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Veronica R. Clifford & Stuart A.J. Anderson

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EXECUTIVE SUMMARY

The Canadian Forest Fire Weather Index (FWI) System was implemented in New Zealand in 1980 by the New Zealand Forest Service to provide a system to determine fire danger in plantation forests, predominantly made up of *Pinus radiata*. The FWI System is still in use today and is a core component of the New Zealand Fire Danger Rating System (NZFDRS). The FWI System is based on a reference fuel type, Canadian mature jack (*P. banksiana*) and lodgepole (*P.contorta*) pine stands on level terrain, not too dissimilar to mature pine plantations in New Zealand. The FWI System tracks the effects of weather (temperature, relative humidity, wind speed and rainfall) on fuel moisture content and fire behaviour potential.

The FWI System contains six numerical ratings – three fuel moisture codes and three fire behaviour indices. The moisture codes provide numerical ratings relating to the dryness of three fuel layers (fine surface litter, loosely compacted duff and deep compact organic matter). Each fire behaviour index provides a numerical rating related to potential fire behaviour (rate of fire spread, amount of fuel available to burn, fire intensity and difficulty of control). Because fuel moisture plays a central role in fire danger rating, its accurate determination is essential for fire management decision-making. To date, very little validation of the fuel moisture codes of the FWI System has taken place in New Zealand.

The aim of this study was to undertake an initial investigation of the applicability of the FWI System fuel moisture codes to New Zealand pine plantation fuels. Field sampling was carried out in two commercial pine plantations near Christchurch from three fuel layers that corresponded to the three moisture codes of the FWI System. Destructive sampling of fuel moisture content was measured using two approaches at both field sites. The first approach involved daily collection of fuel moisture samples under the forest canopy around 1600 hours (NZST), reflecting the peak burning period that the daily noon calculations of the FWI System represent. The second approach involved hourly sampling of fuel moisture content under the forest canopy from 0700 and 1900 hours (NZST) on selected days. The sampled moisture contents were then compared against the moisture contents predicted by the moisture codes of the FWI System.

Daily results showed that the standard noon FWI System fuel moisture codes did not adequately represent fuel moisture content around 1600 hours. The moisture content of elevated and surface (litter) needles was best predicted by using the Fine Fuel Moisture Code (FFMC) of the FWI System calculated for the hour of sampling (at 1600 hours), rather than the noon standard value. The moisture content of the decomposing organic layers (below the surface needles) was also poorly predicted using the standard noon Duff Moisture Code (DMC) and Drought Code (DC). The hourly sampling indicated that the hourly FFMC also predicted fine fuel moisture content poorly throughout the day.

The poor prediction of moisture content using the hourly FFMC could be due to different response times of the fine fuels compared to those calculated by the hourly FFMC. The FFMC equations are based on empirical data from Canadian conifer forests, which could be very different to the two Canterbury forests. It is possible that the fuels at these sites had different response rates to wetting and drying than those that the hourly FFMC equations determined. Poor prediction of moisture content of the duff layers by the DMC and DC is probably due to the significant differences between the duff layers at the two Canterbury sites and the Canadian reference fuel

type. The duff layers were very shallow (ranging from 1 – 4 cm deep) in comparison to the deep organic layers within Canadian forests (7 – 18 cm deep). A further explanation for the poor performance of the FWI System codes could be due to inaccurate quantification of rainfall interception by the forest canopy. Less rainfall could be passing through the canopy and collecting on and penetrating the fuel layers, than currently assumed for each of the fuel moisture codes (FFMC, DMC and D). This may explain the overprediction of moisture content by the FWI System.

From a fire management perspective, these results indicate that the standard FWI System codes and indices calculated at noon most likely do not reflect actual conditions around 1600 hours, as the system is designed to do. It would probably be more appropriate to use forecasted weather conditions to calculate the FFMC at1600 hours each day. These findings suggest that the fuel moisture codes of the FWI System in their current form may not be performing adequately for accurate fire danger assessment in New Zealand plantation forests. However, this study was only based on two forest sites in Canterbury, and further research is required to fully assess the applicability of the FWI System to New Zealand pine plantations.

It is therefore important to note that the results found in this study may not be applicable to the entire country. This is because the study was an initial attempt to validate the FWI System using just two pine plantation sites in Canterbury. Further validation is required before any changes are made to the FWI System. However, several recommendations are provided in this report to ensure that the FWI System can be applied reliably in plantation forests in New Zealand:

- The study should be extended to include a broader range of plantation forests across New Zealand.
- Determine the response times (drying and wetting rates) of fine fuels in pine plantations using experiments under controlled conditions in an environmental chamber and through extensive field data collection.
- Determine the amount of rainfall intercepted by forest canopies under different silvicultural regimes and different age classes.
- Studies could also be undertaken to compare weather conditions under the forest canopy to those observed in the open (as currently measured by weather stations on the fire weather network), to develop models to better predict weather conditions influencing fuels within the forest.

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INTRODUCTION

Although wildfires do not occur on the same scale in New Zealand as some other regions of the world, there is still a very real threat of wildfires throughout many parts of the country. This is because high to extreme fire danger conditions can be common; the rural/urban interface is constantly expanding; fire continues to be used in many parts of the country as a land management tool; and climate change will increase fire danger levels in some areas in the future. Accurate assessment of fire danger conditions is essential for effective fire management and to protect life and property from wildfires.

The term "fire danger" is used by rural fire managers to assess both the fixed and variable factors of the fire environment that affect the ease of ignition, rate of spread and difficulty of control of fires (Merrill and Alexander, 1987). Fixed fire environment factors are those that change very little over time but can vary from area to area (such as topography and fuel types). Variable fire environment factors are those that can change quickly over time, during the day and from day to day (such as weather conditions). A fire danger rating system evaluates these fire environment factors on a daily or hourly basis. Fuel moisture plays a central role in a fire danger rating system as it controls most aspects of fire behaviour (i.e. ease of ignition and availability of fuels for combustion). Dead fine fuels (less than 5 mm diameter) are particularly important for fire development and spread. Therefore, accurate calculation of fuel moisture is essential for fire management decision-making.

A fire danger rating system represents fire danger in the form of one or more codes and indices to assess the probability of a fire starting, spreading and doing damage. This then provides fire managers with information on potential burning conditions to make fire prevention, suppression and preparedness arrangements. The New Zealand Fire Danger Rating System (NZFDRS) is used to aid in the decision-making process for management and control of fire activities (Figure 1a) (Anderson, 2005). The NZFDRS is based on the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.*, 1989), and has been adapted for use in New Zealand. The Fire Weather Index (FWI) System is the core component of the NZFDRS.

In 1980, the New Zealand Forest Service adopted the FWI System component of the CFFDRS (Valentine, 1978). The NZ Forest Service priority for fire management was the protection of plantation forests, predominantly made up of *Pinus radiata.* The FWI system was chosen for use in New Zealand because of the considerable amount of research during its development (since 1925), it was developed in conifer forests with a similar maritime climate to New Zealand, and the system was simple to use and easy to understand. In 1978, the FWI System was evaluated against other fire danger rating systems from around the world and was found to be the most suitable for use in New Zealand. The only modification of the FWI System was to suit New Zealand's daylengths, seasons and latitude (Anon, 1993). Other than the implementation of the FWI System in 1980, no further validation or modification for New Zealand fuels have taken place.

The FWI System (Figure 1b) indicates the moisture content of three main layers of dead forest floor fuels and combines these with the influence of wind speed to estimate fire behaviour potential. The system uses Canadian mature jack (*P. banksiana*) and lodgepole (*P. contorta*) pine stands on level terrain as its reference fuel type. It comprises six numerical ratings: three fuel moisture codes (Fine Fuel Moisture Code, Duff Moisture Code and Drought Code) and three fire behaviour indices (Initial Spread Index, Buildup Index and Fire Weather Index). The moisture codes provide numerical ratings relating to the dryness of three fuel layers (fine surface litter, loosely compacted duff and deep compact organic matter). Each fire behaviour index provides numerical ratings related to likely fire behaviour (potential rate of fire spread, amount of fuel available to burn, fire intensity and difficulty of control).

These numerical ratings represent fire danger conditions during the peak fire danger period, generally around 1600 hours (LST). The FWI System uses standard, daily weather inputs of noon (LST) temperature, relative humidity, wind speed and 24 hour accumulated rainfall. For each of the codes, moisture is added after rain and deducted after each day's drying. All codes have built-in time lags and rainfall thresholds (below which precipitation will not lower the value). Higher values of the codes correspond to lower moisture contents and therefore drier fuels (Stocks *et al*., 1989). Because the FWI System utilises weather conditions, fire danger can be predicted using weather forecasts.

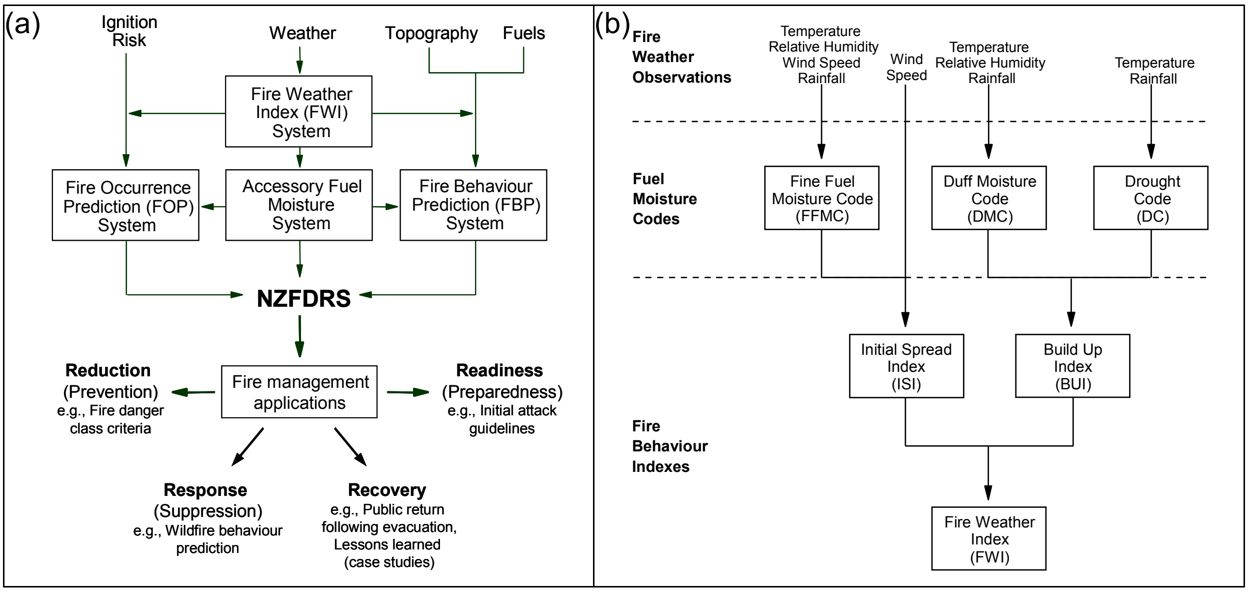


Figure 1. Structure diagrams for (a) the New Zealand Fire Danger Rating System (NZFDRS) illustrating the linkage to fire management actions (after Fogarty *et al*., 1998); and (b) the Fire Weather Index (FWI) System (after Anon, 1993) illustrating the linkages between weather conditions, fuel moisture and fire behaviour.

The Fine Fuel Moisture Code (FFMC) is a numerical rating of the moisture content of surface litter (0-50 mm deep) and other fine fuels, such as dead pine needles, small twigs (< 5 mm diameter) and cured grass on the forest floor. It provides an indication of the ease of ignition and flammability of fine fuels. This code is very sensitive to all four weather inputs, since changes in these weather conditions alter the amount of moisture in the atmosphere. Because fine fuels have small diameters and a larger surface area-to-volume ratio (compared to medium and heavy fuels), they respond rapidly to changes in moisture levels in the surrounding atmosphere. A time lag of two-thirds of a day (16 hours) is used for the FFMC and reflects the more rapid response time of the fine fuels to changes in moisture (Van Wagner, 1987). It has a rainfall threshold of 0.6 mm, meaning that rainfall amounts below this value will not affect the FFMC value due to interception by the forest canopy. Ignitions will generally be unsuccessful at FFMC values under 70 (De Groot, 1988 & Alexander, 1991). Ignition will readily occur at values over 86, and fine fuels are regarded to be extremely dry and highly susceptible to ignition at values above 92.

