 1300 and 1700 hours. Burns were lit on the upwind side of the plot (Fig. 8), and the rate and direction of fire spread was determined by the prevailing wind (thereby simulating the spread of a wildfire or large controlled burn) (also see Fig. 5). However, where fire safety personnel deemed it necessary, the downwind side of the plot was in some cases initially back-burned to increase the width of the firebreak and minimise the chance of an escape. In these instances, care was taken when recording fire behaviour observations to avoid (or at least document) where fire spread was impacted by the drawing together of the main fire run and the back-burn.

Figure 8. Ignition of an experimental burn.

Fires were lit using line ignitions 70 to 100 m in length, typically by two igniters with gas burners commencing in the centre of the upwind edge of the burn plot and each working outwards to the plot corners (see Fig. 8). However, depending on the alignment of the prevailing wind in relation to the plot edge, ignitions sometimes commenced closer to the upwind corner to maximise the length of fire run and limit the chances of the fire running out the side of the burn plot before the head fire had reached the downwind edge.

RESULTS AND DISCUSSION

Experimental burn timing and conditions

The experimental burns were completed between November 2000 and March 2006. The study's duration was prolonged as a result of several delays, including the location and establishment of a suitable inland site (at Mt Benger), and a change in the rural fire authority responsible for this site (from Central Otago District Council to the Department of Conservation). The completion of the Mt Benger summer burns was also delayed by the occurrence of unsuitable weather conditions over several seasons that did not meet the required burn target ranges. Conditions were either too dry with fire prohibitions declared (i.e. 2002/03), or too wet and unrepresentative of the required dry summer conditions (i.e. 2003/04, 2004/05 and 2005/06).

At Deep Stream, the spring burns took place on 2 October 2001, during a 2-week dry spell in what was an otherwise damp end to spring (Fig. 9). All fire weather indices were in the mid- to upper quartiles of the spring-burn range, with the exception of DC, which was just below the spring-burn threshold (Table 1). In 2001, the Deep Stream grasslands did not dry out sufficiently for a summer burn until early March (Fig. 9), when the plots were burned on 7 March 2001, which was the first day that all of the fire weather indices were within the summer-burn range (Table 1).

At Mt Benger, the spring burns were lit on 3 November 2000 (Fig. 10). This was later than pastoral burns are usually permitted, but weather conditions and fire weather indices were still well within the target range for spring burns (Table 1). There was a crisp frost on the morning of the fires, and snow blanketed the site several days later. The summer burns at Mt Benger were delayed until 31 March 2006, owing to previous seasons not meeting the prescribed ranges for summer burning due to initially being too dry then too wet (Fig. 10). After a damp start to the 2005/06 summer, conditions exceeded the summer-burn thresholds for only a brief period in late February 2006. A dry spell during March was not sufficient to enable all fire weather indices to reach the summer-burn thresholds (Table 1), but did allow the grasslands to dry out sufficiently to carry a fire[4].

[4] Rather than delay the project further and risk not being able to complete it due to issues with ongoing support, the burns were carried out despite not meeting some of the threshold conditions in the interests of completing the project.

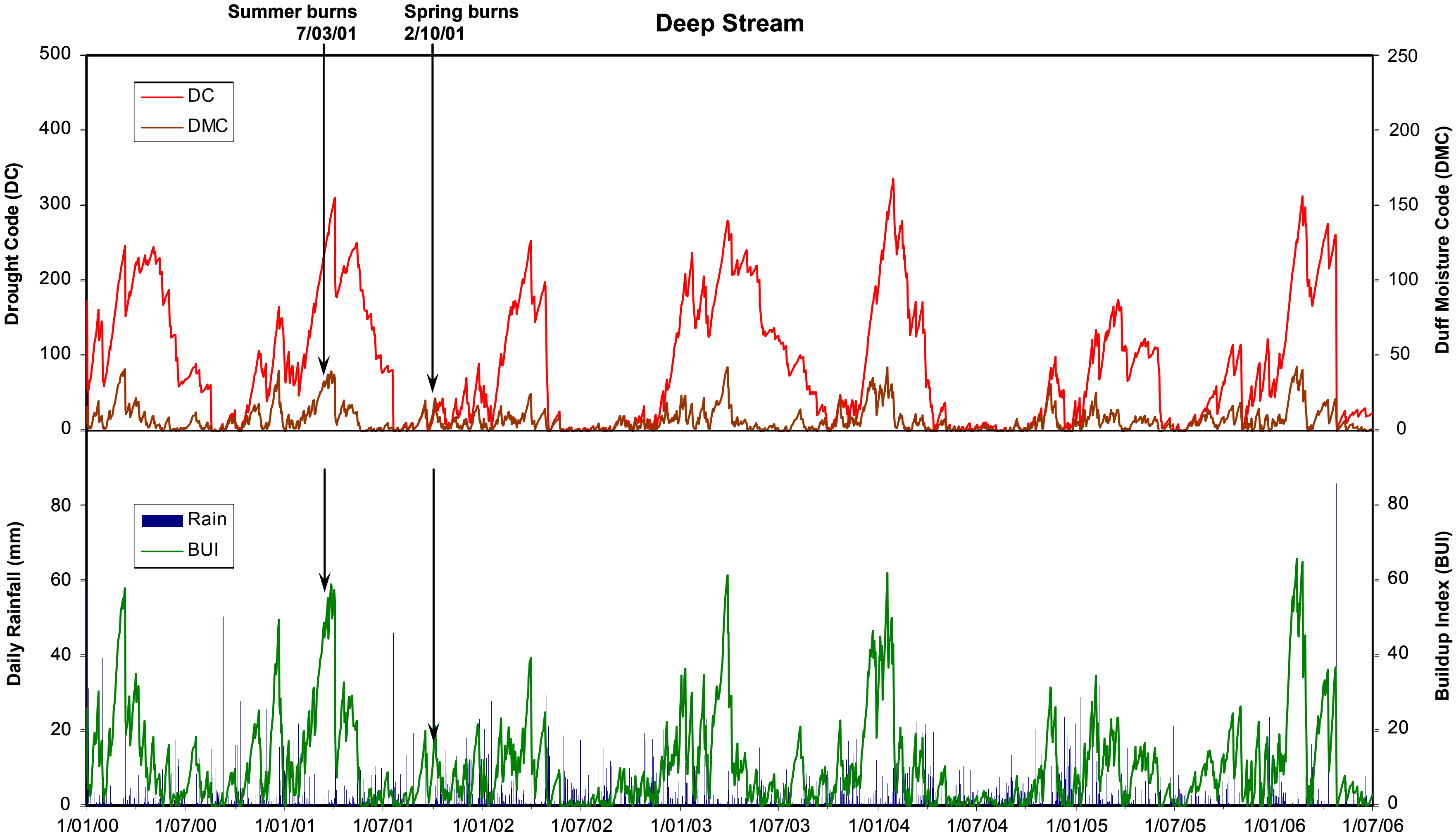

Figure 9. Fire weather conditions at the time of the spring and summer burn experiments (indicated by the arrows) at Deep Stream.