The Duff Moisture Code (DMC) is a numerical rating of the moisture content of loosely compacted organic layers of moderate depth below the surface litter (50-100 mm) and of medium-sized (50-300 mm diameter) dead woody material lying on the forest floor. This code indicates the ability for fires to ignite and burn into these duff layers and medium-sized fuels. These fuels take longer than surface fuels to dry out because the buried layers are not exposed to the atmosphere and medium-sized fuels have a greater surface area-to-volume ratio than fine fuels. The DMC has a rainfall threshold of 1.5 mm and a time lag of 15 days (Van Wagner, 1987 & Lawson and Armitage 2008). The rainfall threshold of the DMC is higher compared to the FFMC due to the additional interception of rain by the litter layer above. DMC values above 30 indicate dry conditions in this fuel layer, and values above 40 indicate that burning into duff layers is likely (De Groot, 1988).

The Drought Code (DC) is a numerical rating of the moisture content in deep compact organic layers (100 - 200 mm below the surface fuel layer). The DC indicates the effects of seasonal or long-term drying on this fuel layer and the likelihood of deep-seated burning in these organic layers and large woody material, such as logs or branches greater than 30 mm in diameter. A long period of warm dry weather is required to affect the DC, and it has a timelag of 53 days. The rainfall threshold is 2.9 mm (Van Wagner, 1987 and Armitage 2008) due to greater interception by the duff, litter layer and canopy above. A DC value over 200 is considered high, and at values above 300 it is likely that deep-seated burning will occur in the subsurface and heavy fuels (De Groot, 1988).

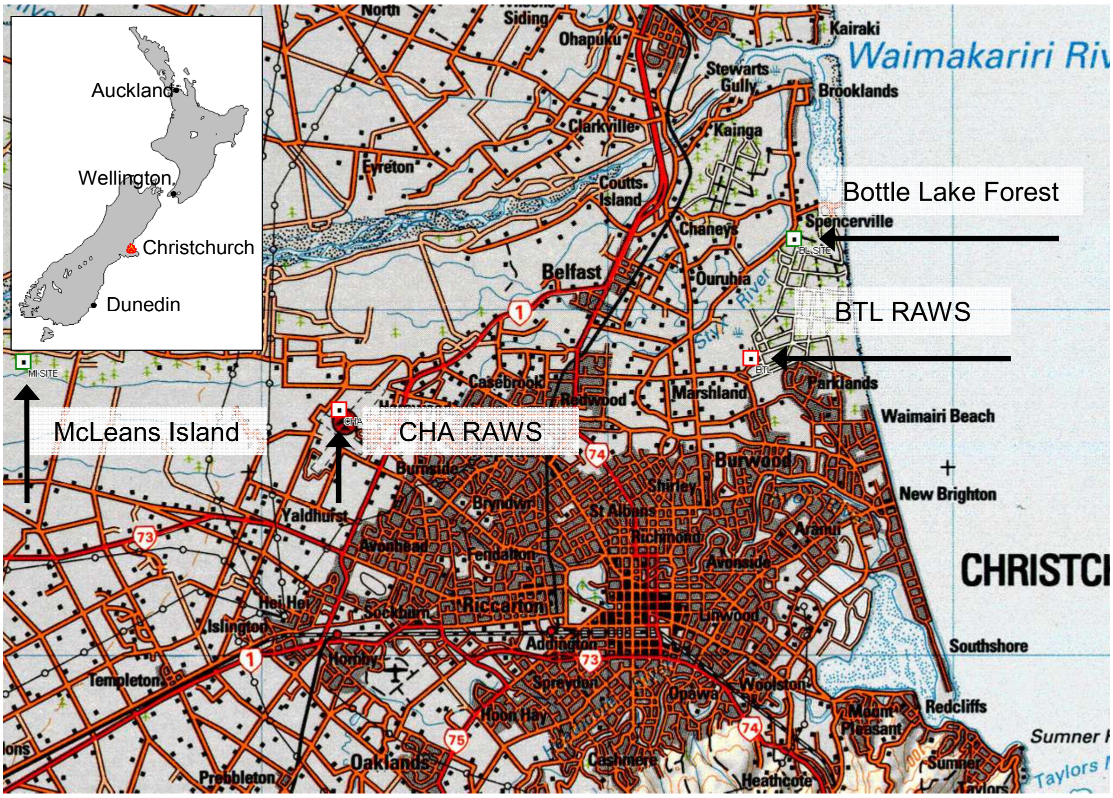
The three fuel moisture codes (FFMC, DMC and DC) are linked together with wind speed to form three fire behaviour indices that give an indication of fire behaviour potential. The Initial Spread Index (ISI) combines wind speed with the FFMC to give a numerical rating of the expected rate of fire spread shortly after ignition. The Buildup Index (BUI) combines the DMC and DC to indicate the total amount of fuel available for combustion. This index provides an indication of the difficulty of control and potential mop-up problems. The Fire Weather Index (FWI) combines ISI and the BUI to indicate the potential intensity of a fire and is used as a general indicator of fire danger. As a general rule of thumb, the lower the fuel moisture content, the higher the moisture codes and the higher the fire behaviour indices will be. A complete description of the derivation of the codes and indices of the FWI System is contained in Van Wagner (1987).

Although implemented in 1980, the FWI System has had limited validation in the New Zealand fire environment, including plantation forests despite a recommendation to do so (Valentine, 1978). The focus of fire research to date has been to develop models to predict fire behaviour (rate of spread and intensity) in various New Zealand fuel types. The objective of this study was to explore the applicability of the FWI System moisture codes to plantation forests in New Zealand. Findings from this study will indicate whether further validation and modification of the FWI System is required to accurately represent fuel moisture and fire potential conditions in these fuels.

MATERIALS AND METHODS

Study sites

Fuel moisture content and weather data were collected daily and hourly in the field from two study sites in Canterbury, Bottle Lake Forest and McLeans Island Forest (Map 1).



Map 1. Location of the two Canterbury sampling sites (Bottle Lake and McLeans Island Forests) and the nearest RAWS. Source: Map Toaster Topo/NZ (Scale: 1:250,000).

Bottle Lake Forest

The Bottle Lake site was situated approximately 10 km northeast of central Christchurch in the South Island of New Zealand (Map 1 & 2). Bottle Lake Forest Park is a recreational park and production forest managed by the Selwyn Plantation Board and Christchurch City Council, planted with mostly *P. radiata* managed on roughly 30-year rotations. The forest was established in the early 1900s and covers approximately 800 hectares of land. The topography of the area is generally flat but also comprises gently rolling coastal sand dunes. The soil type is loam sands derived from Greywacke rocks (Kear *et al.*, 1967 & NZ Soil Bureau, 1968). The sandy soil allows fast drainage, so the forest floor is generally dry over summer. Daily and hourly weather data (temperature, relative humidity, wind speed and direction, and rainfall) were retrieved from the nearest Remote Automatic Weather Station (RAWS), Bottle Lake located at the forest headquarters 3.6 km from the sampling site.

The sampling site was planted in 1978 (second rotation) and pruned in 1991 and thinned in 1997. There was an average of 475 stems per hectare, total volume of 630 m^3/ha, average diameter at breast height (DBH) of 31.4 cm, mean top height of 33.1 m and mean annual increment of 21 (Table 1).

McLeans Island Forest

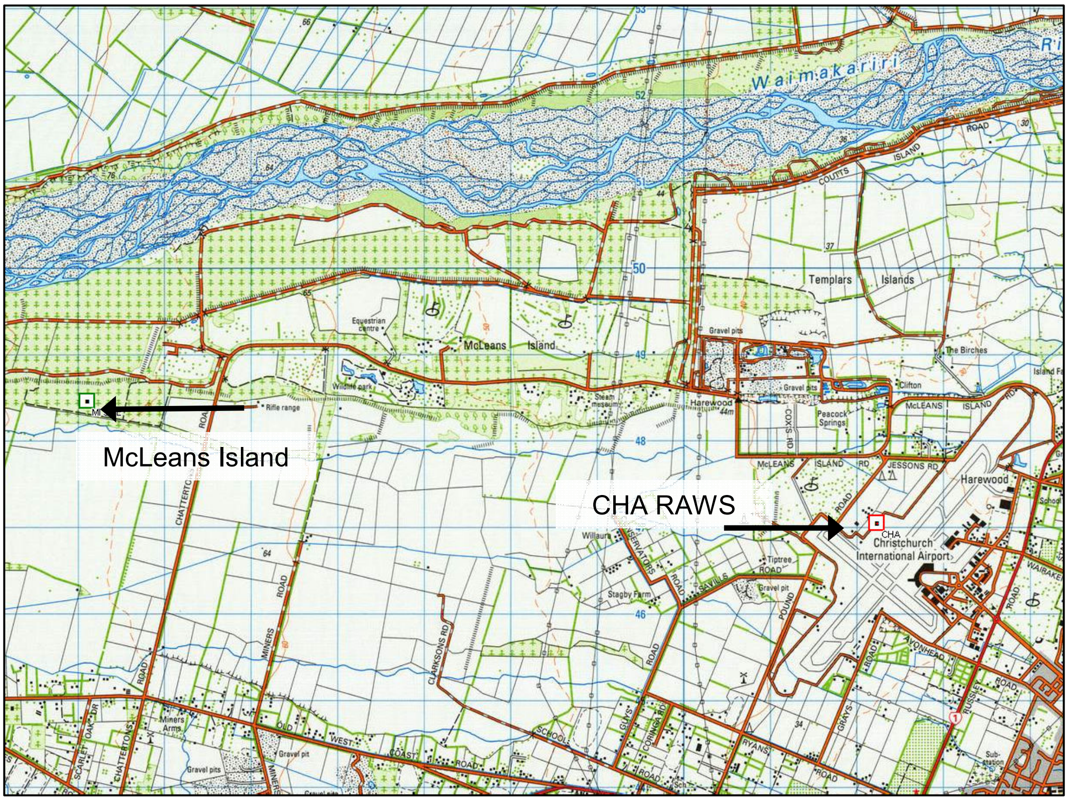
The McLeans Island site was located 10 km northwest of central Christchurch (Map 1 & 3) and on the southern side of the Waimakariri River. McLeans Forest is part of the Waimakariri River Regional Park, managed by Environment Canterbury. The forest is planted with *P. radiata*, also managed on roughly 30-year rotations. The soil type is shallow loamy sands with stony loam underneath that are derived from Greywacke rocks (Kear *et al*, 1967 & NZ Soil Bureau, 1968). The sandy soil at this site also allows for fast drainage. The location of the nearest RAWS is the Christchurch airport weather station (CHA), 9 km from the study site. The difference in soil characteristics between the two sites was that the Bottle Lake Forest site had a lower soil bulk density, meaning that it had greater porosity and less compaction than the McLeans Island site (Table 2).

The sampling site was planted in 1980 (second rotation) and pruned in 1986. There was an average of 456 stems per hectare, total recoverable volume of 320-340 tonnes/ha, average diameter at breast height of 30.0 cm and mean top height of 20.4m (Table 1).

Table 1. Summary of forest stand characteristics for the field sites at Bottle Lake and McLeans Island forests (stand information from Christchurch City Council and Environment Canterbury).

Forest Stand Characteristics	Bottle Lake	McLeans Island
Year planted	1978	1980
Age of trees (years)	31	29
Rotation	2	2
Inventory date (year)	2003	2000
Block area (ha)	6.15	5.05
Stocking (stems/ ha)	475	456
Diameter at Breast Height (cm)	31.4	30
Basal Area (m^2/ha)	49.95	33.39
Mean Top Height (m)	33.1	20.4
Mean Annual Increment	21	n/a
Total standing volume of timber (t/ha)	630	n/a
Recoverable volume (80% of standing volume) (m^3/ha)	n/a	340

Map 2. Locations of the Bottle Lake Forest sampling site (2485380E & 5751998N) and nearest RAWS (2484124E & 5747110N). Source: MapToaster Topo/NZ (Scale: 1:50,000).



Map 3. Locations of the McLeans Island Forest sampling site (2463112E & 5748455N) and nearest RAWS (2472232E & 5747054N). Source: Map Toaster Topo/NZ (Scale: 1:50,000).

Field sampling

Destructive sampling of fuel moisture was carried out using two approaches. The first approach involved daily collection of fuel moisture from six fuel layers (see below) under the forest canopy. The second approach involved hourly sampling of elevated and surface fuels.

Destructive samples of each fuel layer were gathered under the forest canopy within a 5 m radius of the sampling spot at least 10 m from the stand boundary to avoid edge effects. Each daily or hourly destructive sampling event was sampled from a different spot within the forest stand to the previous point to prevent sampling in the same area. Samples were collected and sealed in airtight containers and transported to the laboratory.

Fuel layers

Destructive samples were collected from various fuel layers (see Appendix 1 for photographs) within each forest site to represent moisture content as predicted by the relevant moisture codes of the FWI System:

FFMC:

1. Elevated fuel: dead needles suspended 2 – 3 m above the ground.
2. Surface fuel: the top 0-10 mm of dead needles of the litter layer.

DMC:

3. Loose duff: loosely compacted organic layers (0-30 mm deep), below the surface litter layer, and in the early stages of decomposition (needle and twig fragments visible).

DC:

4. Compact duff: deep, compact organic layer in advanced state of decay down to the mineral soil layer (30-60 mm deep), below the loose duff layer. Needle and twig fragments are still visible, but are tightly bounded by fungal mycelia.
5. Mineral soil (0-100 mm): no signs of needle or twig fragments visible at a depth of 0-100 mm beneath the litter and organic layers.
6. Mineral soil (100-200 mm): no signs of needle or twig fragments visible at a depth of 100-200 mm beneath the litter and organic layers.

Elevated fuels were collected from branches at a height of 2-3 m above the ground/forest floor. Surface litter was collected from the top 0-10 mm of the litter layer on the ground. Both the Bottle Lake and McLeans Island sites had sandy soil, and lacked the very deep organic layers would normally be considered to represent the DMC and DC components of the FWI System. The duff layer was divided into two types, due to clear differences in this layer: loose duff had signs of decomposition that easily broke apart when removed from the ground; and compact duff had signs of more advanced decomposition that was clumped together when removed from the ground. The two duff layers were variable in the layer thickness and not as deep as defined for Canadian fuels (Van Wagner, 1987). Loose duff was usually 0-30 mm deep and was collected from under the surface litter layer. Compact duff was usually 30-60 mm deep and collected under the loose duff layer. Mineral soil was sampled at two depths (0-100 and 100-200 mm) to determine whether the soil moisture content was aligned with the DC.

Forest floor characteristics (Table 2) were measured by collecting 5 samples from each layer using a 300 x 300 mm quadrat. The depths were measured for each layer (or height in the case for elevated fuel), and the entire fuel layer within the quadrat was collected, bagged and oven dried at 70ºC for 78 hours. The dry weight of each fuel sample was also recorded and the fuel load and bulk density calculated (Table 2). The leaf area index was measured at each site by taking 10 readings under the forest canopy using a plant canopy analyzer (LI-COR, LAI-2000).

Both sites had a very similar Leaf Area Index, and similar bulk densities and fuel loads for the surface, loose duff and soil (at 0-100 mm depth) layers (Table 2). Compact duff fuel loads at the Bottle Lake site were higher than at the Mcleans Island site. The McLeans Island site had a greater bulk density for the compact duff and both soil samples at two different depths. Fuel loads for the surface layer (representing the FFMC of the FWI System) at both Canterbury sites were similar to that detailed in Van Wagner (1987), where the FFMC fuel load was 0.25 kg/m^2 (dry weight). However, the fuel loads of the loose and compact duff layers were significantly lower than that described in Van Wagner (1987) (DMC 5 kg/m^2 and DC 25 kg/m^2). Both the surface and loose duff fuel layers had lower bulk densities compared to that reported in Lawson and Armitage (2008) (21 kg/m^3 and 71 kg/m^3 respectively). The bulk density of the compact duff layer at Bottle Lake forest was almost identical to that reported in Lawson and Armitage (2008) (139 kg/m^3), whereas the McLeans Island site was much greater.

Table 2. Summary of forest floor characteristics for the field sites at Bottle Lake and McLeans Island forest. Values shown are averages with associated standard error (n = 5).

Fuel moisture code	Fuel layer	Characteristics	Sampling site: Bottle Lake	McLeans Island	Canadian Standard [1, 2]
	Leaf Area Index		4.85 ± 0.32	4.79 ± 0.13	
	Elevated fuels	Height (m)	2 - 2.5	2 - 2.5	
FFMC	Surface fuels	Depth (cm)	2.5	1.5	1.2
		Fuel Load (kg/m^2)	0.35 ± 0.04	0.20 ± 0.03	0.25
		Bulk Density (kg/m^3)	16.26 ± 3.01	12.83 ± 1.37	20.83
DMC	Loose Duff	Depth (cm)	2	2	7
		Fuel Load (kg/m^2)	0.36 ± 0.07	0.55 ± 0.08	5
		Bulk Density (kg/m^3)	24.22 ± 5.11	26.75 ± 4.94	71.43
DC	Compact Duff	Depth (cm)	2.5	1.5	18
		Fuel Load (kg/m^2)	3.39 ± 0.31	2.41 ± 0.46	25
		Bulk Density (kg/m^3)	139.38 ± 22.92	158.00 ± 27.72	138.89
	Soil 0-100 mm	Depth (cm)	0-10	0-10	
		Bulk Density (kg/m^3)	1177.29 ± 74. 64	1268.07 ± 44.74	
	Soil 100-200 mm	Depth (cm)	10-20	10-20	
		Bulk Density (kg/m^3)	1279.80 ± 38.51	1439.60 ± 12.13	

Daily moisture content sampling

For both study sites, samples of moisture content were collected daily around 1600 hours (NZST) for a period of 21 consecutive days from each of the fuel layers as described above. Samples were collected at this time to reflect the peak burning

[1] Van Wagner, 1987
[2] Lawson and Armitage, 2008

period that the FWI System represents. Sampling occurred from 18 November to 6 December 2008 at the Bottle Lake Forest site and from 16 January to 5 February 2009 at the McLeans Island site. Sampling was re-assessed for the next day following major rain events, since the FWI System does not account for surface moisture on fuels. Sampling did not take place following rainfall events where surface moisture was present on fuels.

An aspirated psychrometer (Sato SK-RHG No.7450) was set up under the canopy 10 minutes prior to sampling to obtain temperature and relative humidity. The readings under the canopy were used to compare against the weather readings from the nearest RAWS. These readings were taken before and after each sampling event which usually took 15-20 minuets to complete. Five destructive samples of approximately 130 g (dry weight) were collected daily from each of the fuel six fuel layers. Each sample was weighed, oven-dried at 105ºC for 48 hours, and reweighed. Daily fuel moisture sampling forms and a summary table of moisture contents is contained in Appendix 2 & 3 respectively. Moisture content (*m*) was calculated as a percentage of the dry weight of the fuel:

$$m = \left(\frac{weight(wet) - weight(dry)}{weight(dry)} \right) \times 100$$

The actual moisture content (*m*), derived from sampling was then compared to the moisture content predicted by the noon FFMC, DMC and DC values from the FWI System derived from the nearest RAWS.

Hourly moisture content sampling

In addition to the once daily sampling, fuel moisture content was sampled twice at each site on an hourly basis from 0700 to 1900 (NZST). Sampling at the McLeans Island site occurred on 23 January and 3 February 2009. Sampling at the Bottle Lake site occurred on 10 February and 19 March 2009. The hourly sampling at Bottle Lake Forest on 19 March started later than the usual 0700 (NZST) start time (at 0900 hours) due to uncertainty with the weather forecasts. Sampling finished early at 1700 (NZST) on the 10 February due to little change in weather over the sampling time frame that resulted in little change in the moisture content over the course of the day..

The days on which hourly sampling occurred were selected at least 1 week following a significant rainfall event (greater than 0.6 mm rain). This was to ensure that the hourly samples would be collected under conditions where fuels were only responding to changes in the surrounding atmospheric conditions, i.e. they were not in a drying or wetting phase from precipitation. Hourly fuel moisture sampling forms are contained in Appendix 2. Five moisture samples were collected from the elevated and surface layers each hour as these fuels are responding quickly to atmospheric changes. Duff and soil layers were sampled at 0700 and 1600 hours, because these layers respond slowly to atmospheric changes and take longer than fine surface fuels to dry out (due to large diameters and/or not exposed to the atmosphere). Samples were processed as previously described for the daily sampling.

A portable automatic weather station (Vaisala, MAWS 201) was set up under the canopy before sampling to record 10-minute and hourly temperature (ºC), relative humidity (%), solar radiation (W/m^{-2}) at a height of 1 m above the ground, wind speed (km/h) and direction (º) at a height of 2m above the ground. Weather data from the nearest RAWS and under the canopy were used to calculate daily and hourly values of the FWI System codes and indices for the duration of the sampling. A summary of the hourly fire weather conditions from the nearby RAWS, weather under the canopy and moisture content sampled is contained in Appendix 4. Actual moisture content (*m*) sampled on the hour was compared to the moisture content predicted by the three codes of the FWI System derived from weather inputs from the nearest RAWS and under the canopy.

Data comparison and analysis

Daily and hourly sampled moisture contents were compared to the predicted values calculated from the FWI System moisture codes.

The moisture content predicted by the Fine Fuel Moisture Code (FFMC) was compared against actual moisture content sampled from dead elevated and surface needles in the field. This comparison provides an indication of the suitability of the FFMC for determining the moisture content of elevated and surface fuels in New Zealand pine forests. Each daily and hourly FFMC value was converted to predicted moisture content, using the standard FWI System conversion (Van Wagner, 1987):

$$m_{FF} = 147.2 \times \left(\frac{101 - F}{59.5 + F} \right),$$

Where m_{FF} is the moisture content predicted by the FF-scale, and F is the FFMC value. The FF-scale (m_{FF}) of the FFMC is a revised version of the original Tracer Index that allows for realistic conversion from the FFMC code to moisture content (Van Wagner, 1987).

Hourly and daily FFMC values were also converted to a predicted moisture content using the FX-scale (m_{FX}) of the FFMC (Lawson *et al*, 1996). This is an amended version of the FFMC recommended for use in countries with hot and dry climates. This scale provides a greater degree of drying at the lower end of the FFMC range:

$$m_{FX} = 32.9 \times \left(\frac{101 - F}{13.3 + F} \right),$$

Moisture contents predicted by the Duff Moisture Code (DMC) and Drought Code (DC) were compared to actual moisture content sampled from the duff layers. This comparison provides an indication of the suitability of the DMC and DC for determining the moisture content of the duff layers. Each daily and hourly DMC value was converted to a predicted moisture content using the standard FWI System conversion (Van Wagner, 1987).

$$m = 20 + e^{\left(5.6 - \frac{DMC}{43.4}\right)},$$

Where *m* is the moisture content predicted, and *DMC* is the Duff Moisture Code value from the FWI System.

The DC value was converted using a corrected version of the standard DC equation (Lawson & Armitage, 2008):

$$m = 400 \times e^{\left(\frac{-DC}{400}\right)},$$

Where *DC* is the Drought Code value from the FWI System.

Data analysis

Statistical analyses of daily and hourly moisture content data were carried out using Minitab 15 for Windows (Appendix 3.9 & 4.7). Both daily and hourly data sets were tested for normality using histograms, boxplots and the Anderson-Darling test. These revealed that hourly data appeared normally distributed, but most of the daily data were not. For straight comparisons of actual versus predicted moisture values, transforming the data was not necessary (only if developing a regression model). One-way ANOVA were used to indicate if actual moisture content from a fuel layer differed from that predicted, using a significance level (α) of 0.05. The 95% Confidence Intervals (CIs) in a Tukey test provided a crude means of confirming a difference between two groups (actual and predicted moisture content). The difference between two group sample means was considered to be significant if its confidence interval did not contain zero; that is, if its endpoints both had the same sign.

The goodness-of-fit was reported for the comparison of actual versus predicted moisture content by the values of the coefficient of determination (R^2), mean error (ME) and root mean square error (RMSE). The R^2-value was based on the regression of observed on predicted values, and provided a measure of model precision (the proportion of the variation in the observed values explained by the predicted (model) values). The ME was simply the average of the differences between observed and predicted values, and provided an indication of bias in the model. The RMSE combined the measures of precision (R^2) and bias (ME), and provides the most reliable indicator of the most appropriate model. Each actual versus predicted moisture content plot includes a solid line that represents the line of perfect agreement between observed and predicted, and a thin coloured line that represents the regression of observed versus predicted values.

DAILY RESULTS

Fire weather conditions

A summary of the fire weather conditions leading up to sampling from the nearest RAWS at each site is contained in Table 3. Refer to Appendix 3 (Figures 23 -26) for fire weather conditions leading up to and during daily and hourly sampling. During the period from September 2008 to March 2009, the McLeans Island site was generally wetter and windier than the Bottle Lake site. The Bottle Lake site was slightly warmer and less humid until December. Bottle Lake Forest had higher FWI System codes and indices (FFMC, DMC, DC and BUI) but the McLeans Island site had higher ISI and FWI values due to its greater exposure to wind.