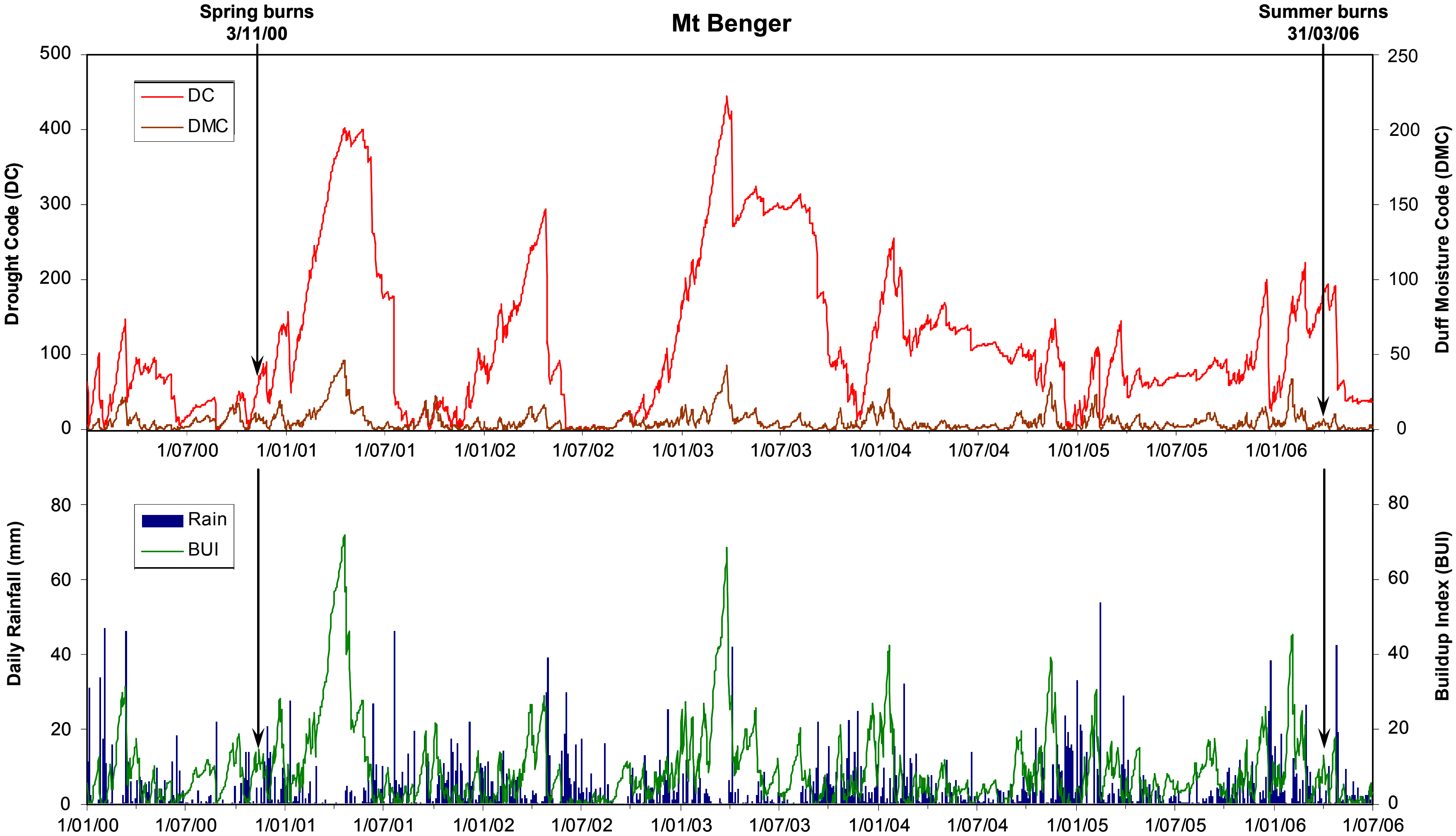

Figure 10. Fire weather conditions at the time of the spring and summer burn experiments (indicated by the arrows) at Mt Benger.

Table 1. Comparison of actual and prescribed burn conditions for the spring and summer fire experiments at Deep Stream and Mt Benger. Coloured numbers indicated where values were below (blue) or above (red) the prescribed ranges.

	Deep Stream (Oct' 01)	Mt Benger (Nov '00)	Spring prescription
Temp. (ºC)	18.3 - 21.4	7.8 - 10.8	5 - 25
RH (%)	41 - 51	57 - 70	20 - 95
10m WS (km/h)	17.4 - **25.3**	11.1 - 18.1	0 - 20
DSR >1.5mm	**8**	2	2 - 5
FFMC	88.7 - 89.9	78.7 - 81.4	70 - 90
DMC	14	6	0 - 20
DC	**20**	33	30 - 200
ISI	10.1 - **13.6**	1.7 - 3.3	0 - 12
BUI	14	**9**	10 - 30
FWI	**11.8 - 14.9**	1.0 - 3.2	0 - 5

	Deep Stream (Mar '01)	Mt Benger (Mar '06)	Summer prescription
Temp. (ºC)	18.0 - 18.7	11.2 - 12.1	10 - 35
RH (%)	59 - 60	68 - 73	15 - 90
10m WS (km/h)	**21.8 - 26.6**	8.1 - 12.4	0 - 20
DSR >0.6 mm	10	**2**	>5
FFMC	86.6 - 86.7	**74.6** - 75.9	75 - 95
DMC	26	**5**	10 - 30
DC	204	**178**	200 - 500
ISI	7.9 - 10.0	1.1 - 1.5	0 - 24
BUI	39	**9**	20 - 50
FWI	16.4 - 19.6	**0.6 - 0.8**	1 - 40

Both spring and summer burns at Mt Benger were conducted under cooler and damper conditions than corresponding burns at Deep Stream, and had correspondingly lower FWI System codes and indices (Table 1; also see Appendix 2). This was due in part to the higher altitude of the Mt Benger site (1100 m *cf*. 700 m a.s.l. at Deep Stream), although differences in seasonal conditions were also a factor. Despite the variance between the two sites, the spring and summer burns at each location were still conducted under different conditions generally reflective of the desired differences between damp, spring burns and drier, summer fires. In combination with the differences in the plant growth phase associated with the burns conducted at different times of year, the variance in weather and fire danger conditions (and resulting moisture conditions) meant that contrasting fire impacts between seasons were obtained.

Fire weather conditions

The variation in seasonal fire danger conditions over the 2000-2006 period at the two burns sites is illustrated in Figures 9 & 10. The ranges of weather and FWI System values associated with each set of burns are also shown in Table 1, and details of the conditions associated with each individual burn experiment are given in Appendix 2.

Values of the FFMC (an indicator of the moisture content of fine fuels, and ease of ignition) for the Mt Benger spring burns (approx. 79-81) were in the middle of the prescribed spring burn range (Table 1), but were lower than those for the corresponding burns at Deep Stream (at around 89-90) due to the lower temperatures (8-11 °C *cf*. 18-21 °C), higher humidity (57-70% *cf*. 41-51%) and more recent rainfall (DSR >1.5 mm of 2 *cf*. 8 days). DMC (6 *cf*. 14) and BUI (9 *cf*. 14) values were also lower at Mt Benger, although DC values (33 vs 20) were higher than at Deep Stream due to a longer period without heavy rain (>2.8 mm). However, all these values (which indicate the moisture content and availability of soil organic layers and heavier fuels[5] to burn) were relatively low reflecting the recent rainfall and generally cool, damp spring conditions. Values of the ISI component (which reflects potential rate of fire spread) were significantly higher for the spring burns at Deep Stream (10-14) than at Mt Benger (2-3), due to higher wind speeds (17-25 km/h *cf*. 11-18 km/h) and the higher FFMC values outlined above. Similarly, FWI values (a measure of potential fire intensity) were also significantly higher at Deep Stream (and considerably above the prescribed range, at 12-15 *cf*. 1-3), as a result of the higher ISI and BUI values for these burns.

Differences between the FWI System components at the two sites for the summer burns were even more contrasting. FFMC values at Mt Benger were on or below the summer threshold (75-76), whereas those at Deep Stream were mid-range (86-87), as a result of considerable differences in temperature (11-12 °C *cf*. 18-19 °C), period without rain (2 *cf*. 10 days) and, to a lesser extent, humidity (68-73% *cf*. 59-60%). DMC (5 *cf*. 26), DC (178 *cf*. 204) and BUI (9 *cf*. 39) were also lower at Mt Benger than at Deep Stream, with the Mt Benger values falling below the prescribed range in all three cases due to the damp seasonal conditions at this site. ISI (1-2 *cf*. 8-10) and FWI (<1 *cf*. 16-20) values were also significantly lower as a result of the lower wind speeds (8-12 *cf*. 22-27 km/h) and moisture code values outlined above at Mt Benger, and again were on or below the lower limit of the prescribed range for the summer burns (see Table 1). This variation in conditions between the two sites is a result of the higher elevation of the Mt Benger site, as well as seasonal differences in the summers in which the two sets of burns were conducted.