Refer to Appendix 4 (Tables 11 & 12) for a summary of the daily weather conditions one and four weeks prior to **daily** sampling. Significant rain (greater than 0.6 mm) fell at the Bottle Lake site 11 and 23 days before sampling (2.4 mm and 16.2 mm respectively). The McLeans Island site had significant rainfall 12 and 27 days before sampling (12.2 mm and 15.4 mm respectively).

A summary of daily conditions one day and one week prior to **hourly** sampling is contained in Appendix 5 (Tables 19 – 22). Significant rain (greater than 0.6 mm) rain fell 5 days (2.2 mm) and 7 days (2.6 mm) before sampling at Bottle Lake on 10 February and 19 March 2009 respectively. Significant rain fell 4 days (9.8 mm) and 7 days (0.6 mm) before sampling at McLeans Island on 23 January 2009 and 3 February 2009.

Table 3. Average noon daily fire weather conditions from 1 September 2008 to 31 March 2009 for the two sample sites collected from the nearest RAWS. Source: NRFA.

Weather conditions	September	October	November	December	January	February	March
Bottle Lake Forest							
Temperature (ºC)	14.4	17.5	19.5	19.2	23.5	19.3	19.4
Relative humidity (%)	63.4	49.2	50.0	62.1	47.7	63.0	57.9
Wind speed (km/h)	8.2	7.2	8.2	9.6	7.9	8.8	8.1
Total rainfall (mm)	26.2	23.8	5.2	36.4	7.6	44.4	26.8
FFMC	76.3	83.9	87.2	76.6	88.2	76.7	81.8
DMC	10.9	35.2	64.3	59.8	68.2	59.4	22.0
DC	25.5	108.1	232.8	390.1	545.3	648.9	575.8
ISI	2.5	4.1	5.1	3.2	5.8	2.9	3.1
BUI	11.0	38.5	75.9	80.7	103.1	91.9	39.8
FWI	2.8	9.3	16.5	11.2	20.6	11.2	7.6
McLeans Island							
Temperature (ºC)	13.5	16.0	18.2	18.7	22.5	18.2	18.5
Relative humidity (%)	64.9	52.7	51.6	60.0	45.8	63.6	56.7
Wind speed (km/h)	17.7	17.8	20.5	23.5	18.8	18.8	20.3
Total rainfall (mm)	34.2	30.6	10.4	44.8	25.6	53.2	28.6
FFMC	75.9	82.4	85.2	77.4	86.7	75.5	83.6
DMC	8.5	29.7	38.1	44.7	44.8	38.1	22.7
DC	22.2	89.2	182.8	326.4	434.4	525.4	479.1
ISI	4.2	6.7	9.4	8.9	11.2	5.0	6.7
BUI	8.7	31.9	49.7	61.6	70.9	61.2	40.3
FWI	4.4	12.1	20.0	19.6	26.4	14.2	13.8

Daily fire weather conditions

The average daily fire weather conditions during sampling at Bottle Lake and McLeans Island forests are shown in Table 4 below, with the raw data located in Appendix 4 (Tables 13 – 16). There was a significant difference in rainfall between the two sites. The Bottle Lake forest (from 18 November to 6 December 2008) had an average temperature of 20ºC, relative humidity of 53%, and total rainfall of 3.2 mm (Table 4 & Figure 2). The McLeans Island forest (from 16 January to 5 February 2009) had an average temperature of 22ºC, relative humidity of 51% and total rainfall of 12.8 mm (Table 4 & Figure 3). The McLeans Island site also had the greatest variability in the FWI System codes and indices due to extremes of conditions (dry and wet) during sampling and a significant rainfall event of 9.8 mm (on 19 January).

Table 4. Summary of daily fire weather during the daily sampling periods from the nearest RAWS (Source: NRFA).

	Average	**Median**	**Min**	**Max**
Bottle Lake Forest, 18 November to 6 December 2008 (n = 19)				
Temperature (ºC)	20.2	19.6	16.2	26.9
Relative humidity (%)	53.2	55.0	30.0	83.0
Wind speed (km/h)	9.7	9.0	4.5	15.2
Wind direction (º)	123	90	11	355
Rainfall (mm)	0.2	0	0	2.0
FFMC	87.4	87.8	71.5	91.7
DMC	85.8	87.4	69.2	96.7
DC	303.0	301.4	247.6	362.8
ISI	5.6	5.2	1.0	11.4
BUI	100.4	102.4	81.5	116.1
FWI	20.4	19.9	5.1	36.2
McLeans Island, 16 January to 5 February 2009 (n = 21)				
Temperature (ºC)	21.8	21.0	13	30
Relative humidity (%)	50.5	48.0	25.0	77.0
Wind speed (km/h)	17.4	17.0	6.0	32.0
Wind direction (º)	110	90	40	230
Rainfall (mm)	0.6	0	0	9.8
FFMC	85.9	88.7	62.1	93.4
DMC	55.8	58.4	33.4	73.6
DC	488.7	485.8	429.1	554.8
ISI	8.3	8.2	1.0	19.0
BUI	86.5	88.5	55.9	109.9
FWI	24.4	25.9	3.1	45.5

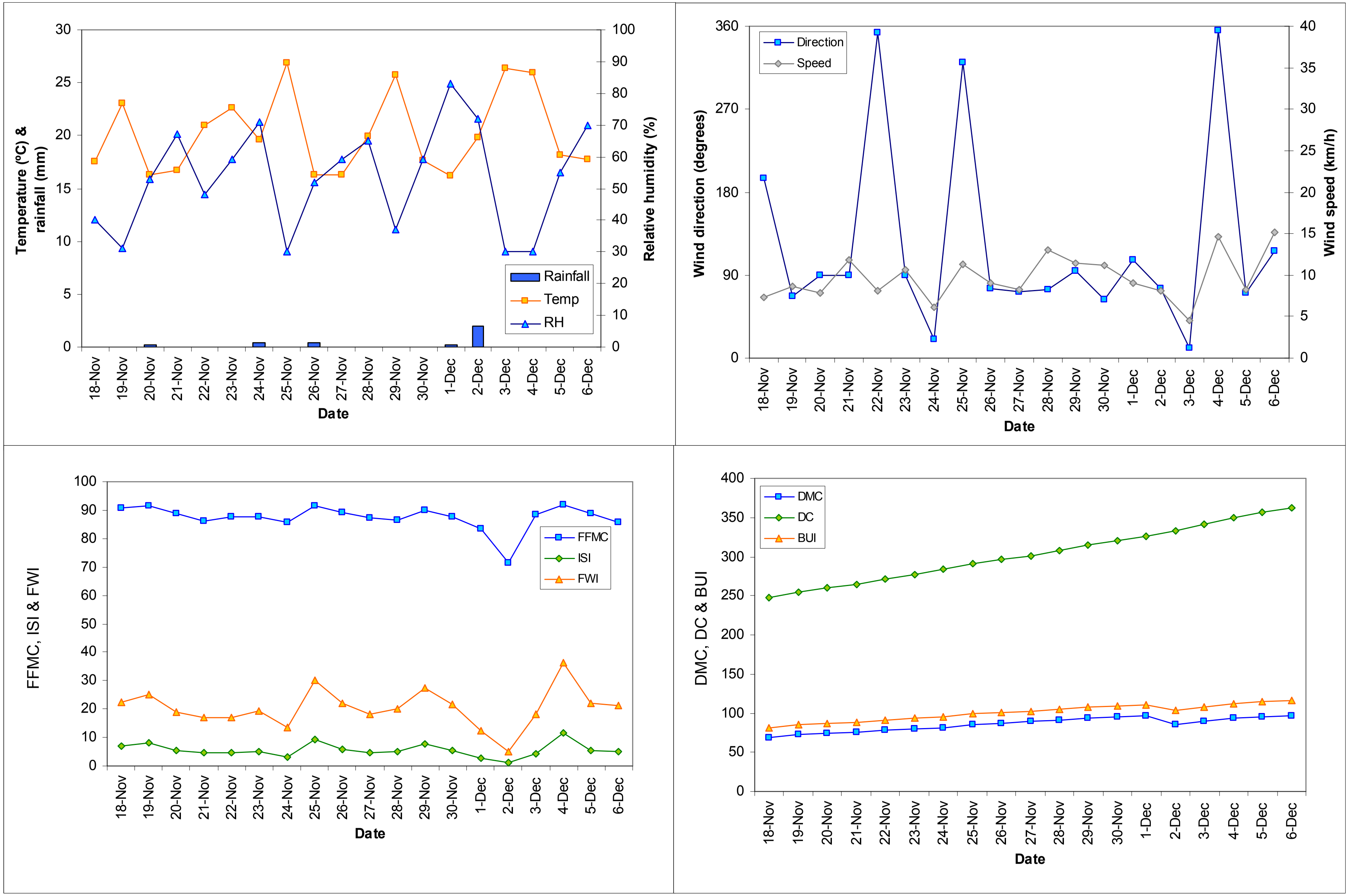


Figure 2. Daily weather readings during daily sampling from the Bottle Lake RAWS (Source: NRFA).

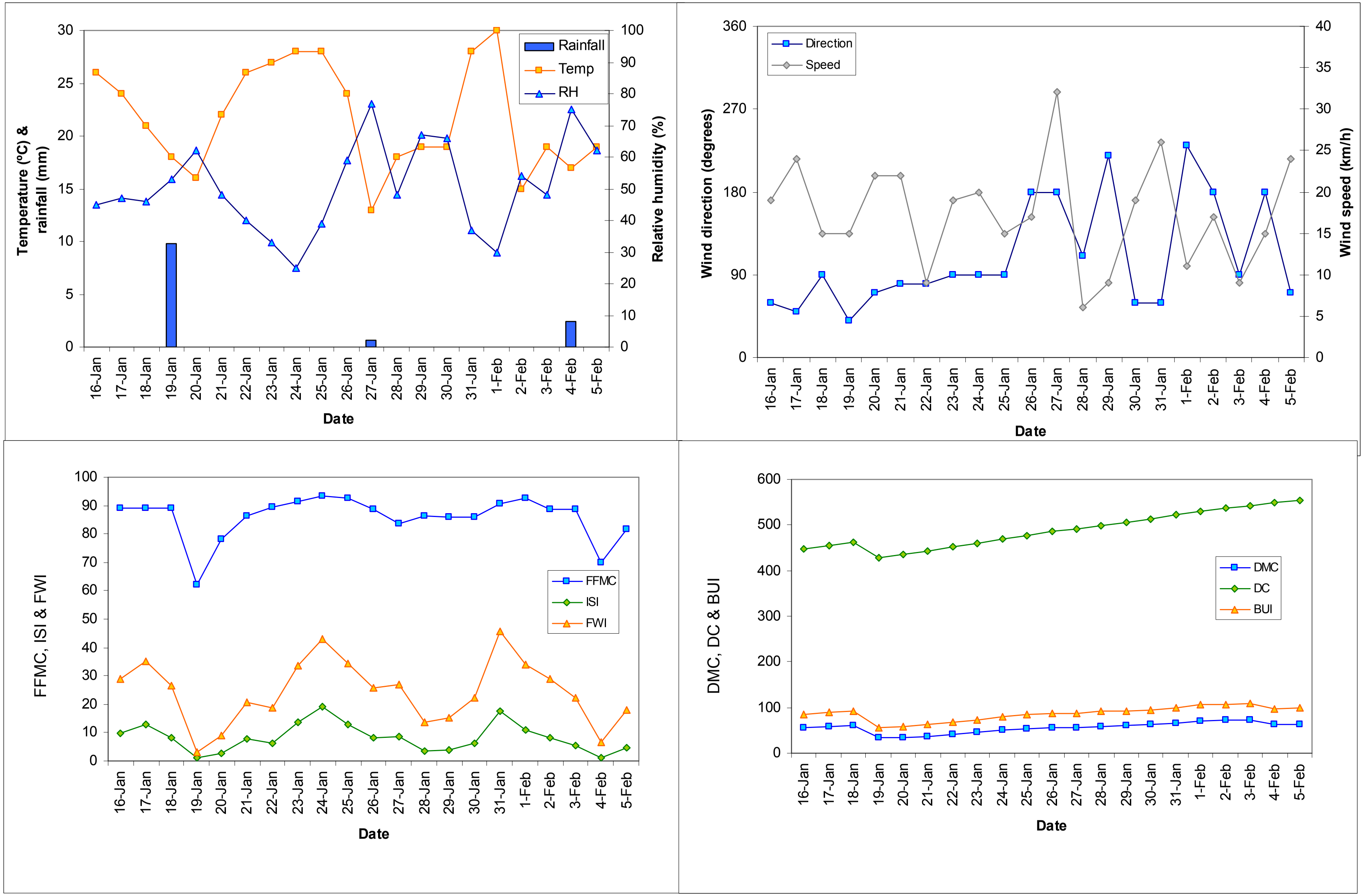


Figure 3. Daily weather readings during daily sampling from the Christchurch Aero RAWS (Source: NRFA).