Fuel moisture contents

Moisture content data for the range of vegetation and soil components sampled for each burn are contained in Appendix 2, and are summarised in Table 2. There were few clear differences in moisture contents between the spring and summer burns conducted at each site, or associated with the season of burning generally. Moisture contents for the Mt Benger summer burns were damper than those for the spring burns at the same site. However, conditions for the Deep Stream spring and summer burns were very similar, and were both considerably drier than the Mt Benger burns.

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[5] Originally developed for forests with woody fuels such as branches and logs on the forest floor, the relevance of the FWI System's DMC, DC and BUI components to grassland fuels is limited; however, these moisture codes are still useful indicators of the moisture content of the soil and, perhaps, of dense fuels such as tussock clump bases.

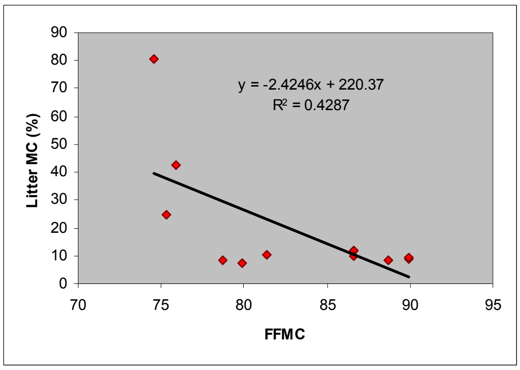
Table 2. Moisture contents (% dry weight) of vegetation and soil components sampled during the experimental burns. Values are the average of immediate pre- and post-burn samples, and are expressed as the mean ± standard error of 5 samples per burn plot and three plots per burn treatment.

<table>
<tr><th><u>Scion</u></th><th colspan="2">Deep Stream</th><th colspan="2">Mt Benger</th></tr>
<tr><th></th><th>Spring</th><th>Summer</th><th>Spring</th><th>Summer</th></tr>
<tr><td>Surface litter</td><td>8.9 ± 0.2</td><td>11.1 ± 0.6</td><td>8.8 ± 0.8</td><td>49.3 ± 16.4</td></tr>
<tr><td>Tussock base</td><td>84.0 ± 5.6</td><td>96.5 ± 10.4</td><td>100.2 ± 8.8</td><td>136.5 ± 5.8</td></tr>
<tr><td>Live tussock tillers</td><td rowspan="2">41.3 ± 3.6*</td><td rowspan="2">63.1 ± 1.4*</td><td>51.3 ± 4.3</td><td>100.5 ± 0.5</td></tr>
<tr><td>Elevated dead</td><td>22.8 ± 2.4</td><td>39.1 ± 3.0</td></tr>
</table>

* NB. Composite samples of elevated live and dead tussock tillers

The best predictor of litter fuel moisture content was the FFMC (R^2 = 0.43, p = 0.021) (Fig. 11a), and relationships with other FWI system components were not significant. Comparison of actual litter moisture content with values predicted from the FFMC showed a similar strength relationship (R^2 = 0.45, p = 0.018) (Fig. 11b), with actual moisture content values significantly higher than those predicted at lower FFMC values (i.e. Mt Benger summer burns). However, removing these data points produced a worse relationship (with a negative trend of lower predicted moisture content at higher actual litter moisture values). Litter fuel moisture content values were also strongly correlated with the moisture contents for elevated dead (r_s[6] = 1.00, $p < 0.001$), elevated live (r_s = 0.80, p = 0.002) and tussock bases (r_s = 0.63, p = 0.029).

(a)



(b)

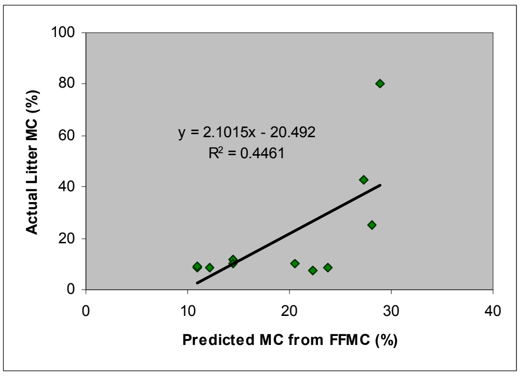


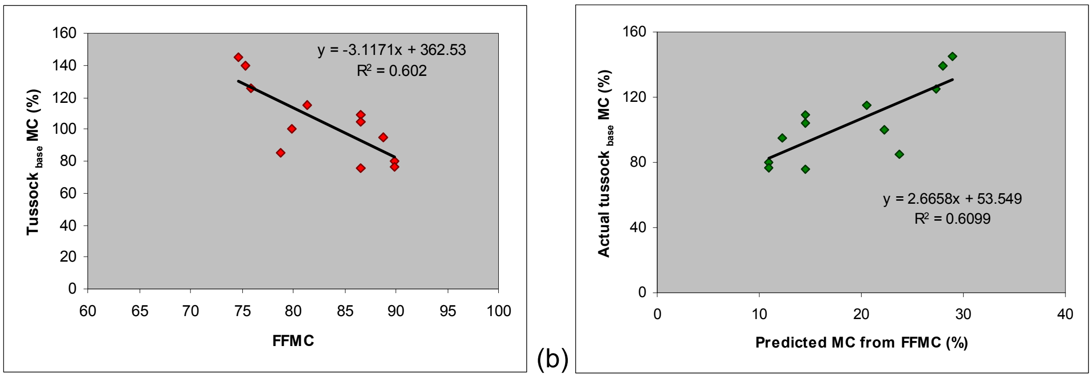
Figure 11. Relationships between the observed moisture content of tussock litter and **(a)** the Fine Fuel Moisture Code (FFMC) component of the FWI System, and **(b)** predicted moisture content determined from the FFMC component.

Moisture samples for the elevated dead component were only collected for the Mt Benger burns (as composite elevated samples, comprising both live and dead tussock material, had been collected previously for the Deep Stream burns). The reduced sample size meant that DMC, DC and FFMC all proved to be equally capable of predicting the elevated dead fuel moisture content (R^2 = 0.62-0.65, p = 0.052-0.064). When investigated separately, the composite values for Deep Stream were also strongly correlated with all three

6 Spearman rank correlation coefficient, r_s.

FWI System moisture codes, although the DMC and DC were better predictors than the FFMC (due to the inclusion of the live tussock tillers).

For tussock base moisture contents, the FFMC again proved to be the best predictor of the FWI System components (R^2 = 0.60, p = 0.003) (Fig. 12a), and relationships for other components were not significant. The predicted moisture content derived from the FFMC was also a similar strength predictor (R^2 = 0.61, p = 0.003) (Fig. 12b). Tussock base moisture contents were correlated with elevated live fuel moisture (r_s = 0.69, p = 0.013) and soil moisture contents for both $soil_{0\text{-}5cm}$ (r_s = 0.61, p = 0.036) and $soil_{5\text{-}10cm}$ (r_s = 0.60, p = 0.039).

(a) 

(b)

Figure 12. Relationships between the observed moisture content of tussock clump bases and **(a)** the Fine Fuel Moisture Code (FFMC) component of the FWI System, and **(b)** predicted moisture content determined from the FFMC component.

In the case of elevated live tussock tillers, the best predictors of fuel moisture content content were the FFMC (R^2 = 0.59, p = 0.004) and DC (R^2 = 0.51, p = 0.009); however, in the latter case, the DC shows a trend of increasing fuel moisture with higher code values when it would be expected to decrease. As noted previously, the moisture contents for elevated live tussock samples were strongly correlated with tussock base, elevated live and litter moisture contents. However, they were not as strongly correlated with soil moisture (r_s = 0.31-0.38, p = 0.226-0.331).

Soil moisture values sampled (by Landcare Research) from the two different soil depths were very strongly correlated with each other (r_s = 0.94, p < 0.001). However, apart from the tussock base (see above), they were not well correlated with other fuel elements. Of the FWI System components, soil moisture was best predicted by the FFMC[7] (R^2 = 0.70-0.73, p < 0.001) and DMC (R^2 = 0.63, p = 0.002) (Fig. 13), followed by the BUI (R^2 = 0.43-0.44, p = 0.019-0.020); however, it was not well predicted by the DC component (R^2 = 0.00-0.01, p = 0.738-0.890).