Daily fuel moisture contents

A summary of daily fuel moisture contents, temperature and relative humidity recorded under the canopy is located in Table 5 and Figures 4 & 5 below. Summary tables of the raw data and time-series are located in Appendix 4 (Tables 15 & 16, Figures 27 & 28).

For both sites, temperature under the canopy was cooler and more humid compared to the RAWS readings in the open. When comparing weather under the canopy at both sites, temperature on average was slightly higher and humidity lower at the McLeans Island site. Elevated and loose duff moisture content was higher at McLeans Island. Moisture contents for surface litter, compact duff and both soil layers were similar for both sites. The fuel layers under the canopy (except the two soil depths) clearly responded to rainfall events by an increase in moisture content (Figure 4 & 5).

Table 5. Summary of under-canopy weather (from psychrometer measurements) and fuel moisture contents (MC) from the two sampling sites.

During sampling	Average	Median	Min	Max
Bottle Lake Forest, 18 November to 6 December 2008				
Temperature (ºC)	17.8	16.3	12.5	24.4
Relative humidity (%)	61.3	60.9	33.8	82.5
Elevated MC (%)	16.9	17.7	10.8	23.5
Surface MC (%)	19.1	16.3	12.7	58.7
Loose MC (%)	30.4	24.8	19.2	99.0
Compact MC (%)	25.8	21.5	11.6	61.6
Soil (0-10cm) MC (%)	4.2	3.8	2.1	6.4
Soil (10-20cm) MC (%)	2.5	2.4	1.5	4.0
McLeans Island, 16 January to 5 February 2009				
Temperature (ºC)	20.8	21.2	12.9	27.4
Relative humidity (%)	53.8	54.2	30.9	77.0
Elevated MC (%)	14.4	13.8	8.3	20.3
Surface MC (%)	18.8	14.6	11.3	54.1
Loose MC (%)	38.5	19.2	13.7	128.2
Compact MC (%)	26.2	19.2	7.9	63.8
Soil (0-10cm) MC (%)	4.2	3.3	1.9	8.5
Soil (10-20cm) MC (%)	3.6	2.8	1.9	8.1

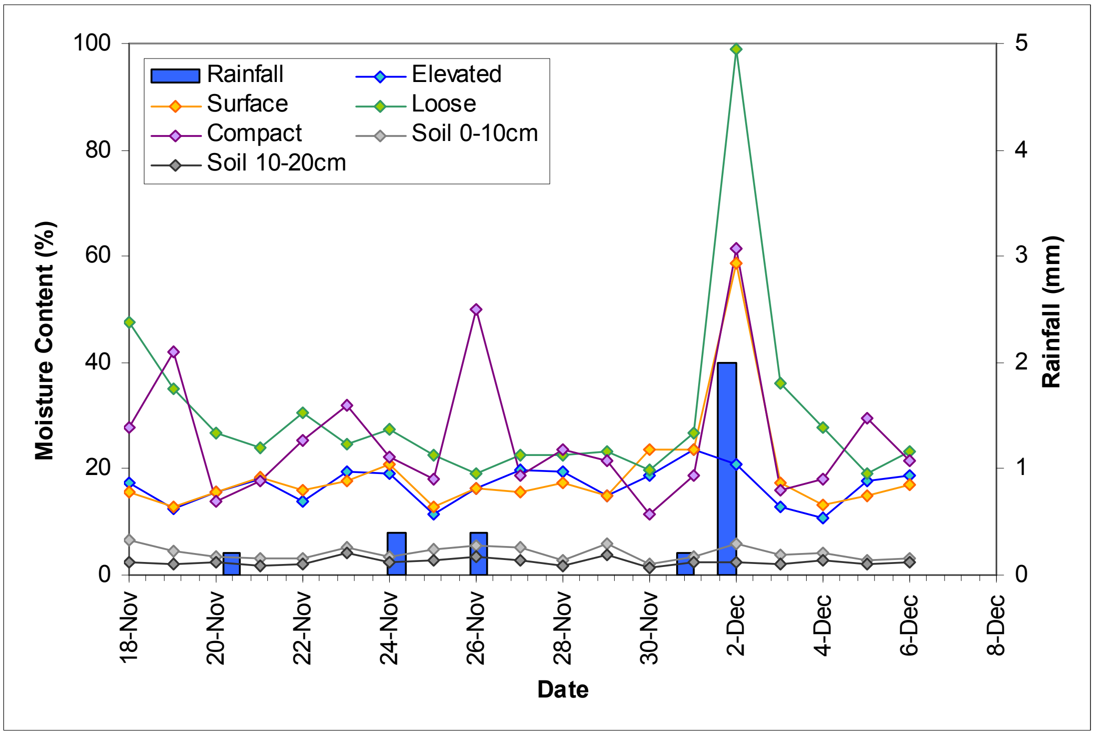


Figure 4. Actual moisture content sampled from the six fuel layers at Bottle Lake Forest from 18 November 2008 to 6 December 2008.

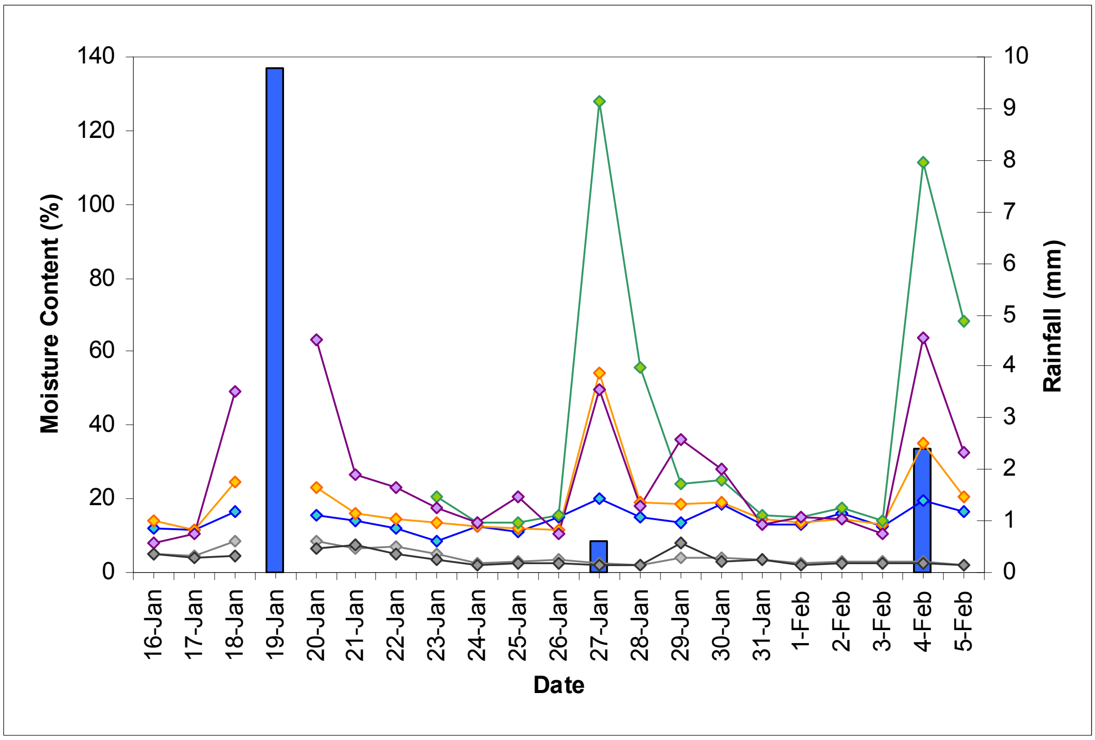


Figure 5. Actual moisture content sampled from the six fuel layers at McLeans Island Forest from 16 January 2009 to 5 February 2009 (Note: legend is the same as Figure 6).

Actual versus predicted daily moisture contents

Comparisons using FFMC at the time of sampling (1600 NZST)

Plots of observed versus predicted moisture content by the FFMC (FF- and FX-scales) using weather observations obtained from the closest RAWS at the time of sampling (1600 hours NZST) are shown (Figures 6 & 7 and Table 6) using a combined dataset from both the Bottle Lake and McLeans Island Forest sites. Please refer to Appendix 4.6 (Figures 33- 36) for plots of individual sites and statistical comparisons.

<u>Elevated layer</u>

The plots of actual versus predicted elevated dead fuel moisture content, calculated from the FF- and FX-scales of the FFMC, are shown in Figures 6 a & b. The FFMC FF-scale predicted elevated moisture content reasonably well under dry conditions (Figure 6a & Table 6). However, rainfall events resulted in the FFMC over-predicting moisture content (highlighted outliers). Elevated moisture content predictions using the FX-scale of the FFMC were poor, tending to severely under-predict moisture content. These results are highlighted in the time-series graphs shown in Appendix 4.5 (Figures 29 & 31). Elevated fuel moisture content was predicted marginally better at the Bottle Lake Forest site compared to that at McLeans Island (Table 6).

A one-way ANOVA showed that there was a significant difference between actual and predicted moisture content ($p < 0.0001$). The Tukey test revealed that predicted moisture content using the FFMC FF-scale was not significantly different to actual moisture content, but predictions using the FX-scale were (Appendix 4.9).

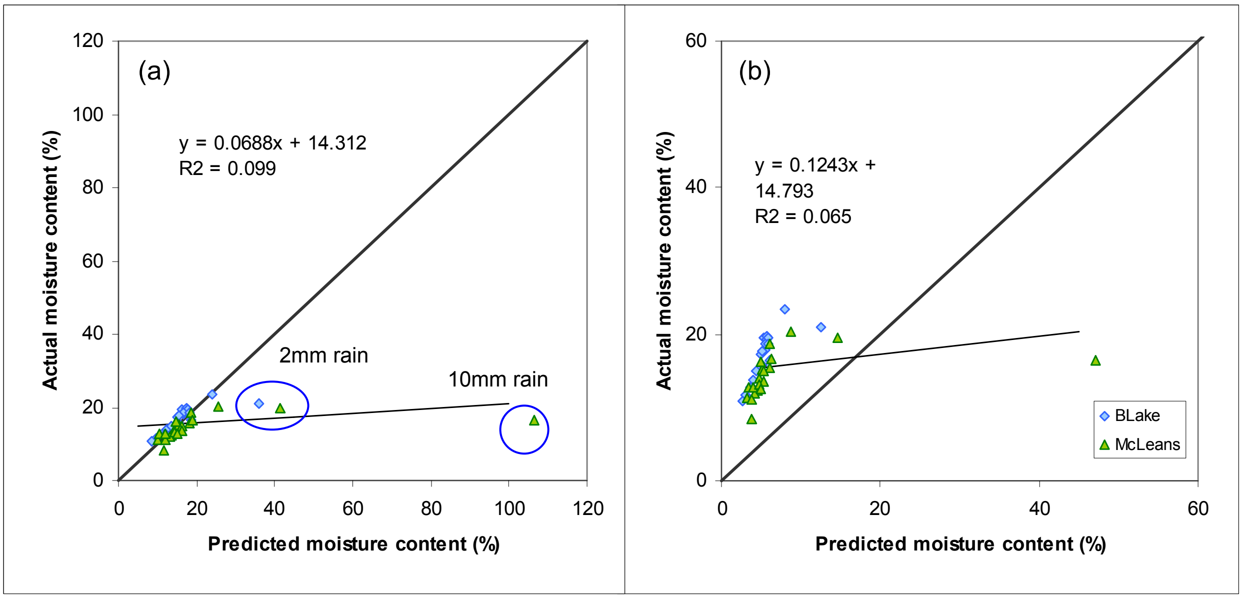


Figure 6. Combined actual versus predicted **elevated** moisture content using the 1600 hour FFMC calculated from the: (a) FF-scale, (b) FX-scale. Data were combined from both sampling sites into a single dataset (Source: NRFA & NIWA, n = 39).