[7] While FFMC was most strongly correlated with soil moisture, this may be a statistical anomaly, as logically the FFMC would be better correlated with fine fuel elements such as litter and soil moisture with other FWI System components such as the DMC or DC.

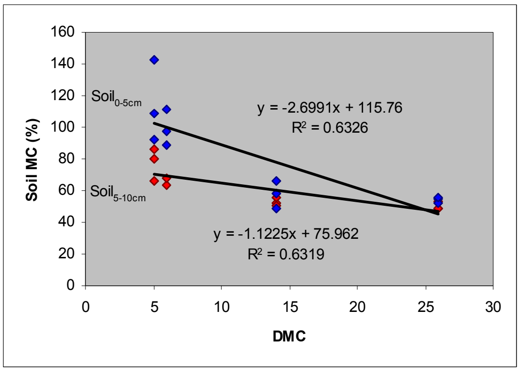


Figure 13. Relationships between the Duff Moisture Code (DMC) component of the FWI System and soil moisture contents for soil depths of 0-5 cm and 5-10 cm in tussock fuels.

Fuel consumption

Fuel consumption during the burn experiments ranged from 10-39 t/ha (Appendix 2). However, this varied considerably between sites due to the occurrence of a tussock mast flowering season during the summer burns at Mt Benger which dramatically increased fuel loads. Fuel consumption was relatively consistent for the Deep Stream burns (22-29 t/ha), but was significantly lower at Mt Benger during spring burns (10-18 t/ha) compared with summer burns (20-39 t/ha).

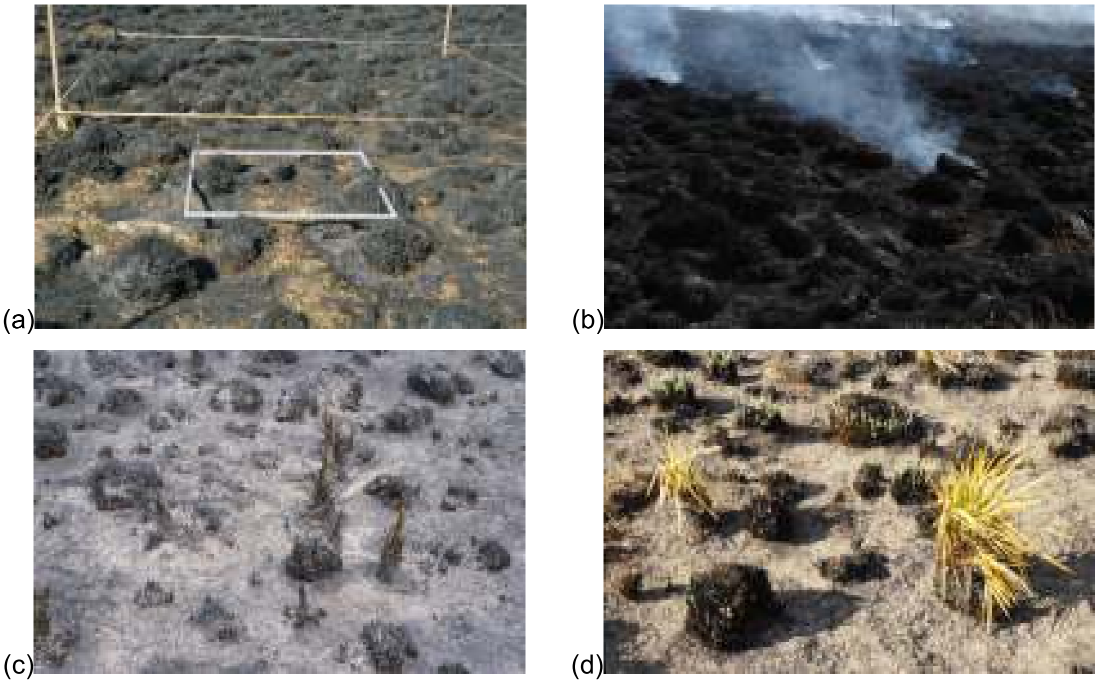
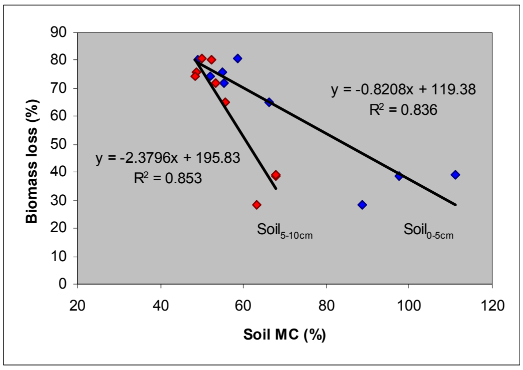


Figure 14. Post-burn biomass consumption following: **(a)** Mt Benger damp spring burn, **(b)** Mt Benger damp summer burn, **(c)** Deep Stream drier spring burn, and **(d)** Deep Stream drier summer burn.

Trends in fuel consumption were more apparent when considered on a percentage basis. At Mt Benger, the spring burns consumed an average of 36% (± 3%) of the above-ground biomass, whereas the consumption for the summer burns at this site, which were conducted under similar moisture levels to those at the time of the spring burns, was 63% (± 4%). Both sets of burns at Mt Benger consumed much of the standing plant material, but left almost all of the ground-cover layer intact (Fig. 14 a & b). At Deep Stream, where the fire weather indices and the moisture content data indicated that conditions during both the spring and summer burns were much drier, the biomass loss averaged 75% (± 5%) for the spring burns and 74% (± 1%) for the summer burns. Both sets of burns at Deep Stream removed not only the majority of the standing plant material, but also most of the ground-cover layer (Fig. 14 c & d). Payton and Pearce (2009) contains a more detailed description of biomass losses.

Identification of relationships between biomass loss and measurements of plant and soil moisture was complicated by the fact that the summer burns at Mt Benger occurred during a tussock mast flowering season, which substantially increased the above-ground tussock biomass relative to that present at the time of the spring burns (Payton and Pearce 2009). However, when these data were removed, there were highly significant relationships between biomass loss and soil moisture$_{(0\text{-}5\ \mathrm{cm})}$ and soil moisture$_{(5\text{-}10\ \mathrm{cm})}$ (R^2 = 0.84-0.85, p < 0.001 (Fig. 15a). While Payton and Pearce (2006) reported that the moisture content of the tussock bases (based on Landcare data) was also well correlated with biomass loss (r_s = -0.82, p = 0.007), the predictive relationship in this case (using Scion data) was not significant (r_s = -0.25, p = 0.517; R^2 = 0.06, p = 0.522). The FWI System's FFMC component (Fig. 15b) was the best predictor of tussock biomass loss (R^2 = 0.86, p < 0.001) followed by DMC (R^2 = 0.57, p = 0.019). DC and BUI were not statistically significant.

(a)



(b)

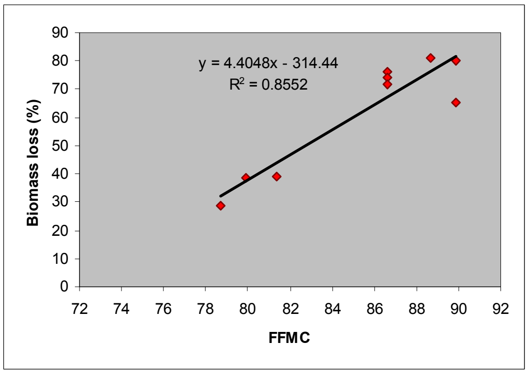


Figure 15. Relationships between tussock biomass loss (%) through burning and **(a)** soil moisture, and **(b)** Fine Fuel Moisture Code (FFMC).

Fire behaviour

Observed rates of fire spread for the burns varied from 350 m/h to 1830 m/h, depending on slope, wind speed and fuel dryness (Appendix 2). However, as the slopes of the burn plots varied from -7.0 to +6.5 degrees, this range decreased slightly to 400 to 1700 m/h when spread rates were corrected to remove the influence of slope steepness using the Canadian slope correction factor (Forestry Canada Fire Danger Group 1992). Wind speeds ranged from 8-27 km/h, but did not appear to significantly influence the spread rates of the burns here, unlike other tussock burn experiments which were more strongly correlated with wind speed (Fig. 16a). This was likely due to the generally damp conditions; however, none of the moisture contents or FWI System fuel moisture codes (e.g. FFMC (see Fig. 16b), which was the best correlated (r_s = 0.42, p = 0.032) of the FWI moisture codes and moisture contents themselves, including moisture content predicted from the FFMC) were sufficiently discriminating to identify whether there was a significant moisture effect on rate of fire spread.

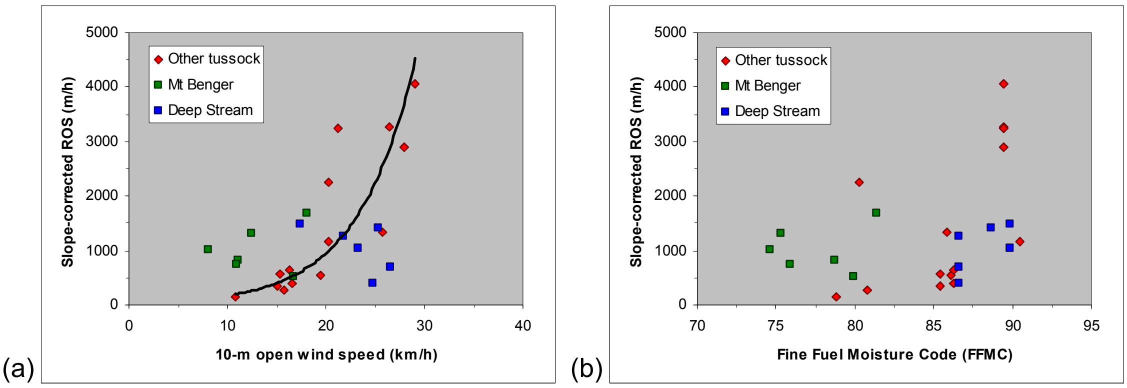


Figure 16. Relationships between fire rate of spread (ROS) and **(a)** wind speed, and **(b)** fuel moisture (as depicted by the Fine Fuel Moisture Code, FFMC) for the tussock fire ecology burns and other experimental tussock fires.

Fire spread rates for the burn data also did not fit well when compared against the Initial Spread Index (ISI) component of the FWI System (Fig. 17a), which integrates the effects of wind speed and fuel dryness. Spread rates for other tussock fires are relatively well predicted by the Natural/Standing Grass (O-1b) model from the Canadian Fire Behaviour Prediction System (assuming 100% grass curing) (Fig. 17b). This model is currently used in New Zealand for predicting fire behaviour in pasture grasslands, and is also recommended for estimating rates of fire spread in tussock (Pearce and Anderson 2008). At low ISI values (i.e. high moisture, lower wind speeds), the experimental fires at Mt Benger spread faster than other tussock burns and than the O-1b model predicted. At higher ISI values (lower moisture, higher wind speeds), the Deep Stream burns spread slower than other tussock fires and than would be predicted by the model. Again, it is likely that the poor fit of the fire ecology burn data is due to the experiments being conducted under comparatively damp conditions; however, collection of fire spread observations from smallscale experiments involving short fire runs (<100 m), where fires may not have reached their equilibrium spread rate for the conditions, is also likely to have been a factor.

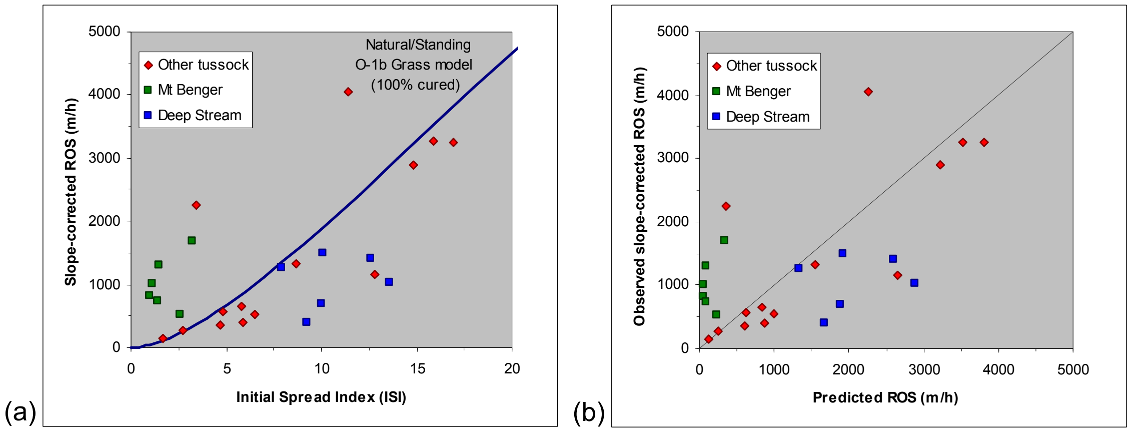


Figure 17. Slope-corrected rates of fire spread for the tussock fire ecology burns and other tussock fires **(a)** compared to the ISI component and Natural/Standing Grass (O-1b) model (assuming 100% curing), and **(b)** versus predicted rates of spread using this O-1b model.

Fireline intensity ranged considerably for the burns from 2600 kW/m to more than 23,000 kW/m (Appendix 2), and there was no consistent pattern with season of burning. Fire intensities for the burn experiments reflected the considerable variation in both fuel consumption (10-39 t/ha, Fig. 18a) and spread rates (350-1830 m/h, Fig. 18b) which, in the latter case, were very strongly correlated with calculated intensities ($r_s = 0.85$, $p < 0.001$). The highest fire intensities were observed during the Deep Stream spring and Mt Benger summer burns (which also had the highest spread rates; Fig. 18b), whereas the lowest intensities occurred during the Mt Benger spring burns (with least fuel consumption, Fig. 18a, and also slower spread rates, Fig. 18b).

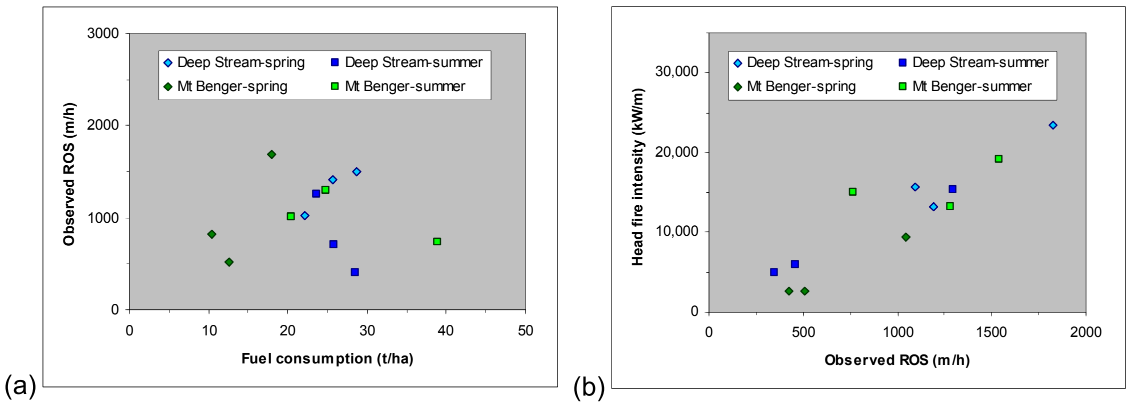
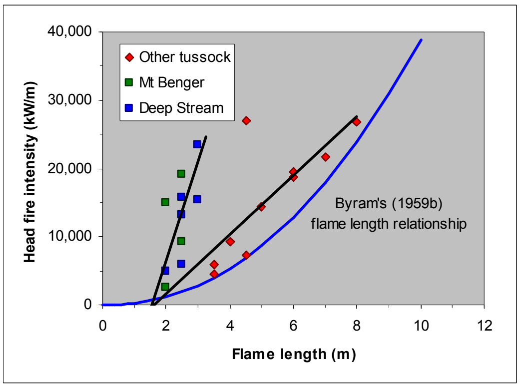


Figure 18. Relationships between **(a)** fuel consumption, and **(b)** fire rate of spread (ROS) as contributors to head fire intensity for the burn experiments.