<u>Surface layer</u>

The plots of actual versus predicted surface litter moisture content, calculated from the FF- and FX-scales of the FFMC, are shown in Figures 7 a & b. Surface moisture content predictions were reasonably good using the FFMC FF-scale but poor using the FX-scale (Table 6). Again there were several outliers when a rainfall event occurred, resulting in the FFMC significantly over-predicting moisture content. These results are highlighted in the time-series graphs of Appendix 4.5 (Figures 30 & 32). Surface fuel moisture content was predicted marginally better at the Bottle Lake forest site compared to that at McLeans Island (Table 6).

A one-way ANOVA indicated that there was a significant difference between actual and predicted moisture contents. The Tukey test revealed that there was no significant difference between predicted moisture content using the FFMC FF-scale to actual moisture content, but predictions using the FX-scale were (Appendix 4.9).

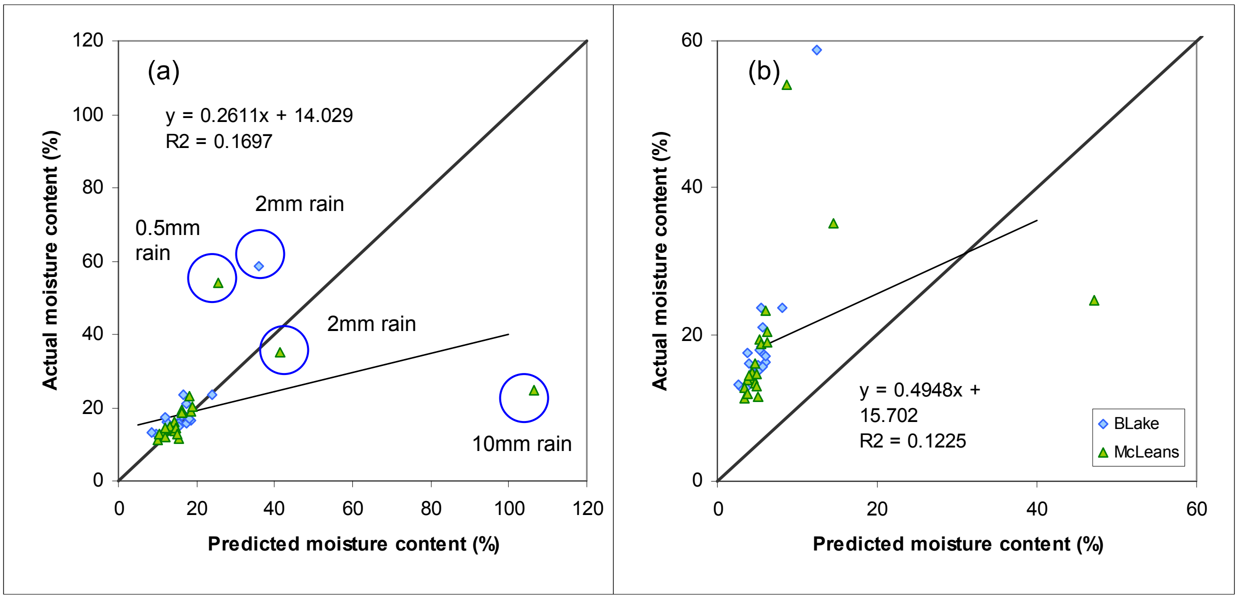


Figure 7. Combined actual versus predicted **surface** moisture content using the 1600 hour FFMC calculated from the: (a) FF-scale, (b) FX-scale. Data were combined from both sampling sites into a single dataset (Source: NRFA & NIWA, n = 39).

Table 6. Comparisons of the actual moisture content for the elevated and surface layers against that predicted using the 1600 hour FFMC (FF- and FX- scales) (Source: NRFA & NIWA).

	Elevated		**Surface**	
	FF-scale	**FX-scale**	**FF-scale**	**FX-scale**
Both sites combined, n = 39				
ME	-3.14	9.09	0.18	12.42
RMSE	15.13	11.43	14.55	15.85
R^2	0.10	0.06	0.17	0.12
Bottle Lake Forest only, n = 19				
ME	0.52	11.50	2.66	13.64
RMSE	3.84	11.71	5.97	15.82
R^2	0.38	0.60	0.89	0.82
McLeans Island Forest only, n = 20				
ME	-6.61	6.81	-2.17	11.25
RMSE	20.79	11.15	19.47	15.88
R^2	0.11	0.12	0.14	0.10

Comparisons using FFMC calculated at 1200 (NZST)

Plots of observed versus predicted moisture content using fire weather observations recorded at the standard 1200 hour observation time are shown (Figures 8 & 9 and Table 7) using a combined dataset from both the Bottle Lake and McLeans Island Forest sites. Please refer to Appendix 4.8 (Figures 45 – 52 and Tables 17 & 18) for plots of individual sites and statistical comparisons.

Elevated layer

The plots of actual versus predicted elevated dead fuel moisture content, calculated from the FF- and FX-scales of the FFMC, are shown in Figures 8 a & b. Elevated moisture content was predicted relatively poorly using both the FF- and FX-scales (Table 7). Both FFMC scales tended to under-predict elevated moisture content, particularly the FX-scale. These results are shown in the time-series graphs located in Appendix 4.7 (Figures 37 & 38).

A one-way ANOVA revealed that there was a significant difference between actual and predicted moisture content ($p < 0.0001$). The Tukey test showed that actual moisture content did not differ significantly from that predicted using the FF-scale, but that there was a significant difference between actual and predicted moisture content using the FX-scale of the FFMC (Appendix 4.9).

Surface layer

The plots of actual versus predicted surface litter moisture content, calculated from the FF- and FX-scales of the FFMC are shown in Figures 9 a & b. Surface moisture content predictions were also poor using both the FFMC scales (Table 7). Both the FF-and FX-scales under-predicted surface fuel moisture content, although the standard FF-scale was somewhat better. These results are highlighted in the time-series graphs of Appendix 4.7 (Figures 39 & 40).

A one-way ANOVA revealed that there was a significant difference between actual and predicted moisture content ($p < 0.0001$). The Tukey test showed that moisture content predicted using both the FF- and FX-scales significantly differed to actual moisture content (Appendix 4.9).

Table 7. Statistical comparison of the actual moisture content against that calculated for each of the fuel layers sampled using weather from the standard 1200 hour observations (combined data from Bottle Lake and McLeans Island).

Fuel layer		Moisture content predicted by: FFMC (FF-scale)	FFMC (FX-scale)	DMC	DC
Elevated	ME	1.58	10.99		
	RMSE	5.02	11.34		
	R^2	0.33	0.32		
Surface	ME	4.90	14.31		
	RMSE	8.30	16.60		
	R^2	0.56	0.56		
Loose	ME	19.87	29.26	-38.87	-122.10
	RMSE	30.81	39.28	49.57	132.83
	R^2	0.58	0.58	0.03	0.03
Compact	ME	11.98	21.39	-53.29	-125.97
	RMSE	16.81	25.41	59.61	132.41
	R^2	0.48	0.48	0.02	0.00

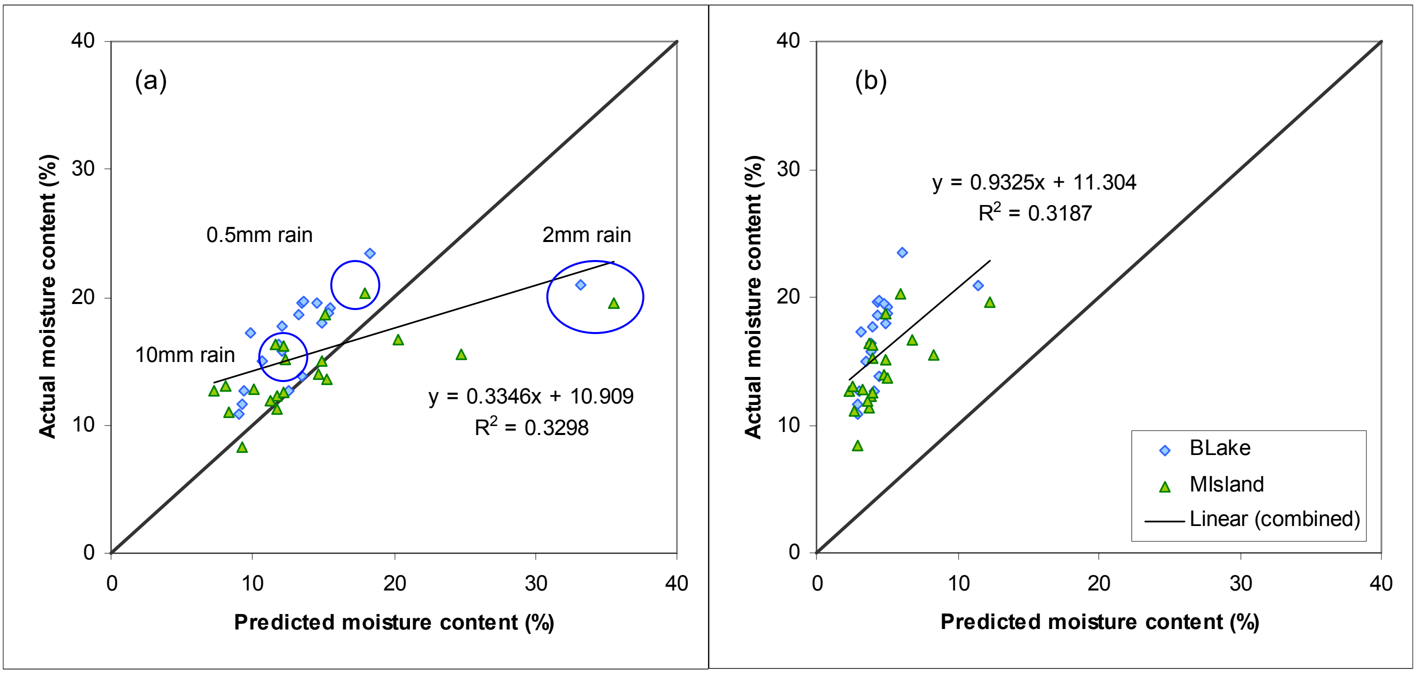


Figure 8. Actual versus predicted moisture content for the **elevated layer** from Bottle Lake Forest (blue circles) and McLeans Island Forest (green triangles), using the: (a) FF-scale and (b) FX-scale of the FFMC.

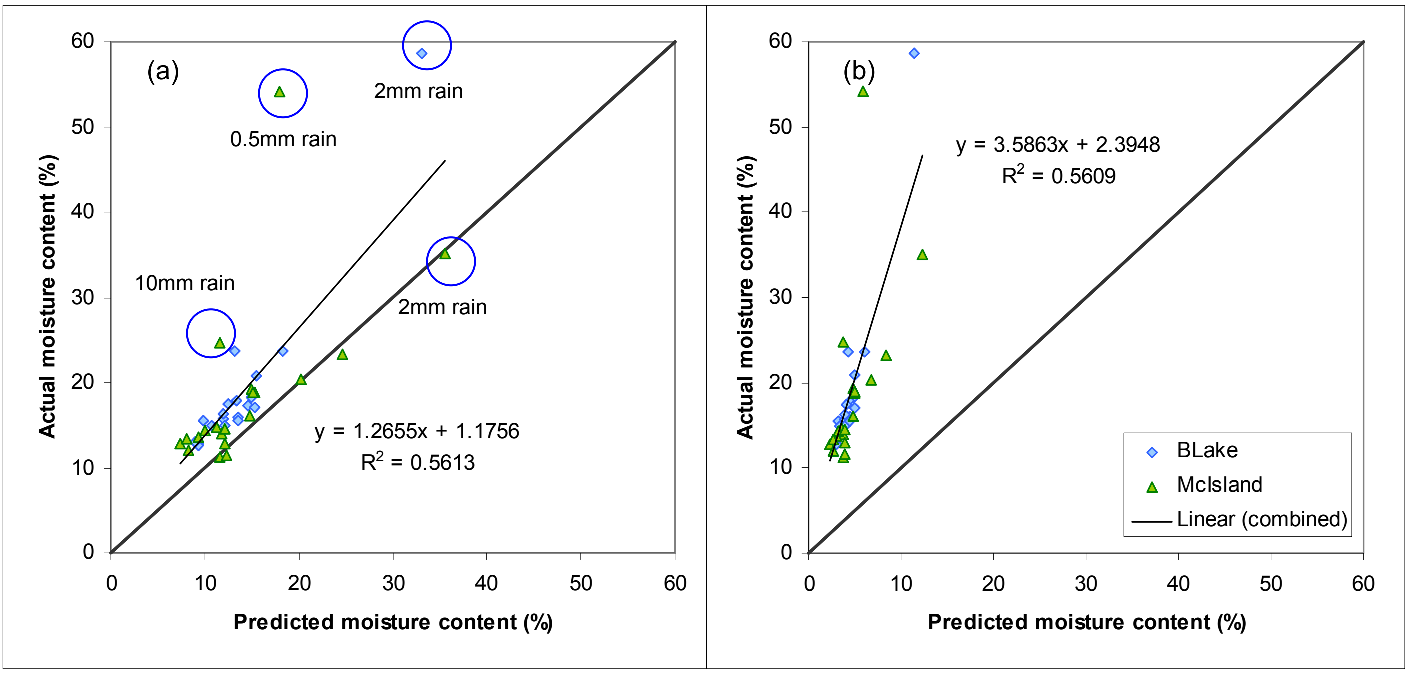


Figure 9. Actual versus predicted moisture content for the **surface layer** from Bottle Lake Forest (blue circles) and McLeans Island Forest (green triangles), using the: (a) FF-scale and FX -scale (b) of the FFMC.