In comparison, flame length, the main visible manifestation of fire intensity (Merrill and Alexander 1987), varied little between the burns. Estimates varied from just 2.0 to 3.0 m, although it should be noted that visual estimation of flame size is difficult and can be inaccurate (Johnson 1982). Despite this, empirical flame length-intensity relationships have been derived for a number of fuel types, although that developed by Byram (1959b) for forest fuels is widely considered to give realistic results over a range of frontal fire intensities (Albini 1976, Alexander 1982). The flame length-fire intensity relationship for tussock fires was therefore initially compared with Byram's (1959b) generic relationship (Fig. 19a). While flame lengths and fire intensity for other tussock fires appeared to more closely fit this model, those for the tussock fire ecology burn experiments did not.

The reason for the clear separation between the two sets of data (indicated by the trendlines in Fig. 19a) for otherwise similar vegetation is not readily apparent, but may be due to inaccuracies in the estimation of fire intensity, particularly with regard to estimation of fire spread rates from relatively short fire runs (Alexander 1982), and also in the determination of fuel consumption in the active combustion zone (versus secondary combustion and/or residual burning; Alexander 1982). Flame lengths for the tussock fire ecology burn experiments were found to be strongly correlated with calculated fire intensities (r_s = 0.70, p = 0.011), but were even more strongly correlated against observed rates of spread (r_s = 0.81, p = 0.001) but not fuel consumption (r_s = 0.07, p = 0.832).



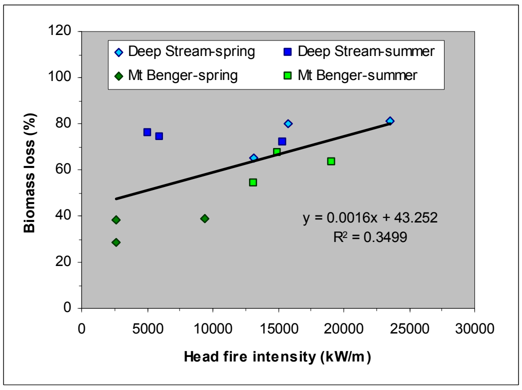


Figure 19. Relationships between fire intensity (kW/m) and **(a)** flame length, and **(b)** biomass loss (%) for the burn experiments and other fires in tussock.

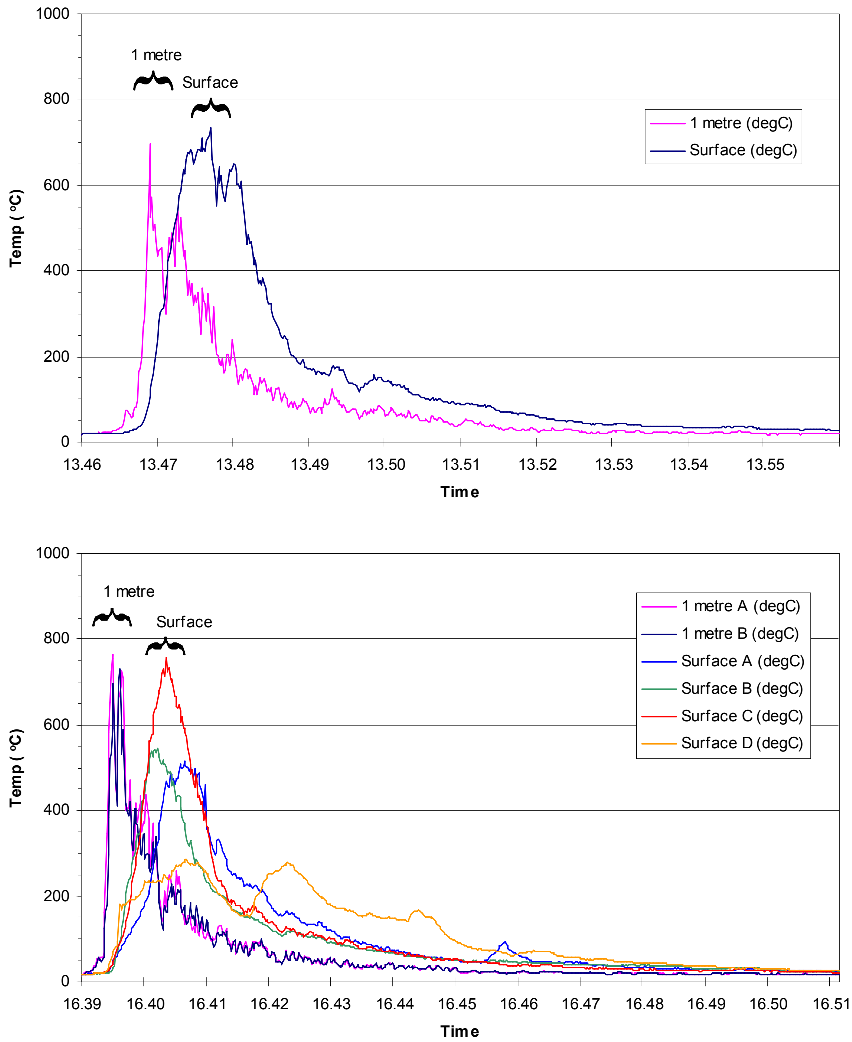
Fire intensity is also a key determinant of certain fire effects (Merrill and Alexander 1987), and has been suggested as a useful indicator of the ecological impacts of burning (e.g. Cheney 1981, Alexander 1982). Fire intensity was therefore compared against biomass loss in an attempt to determine the usefulness of fire intensity in predicting the effects of burning on tussock grasslands. Rather than use biomass loss estimates directly (i.e. fuel consumption in t/ha), percentage loss estimates (Fig. 19b) were favoured due to fuel consumption already being included in the determination of fire intensity. Results indicate that fire intensity did have some capability as a predictor of tussock biomass loss (R^2 = 0.35, p = 0.060), and warrants investigation against other quantified fire effects in tussock such as tiller or plant mortality, or nutrient losses.

In-fire temperatures

In addition to fuel dryness and resulting fuel consumption and head fire intensity, the severity of each of the experimental fires was also compared using observations of in-fire temperatures recorded using heatplates with temperature indicating paints and thermocouple measurements. In general, there was good agreement in the results obtained using the two methods, which showed that temperatures within the tussock fires reached over 1000°C). While the heatplates had the advantage of providing more information on the spatial variability in fire temperatures, they only indicate the maximum temperatures reached and do not indicate how long these peaks last, which is a major advantage of thermocouple measurements.

The maximum temperatures recorded by both methods showed that fire temperatures during early- and late-season fires at both sites were similar, and that the highest temperatures were more commonly observed at the ground surface (typically 500-1010°C) compared with 1 m above-ground (101-760°C) (Appendix 1). However, heatplates placed 2.5 cm and 5.0 cm below the soil surface indicated that this short, sharp burst of heat did not raise soil temperatures during any of the spring or summer burns, at least not above 69°C, the temperature at which the most heat-sensitive paint changed colour (and below which live vegetative tissue is damaged).

Thermocouple temperature traces recorded during the spring burns at Deep Stream showed that, as the fire front approached, temperatures rose steeply and peaked (at approximately 700°C) within 30-70 seconds (Fig. 20a). Temperatures at 1 m above-ground tended to rise first as the flame front approached, and more rapidly than temperatures at the ground surface, but also dropped off more quickly as the flame front moved away; the peak temperatures (e.g. >400°C) generally only existed for 15-30 seconds. Surface temperatures began to increase later than those above-ground, but remained higher longer (typically 45-75 seconds) and tailed off more slowly due to continued burning of surface fuels. The high temperatures were short-lived, however, and both the 1-m and ground-surface sensors recorded near-ambient temperatures 4-8 minutes later. The temperatures reached and duration of burning at the surface were very dependent on thermocouple location, due to the effects of tussock clumps on shielding of the flame front (Fig. 20b, surface traces A & B *cf*. C), but also fuel distribution and residual burning (surface trace D within the tussock clump itself).



(a) (b)

Figure 20. Thermocouple temperatures traces recorded at deep stream during **(a)** the burning of Plot 3, and **(b)** burning of Plot 4.

Other possible measures of fire severity

Fire temperatures in themselves are not a good measure of the severity of burning, as similar temperatures are reached in flames regardless of the fuel type and intensity. Burn severity is more related to the duration of heating, heat transfer and associated fire impacts (Keeley 2009). Other fire behaviour characteristics are therefore likely to provide more effective severity measures, such as fuel consumption or depth of burn, flame residence time, and fireline intensity and/or flame length (Alexander 1982, Keeley 2009). However, these relationships need to be derived for tussock fires before they can be utilised as predictive measures of fire severity and potential impacts.

Depth of burn refers to the degree of reduction of surface fuel or organic layer thickness due to consumption by fire, based on pre- and post-fire measurements (McRae *et al*. 1979, Alexander 1982). It has been successfully related to responses of vegetation following fire, including shrub recovery and seedling re-establishment (Van Wagner 1963, Miller 1977). The flame residence time, which refers to the duration of flaming combustion, has also been found to be important in determining fire effects, including fuel consumption and heat transfer (e.g. to soil and vegetation). It is defined as the length of time for the fire front to pass a given point (Alexander 1982), and can either be observed directly or calculated from the depth of the flame front and the fire's rate of spread. It may therefore be useful to include these measures in future experiments investigating the effects of burning on tussock and other vegetation types.

CONCLUSION AND RECOMMENDATIONS

Payton and Pearce (2009) have described the effects of burning in different seasons on tall-tussock grassland vegetation, and addressed the issues of whether fire causes long-term damage, and if accidental summer fires are more damaging than prescribed burns in late winter or early spring. They found that "*biomass, carbon and nutrient losses were lowest when the grasslands were burned under damp conditions, and increased as soil and plant moisture levels declined. Spring burns under damp conditions killed* [approximately] *35% of the tussock tillers but did not cause the death of tussocks, whereas burns under drier conditions or later in the growing season killed over 75% of tussock tillers and resulted in the death of tussocks. Seedling densities and inflorescence production were also least affected when the grasslands were burned under damp spring conditions; when conditions were drier, both were dramatically reduced and showed little sign of returning to pre-burn levels 4-5 years after the fire. Early season burns under damp conditions posed little threat to the long-term survival of tall-tussock ecosystems, whereas fires later in the season, or when conditions were drier, resulted in substantially greater biomass, carbon and nutrient losses and caused a loss of tussock dominance, at least in the short to medium term. Therefore, minimising their extent should be a priority wherever tussock cover is to be retained.*"

This report focussed on describing the fire behaviour associated with the burn experiments, but also sought to determine whether fire behaviour predicted using fuel load, moisture contents, and onsite weather and fire danger conditions could be used to estimate potential burn severity and subsequent fire effects. Results from the experiments, as well as other experimental fires in tussock vegetation, showed that in many cases tussock fire behaviour could be predicted based on onsite weather and fire danger information. The fuel moisture codes of the FWI System (in particular, the FFMC, but also in some instances, the DMC), were reasonable predictors of the actual moisture contents of litter, tussock bases and soil, and also of biomass loss/fuel consumption. Similarly, the ISI component (or wind speed) was able to be used to predict the rate of spread for tussock fires under some (generally drier) conditions. However, the dependence of fire spread in tussock fuels on fuel moisture has yet to be properly determined. In combination, these predictions of fuel consumption and rate of spread can be used to estimate fire intensity which, in turn, can be used to estimate potential fire effects such as biomass loss.

Fire temperatures (measured using both thermocouples and heat-sensitive paints) were not found to be a useful indicator of burn severity, and other fire behaviour characteristics such as depth of burn and flame residence time may provide more useful measures that should be investigated in future experiments. However, relationships between these and predictors such as fireline intensity or flame length, still need to be derived for a wider range of fire effects (such as tiller or plant mortality and nutrient losses, in addition to biomass loss) before they can be used as predictors of burn severity and fire impacts in tussock grasslands. This will require considerably more data, and further modelling of fire behaviour relationships and associated fire effects, and it is recommended that further fire behaviour and fire ecology experiments continue to be supported and conducted in tussock grasslands. Where possible, existing information on fire impacts should also be incorporated (e.g. biomass recovery rates in tussock following fire from the Waiouru Army Training Ground study; Clifford and Pearce 2009).

A secondary objective of the project was to continue the collection of data for use in modelling fire behaviour in tussock fuels, and the addition of 12 further data points to the dataset for tussock represents a significant accomplishment that will only be realised through more detailed analysis and comparison with existing information for this fuel type. However, it is possible that many of the disparities encountered in the data for these experiments compared with previous tussock burns may result from the estimation of fire behaviour associated with short fire runs (<100 m), where fires have not reached their equilibrium for the conditions. Wherever possible, future experiments should therefore look to collect observations from larger burn plots that enable longer fire runs. Differences in tussock vegetation (e.g. structure (height, density), tussock or understorey species) associated with the collection of data from burn experiments conducted in other parts of the country may also have been a factor.

During the study, differences were identified in fuel moisture values obtained from samples collected by Scion and Landcare Research, with different values being reported for the same (or similar) fuel components. This highlights the potential for problems to be encountered in future studies as a result of differences in the methodology used to process collected samples, and sampling of different vegetation fractions. Oven-drying of samples at a lower temperature (i.e. 70 °C by Landcare *cf*. 105 °C by Scion[8]) would be expected to result in higher moisture content values being reported by Payton and Pearce (2009) compared to those presented here, although this does not appear to have consistently been the case for comparable samples (e.g. litter, tussock bases or live tillers). Therefore differences are more likely to have been due to variability in sampling, particularly in what was sampled and

[8] The standard generally employed in plant chemistry and biomass studies is to dry vegetation samples in a forced-air drying oven at temperatures of 65-70 °C to a constant weight (typically 24-48 hours) (Allen 1974), whereas soil samples are usually dried at 100-105 °C to constant weight (for 8-24 hours) to determine moisture content (Blakemore *et al*. 1987). In fire research, fuel moisture contents are most commonly determined by oven-drying at temperatures of 100-105 °C to a constant weight (typically 16-24 hours) (Norum and Miller 1984, Viegas *et al*. 1992).

where samples were collected. Identification and collection of the various vegetation components is highly subjective. For example, litter could include dead tillers on the ground and/or elevated loose dead material within the tussock clump. Depending on the time and care taken, collection of live tillers may also include some dead or dying tillers. Similarly, tussock bases can be sampled to different depths within the clump, resulting in very different moisture contents being obtained. Within a burn plot, there will also be considerable spatial variability in moisture content resulting from the influence of vegetation cover, shading and micro-topography. It is therefore important that clearly defined protocols are established for identification and sampling of the various fuel components within tussock grasslands (and other fuel types), and that clear descriptions of the fuel fractions sampled are recorded. Replicate moisture content samples (at least 5) should be collected for each fuel component from a range of locations within the burn area and, where possible, samples collected by experienced personnel to aid consistency. It is also recommended that a standard oven-drying method be applied, based on drying of fuel moisture samples to constant weight at 105 °C.

There is also a need to further explore the prediction of fuel moisture contents in tussock, and relationships with the FFMC and other FWI System components. This includes establishing the relevance of the FFMC, DMC, and possibly DC or BUI, to litter and soil layers, as well as other fuel elements. The general applicability and validity of the FWI System to tussock fuels also requires validation. More data are required to determine the influence of fuel load on fuel consumption and fire intensity for tussock vegetation, and the effect of mast years on fuel loads, and resulting fire potential, in particular may also warrant further investigation. Further analysis, and likely additional data collection, is therefore required before definitive models for predicting fire behaviour (rate of fire spread, fuel consumption) in tussock grassland fuels can be developed.

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Appendix 1. New Zealand Fire Weather Index (FWI) System).