Loose duff layer

The DMC, DC and FFMC (FF- and FX-scales) predicted loose duff moisture content poorly (Figure 10 & Table 6). Both the FF- and FX-scales of the FFMC significantly under-predicted moisture content, whereas the DMC and DC over-predicted. These results are highlighted in the time series graphs located in Appendix 4.7 (Figures 41 & 42).

A one-way ANOVA revealed that there was a significant difference between actual and predicted moisture content ($p < 0.0001$) in all cases, and the Tukey test showed a significant difference between actual and predicted moisture content using the DMC, DC and FF- and FX-scales (of the FFMC) (Appendix 4.9).

Compact duff layer

The DC, DMC and FFMC (FF- and FX-scales) also predicted compact duff moisture content poorly (Figure 11 & Table 6). Again, both the FF- and FX-scales of the FFMC significantly under-predicted moisture content whereas the DMC and DC over-predicted moisture content. These differences between actual and predicted moisture content for the compact duff layer are highlighted in Appendix 4.7 (Figures 43 & 44).

A one-way ANOVA revealed that there was a significant difference between actual and predicted moisture content ($p < 0.0001$) and the Tukey test showed a significant difference between actual and predicted moisture content from the DMC, DC and FF- and FX-scales of the FFMC (Appendix 4.9).

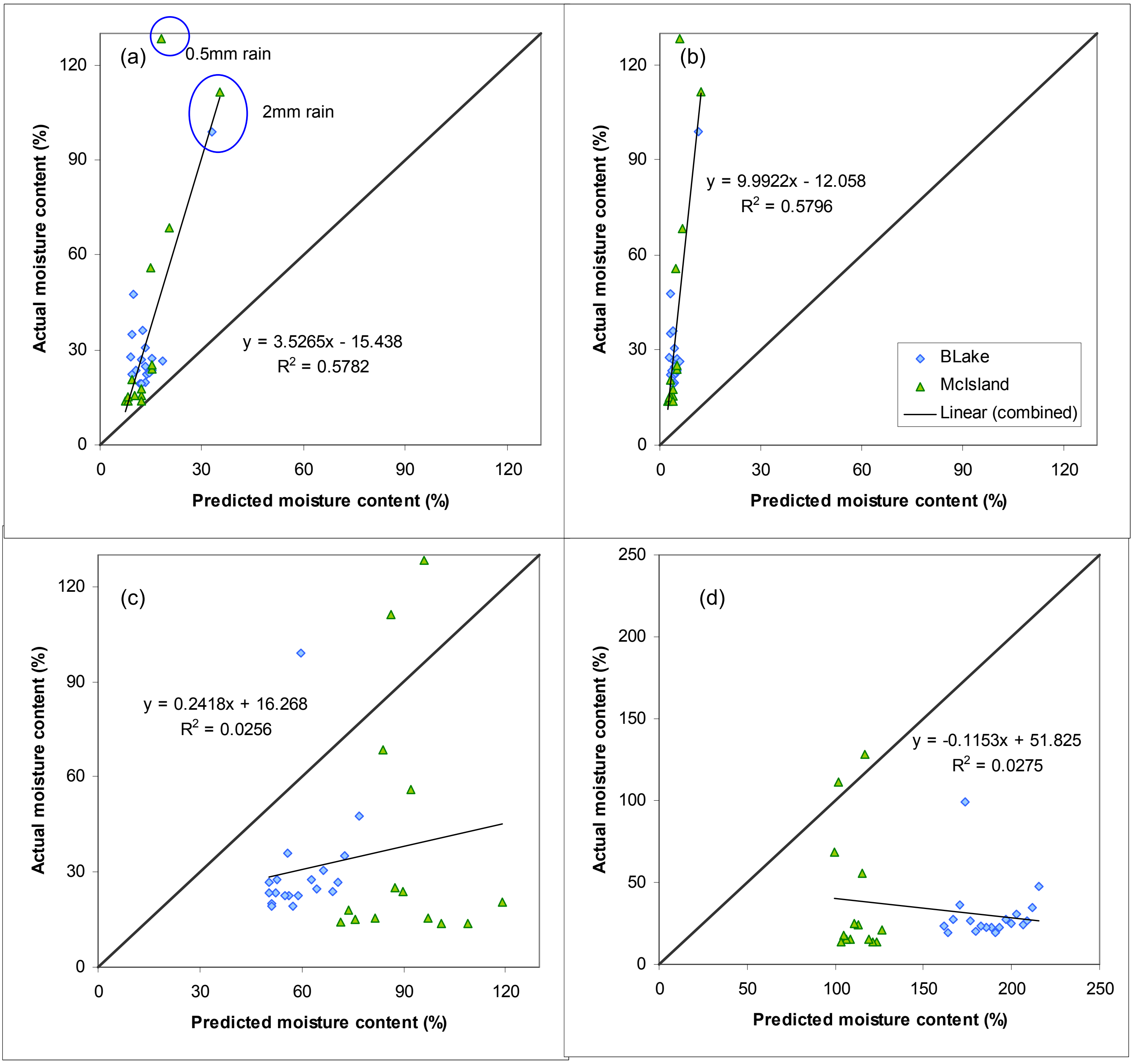


Figure 10. Actual versus predicted moisture content for the loose duff layer from Bottle Lake Forest (blue circles) and McLeans Island Forest (green triangles), using the: (a) FF-scale (a), (b) FX-scale and (c) DMC.

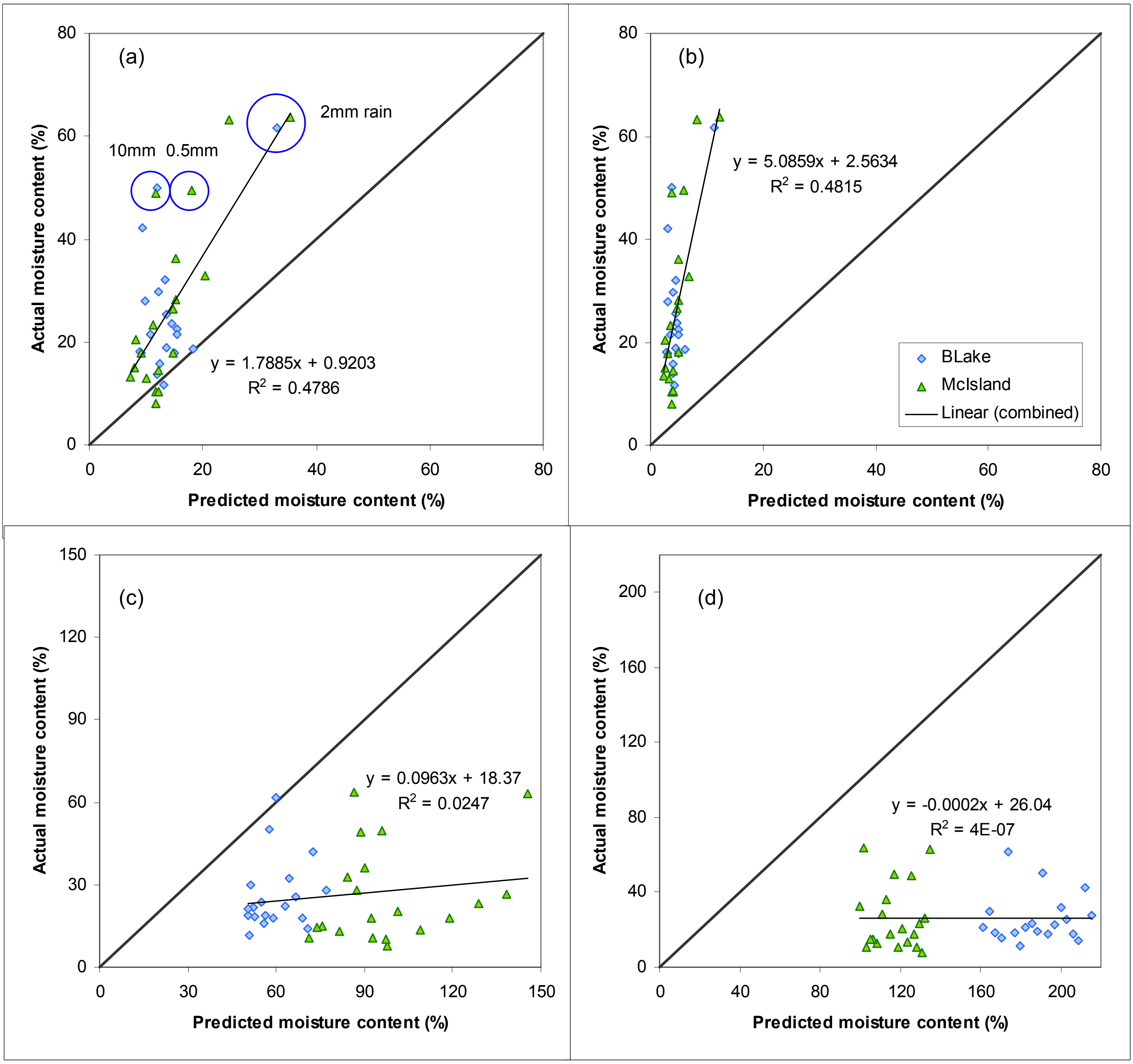


Figure 11. Actual versus predicted moisture content for the compact duff layer from Bottle Lake Forest (blue circles) and McLeans Island Forest (green triangles), using the: (a) FF-scale, (b) FX-scale, (c) DMC, and (d) DC.

HOURLY RESULTS

Hourly fire weather conditions

Bottle Lake Forest

The two hourly sampling days at Bottle Lake were quite different in terms of weather conditions (Table 8 and Figures 12, 13 and 14). Conditions on 10 February 2009 were cool and overcast, with easterly winds at an average speed of 9.2 km/h. The temperature increased from 16ºC at 0700 to a maximum of 19ºC at 1300 hours before dropping back down to 16ºC by 1900 hours. Relative humidity increased from 60% at 0700 to 78% by 1900 hours. A relatively high FWI of 24 and FFMC of 88 were observed due to the previous day having had a maximum temperature of 35ºC and minimum RH of 29%, FFMC of 93 and FWI of 33 (see Appendix 5.2, Table 23).

Conditions on 19 March 2009 were warm with westerly winds, with an average wind speed of 5.1 km/h (and maximum wind speed of 9.6 km/h at 1300 hours). The temperature increased from 15ºC at 0700 to 26.4ºC at 1200 hours before dropping back down to 14ºC by 1900 hours. Relative humidity (RH) decreased from 80% at 0700 to 31% at 1200 before increasing back to 70% at 1900 hours. A maximum FFMC of 88, ISI of 4.8 and FWI of 12 were observed at 1300 hours (see Appendix 5.2, Table 24).

Table 8. Summary of weather conditions during hourly sampling (0700 – 1900 NZST) at Bottle Lake Forest, under the canopy (using data collected from the MAWS) and the nearest RAWS (Source: Bottle Lake RAWS, NRFA).