The Fire Weather Index (FWI) System (see Fig. A1) is the core component of the New Zealand Fire Danger Rating System. It provides the basis for a uniform method of rating fire danger throughout New Zealand (Anderson 2005). It consists of three fuel moisture codes and three fire behaviour indices that are derived from daily observations of weather conditions taken at 1200 hours NZST.

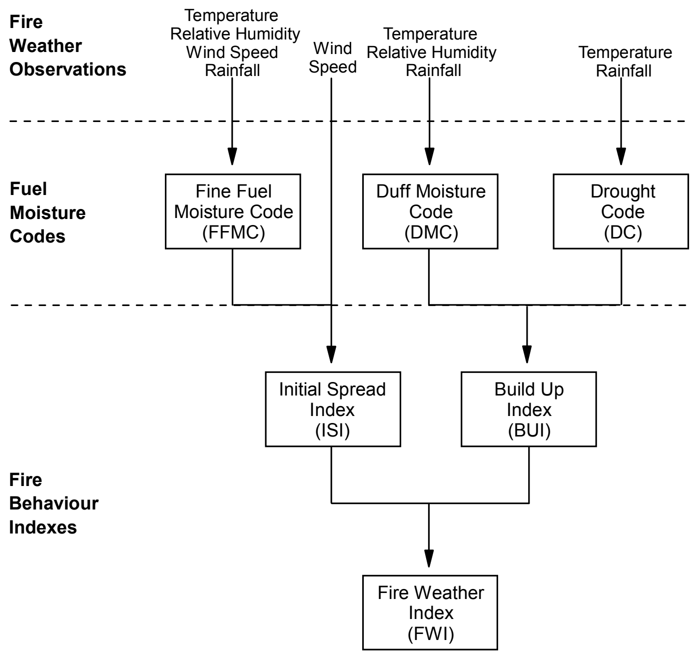

Figure A1. Structure of the Fire Weather Index (FWI) System (after Anon. 1993).

Fuel moisture codes

The following codes are ordered according to length of the response of fuel moistures represented by the code to changes in weather conditions (shorter to longer term).

Fine Fuel Moisture Code (FFMC) – Uses temperature, relative humidity, wind speed and daily rainfall to provide a rating of the moisture content of litter and other cured fine fuels. It is an indicator of flammability and hence the relative ease of ignition of fine dead fuels.

Duff Moisture Code (DMC) – Rates the moisture content of loosely compacted soil organic layers, based on temperature, relative humidity and daily rainfall. For tussock grasslands, it provides a measure of the dryness of ground-layer vegetation (mosses, forbs, etc.) and decaying plant material.

Drought Code (DC) – Uses temperature and daily rainfall to provide a rating of the moisture content of deep, compacted organic soil layers. It is a good indicator of general soil dryness and, for tussock grasslands, and would be expected to be a useful indicator of the dryness of the base of tussock clumps and hence overall tussock fuel consumption.

Fire behaviour indices

Initial Spread Index (ISI) – Provides a rating of the expected rate of fire spread, and is determined using Fine Fuel Moisture Code (FFMC) and wind speed data.

Buildup Index (BUI) – Combines the Duff Moisture Code (DMC) and Drought Code (DC) to provide a rating of the total amount of fuel available for combustion, and would be expected to correlate with the amount of fuel that is actually consumed by the fires.

Fire Weather Index (FWI) – Uses ISI and BUI to provide a rating of potential fire intensity, and would be expected to be a useful indicator of flame length. It also serves as a general index of fire danger.

Appendix 2. Summary of weather, fuel and fire behaviour conditions observed during experimental burns conducted in different seasons at the Deep Stream and Mt Benger research sites.

Tussock fire ecology project	**Deep Stream**						**Mt Benger**					
	spring burns (2/10/01)			summer burns (7/03/01)			spring burns (3/11/00)			summer burns (3/11/00)		
	Plot 3	Plot 8	Plot 4	Plot 2	Plot 5	Plot 9	Plot 9	Plot 1	Plot 6	Plot 8	Plot 3	Plot 5
Weather:												
Temperature (°C)	19.3	21.4	18.3	18.0	18.2	18.7	7.8	9.5	10.8	11.2	12.1	11.9
Relative humidity (%)	41	43	51	59	59	60	70	65	57	73	68	70
10-m wind speed (km/h)	17.4	23.2	25.3	24.8	26.6	21.8	11.1	16.7	18.1	8.1	12.4	11.0
Days since rain (>0.6 / 1.5 mm)	4 / 8	4 / 8	4 / 8	10 / 10	10 / 10	10 / 10	2 / 2	2 / 2	2 / 2	2 / 2	2 / 2	2 / 2
FWI System:												
Fine Fuel Moisture Code (FFMC)	89.9	89.9	88.7	86.6	86.6	86.6	78.7	79.9	81.4	74.6	75.3	75.9
Duff Moisture Code (DMC)	14	14	14	26	26	26	6	6	6	5	5	5
Drought Code (DC)	20	20	20	204	204	204	33	33	33	178	178	178
Initial Spread Index (ISI)	10.1	13.6	12.6	9.2	10.0	7.9	1.7	2.6	3.3	1.1	1.5	1.4
Buildup Index (BUI)	14	14	14	39	39	39	9	9	9	9	9	9
Fire Weather Index (FWI)	11.8	14.9	13.8	18.4	19.6	16.4	1.0	2.3	3.2	0.6	0.8	0.8
Fuel Characteristics:												
Tussock height (m)	0.46	0.52	0.67	0.56	0.52	0.58	0.48	0.49	0.48	0.51	0.39	0.58
Pre-burn biomass (t/ha)	35.8	33.9	31.8	37.6	35.0	33.0	36.3	32.5	46.0	37.6	39.0	57.8
Post-burn biomass (t/ha)	7.1	11.8	6.1	9.1	9.0	9.3	25.9	20.0	28.1	17.1	14.2	18.9
Fuel Moisture:												
Surface litter FMC (%)	8.8	9.3	8.6	11.7	11.7	9.9	8.3	7.6	10.4	80.4	24.9	42.6
Dead elevated FMC (%)	-	-	-	-	-	-	21.7	21.6	25.0	50.0	30.0	37.2
Live elevated FMC (%)	48.5	38.7	36.7	63.4	60.5	65.3	45.2	59.5	49.3	101.4	100.1	100.0
Tussock base FMC (%)	80.4	76.7	94.9	75.8	109.4	104.2	85.0	100.2	115.4	144.7	139.5	125.4
Soil (0-5 cm) MC (%)	48.9	66.3	58.6	55.1	52.1	55.4	88.7	97.4	111.1	91.9	108.4	142.3
Soil (5-10 cm) MC (%)	52.3	55.8	50.1	48.7	48.5	53.2	63.2	67.9	68.0	66.4	79.6	86.1
Fire Behaviour:												
Observed rate of spread (m/h)	1096	1189	1827	351	463	1296	509	422	1043	1283	1542	768
Slope (deg)	-4.5	4.0	6.5	-2.0	-6.0	1.0	-7.0	-3.0	-7.0	6.0	4.5	1.5
Slope-corrected ROS (m/h)	1.37	0.86	0.77	1.15	1.52	0.97	1.62	1.23	1.62	0.79	0.85	0.96
Fuel consumed (t/ha)	28.7	22.2	25.7	28.5	25.9	23.7	10.4	12.5	17.9	20.5	24.8	38.9
Biomass loss (%)	80	65	81	76	74	72	29	39	39	54	64	67
Head fire intensity (kW/m)	15,740	13,170	23,520	5,010	6,000	15,350	2,640	2,640	9,350	13,150	19,130	14,940
Flame lengths (m)	2.5	2.5	3.0	2.0	2.5	3.0	2.0	2.0	2.5	2.5	2.5	2.0
Flame Temperatures:												
1 m above-ground (ºC)	101-302+	101-760	101-760+	101-302	101-302	101-302	101-760	101-760	101-760	101-760	101-760	101-302
Ground surface (ºC)	500-1010	101-760	500-1010	302-500	302-500	302-500	500-1010+	500-1010	500-1010+	500-1010	500-1010+	302-1010
Soil 2.5 cm depth (ºC)	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69
Soil 5 cm depth (ºC)	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69	< 69