	Temp (ºC)	**RH** (%)	**Wind_dir** (degrees)	**Wind_spd** (km/h)	**FFMC**	**ISI**	**FWI**
10/02/2009 RAWS							
Average	17.0	66.8	91	9.2	86.9	4.4	21.1
Median	17.2	65.0	95	10.0	87.1	4.6	21.8
Min	15.5	60.0	70	5.4	85.7	3.1	16.5
Max	18.7	78.0	112	12.9	87.7	5.1	23.5
10/02/2009 Under-canopy							
Average	16.1	68.6	196.9	1.0	81.6	1.4	8.8
Median	16.0	68.5	200.0	1.1	81.6	1.4	8.8
Min	15.3	62.6	7.0	0.7	80.6	1.3	7.8
Max	17.1	77.3	356.0	1.1	82.2	1.5	9.4
19/03/2009 RAWS							
Average	20.6	52.6	275	5.1	86.2	3.4	8.4
Median	22.1	51.0	287	4.5	87.3	3.8	9.0
Min	14.2	31.0	40	0.8	82.9	1.7	4.0
Max	26.4	80.0	354	9.6	88.0	4.8	11.6
19/03/2009 Under-canopy							
Average	19.3	55.4	272.7	2.1	81.0	1.5	3.5
Median	19.6	56.1	289.5	1.4	81.9	1.5	3.6
Min	15.3	40.7	170.0	1.1	77.1	1.0	2.1
Max	22.6	66.9	343.0	7.3	83.0	1.7	4.1

McLeans Island Forest

The two sampling days at McLeans Island were again different in terms of weather, particularly temperature and wind speed, resulting in a difference in FWI System values (FFMC, ISI and FWI). A summary of the fire weather conditions for the two hourly sampling days at McLeans Island is contained in Table 9 and Figures 12, 13 and 14. The two days at McLeans Island also had different conditions to the sampling days at Bottle Lake Forest, with higher ISI and FWI values.

Conditions on 23 January 2009 were hot and dry, with north east and easterly winds averaging 16 km/h (maximum of 24 km/h at 1600 hours). The temperature increased from 16ºC at 0700 hours to a maximum of 28ºC by 1300 hours. The relative humidity decreased from a maximum of 89% at 0700 hours to 30% at 1300 hours. A maximum FFMC 89, ISI of 13 and FWI of 33 were reached at 1600 hours (Appendix 5.2, Table 25).

Conditions on 3 February 2009 were slightly cooler, with easterly winds averaging 12.8 km/h (a maximum speed of 18.5 km/h at 1700 hours). The temperature increased from 11ºC at 0700 hours to 22ºC by 1500 hours. The relative humidity decreased from 81% at 0700 hours to 43% by 1500 hours. A maximum FFMC of 86, ISI of 6 and FWI of 23 was reached at 1700 hours (Appendix 5.2, Table 26).

Table 9. Summary of weather conditions during hourly sampling (0700 – 1900 NZST) at McLeans Island Forest from under the canopy (using weather data collected from the MAWS) and the nearest RAWS (Source: Christchurch Aero RAWS, NRFA).

	Temp (ºC)	**RH** (%)	**Wind_dir** (degrees)	**Wind_spd** (km/h)	**FFMC**	**ISI**	**FWI**
23/01/2009 RAWS							
Average	24.2	48.2	68	16.1	85.7	6.9	19.3
Median	26.0	39.0	70	16.7	86.7	7.5	21.9
Min	16.0	30.0	30	5.6	80.6	1.6	6.0
Max	28.0	89.0	90	24.1	89.9	13.2	32.5
23/01/2009 Under-canopy							
Average	24.3	47.2	80	1.7	81.3	1.9	6.6
Median	26.0	38.5	45	1.8	82.0	1.6	5.9
Min	15.1	25.2	12	1.1	74.0	0.8	2.6
Max	28.6	94.9	332	2.2	88.0	3.5	11.7
3/02/2009 RAWS							
Average	18.6	57.7	66	12.8	83.3	3.5	15.3
Median	19.0	59.0	70	14.8	83.4	3.1	14.0
Min	11.0	43.0	30	7.4	80.2	1.9	9.3
Max	22.0	81.0	90	18.5	85.8	6.0	23.1
3/02/2009 Under-canopy							
Average	18.5	55.5	138	1.1	77.7	1.1	5.6
Median	19.9	54.5	61	1.1	77.8	1.0	5.1
Min	10.8	41.4	1	0.2	72.6	0.7	3.6
Max	22.2	78.7	360	2.0	82.5	1.6	8.1

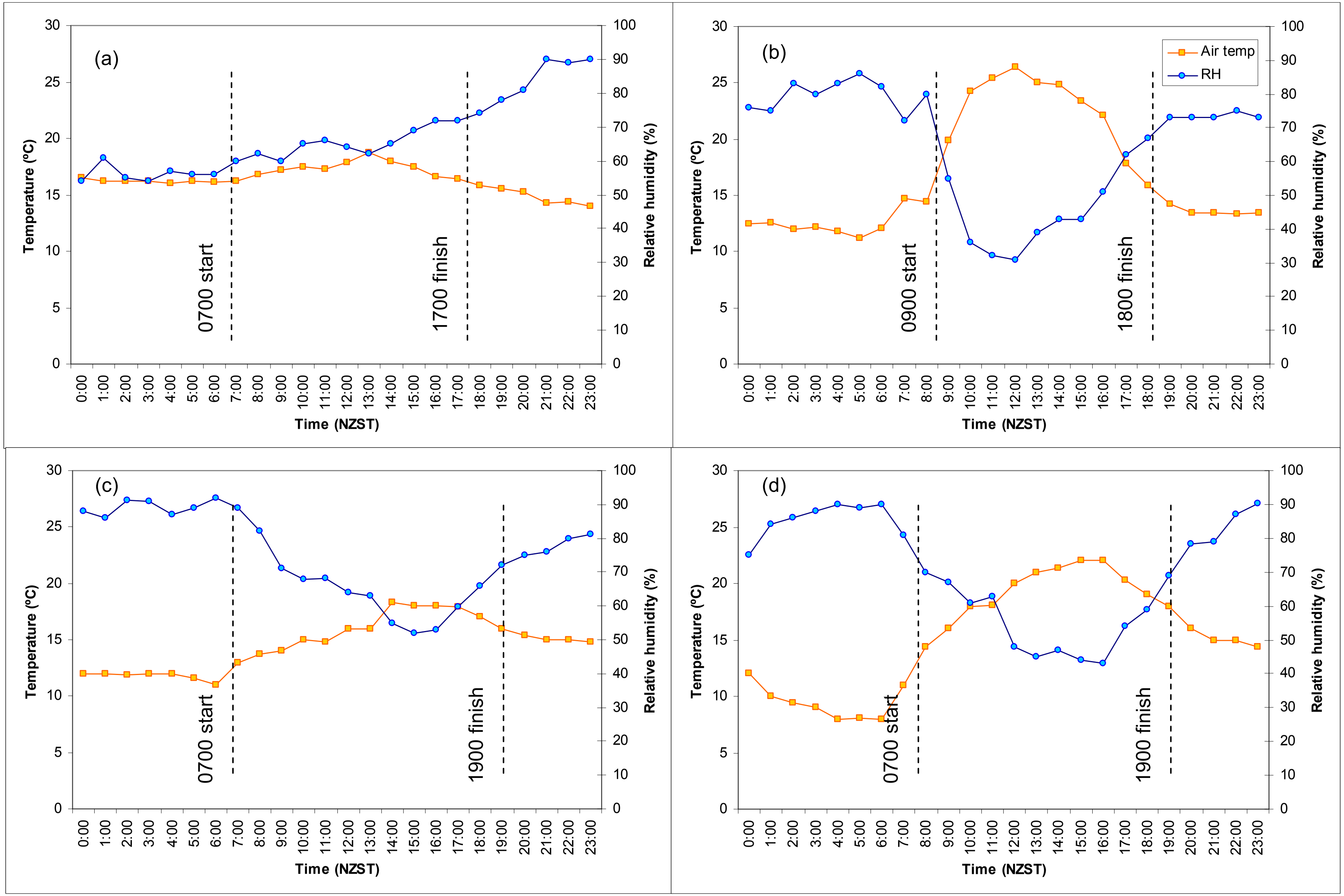


Figure 12. Hourly temperature (ºC) and relative humidity (%) readings from the nearest RAWS: (a) Bottle Lake Forest 10/02/09; (b) Bottle Lake Forest 19/03/09; (c) McLeans Island Forest 23/01/09; (d) McLeans Island Forest 03/02/09; (Source: NRFA & NIWA). Dotted line represents start and finish times for collecting samples.

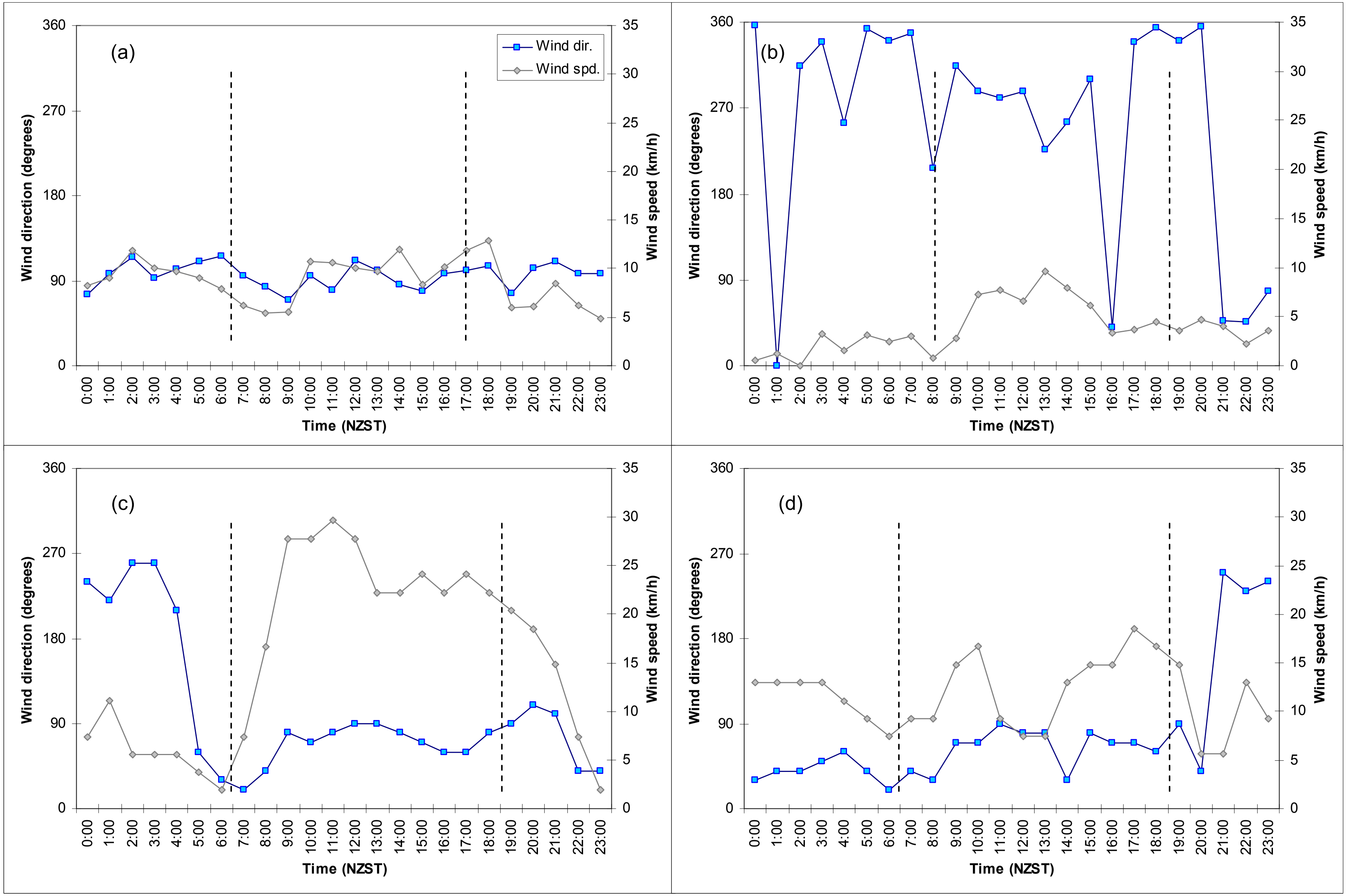


Figure 13. Hourly wind speed (km/hr) and direction (degrees) readings from the nearest RAWS. (a) Bottle Lake Forest 10/02/09; (b) Bottle Lake Forest 19/03/09; (c) McLeans Island Forest 23/01/09; (d) McLeans Island Forest 03/02/09; (Source: NRFA & NIWA). Dotted line represents start and finish times for collecting samples.

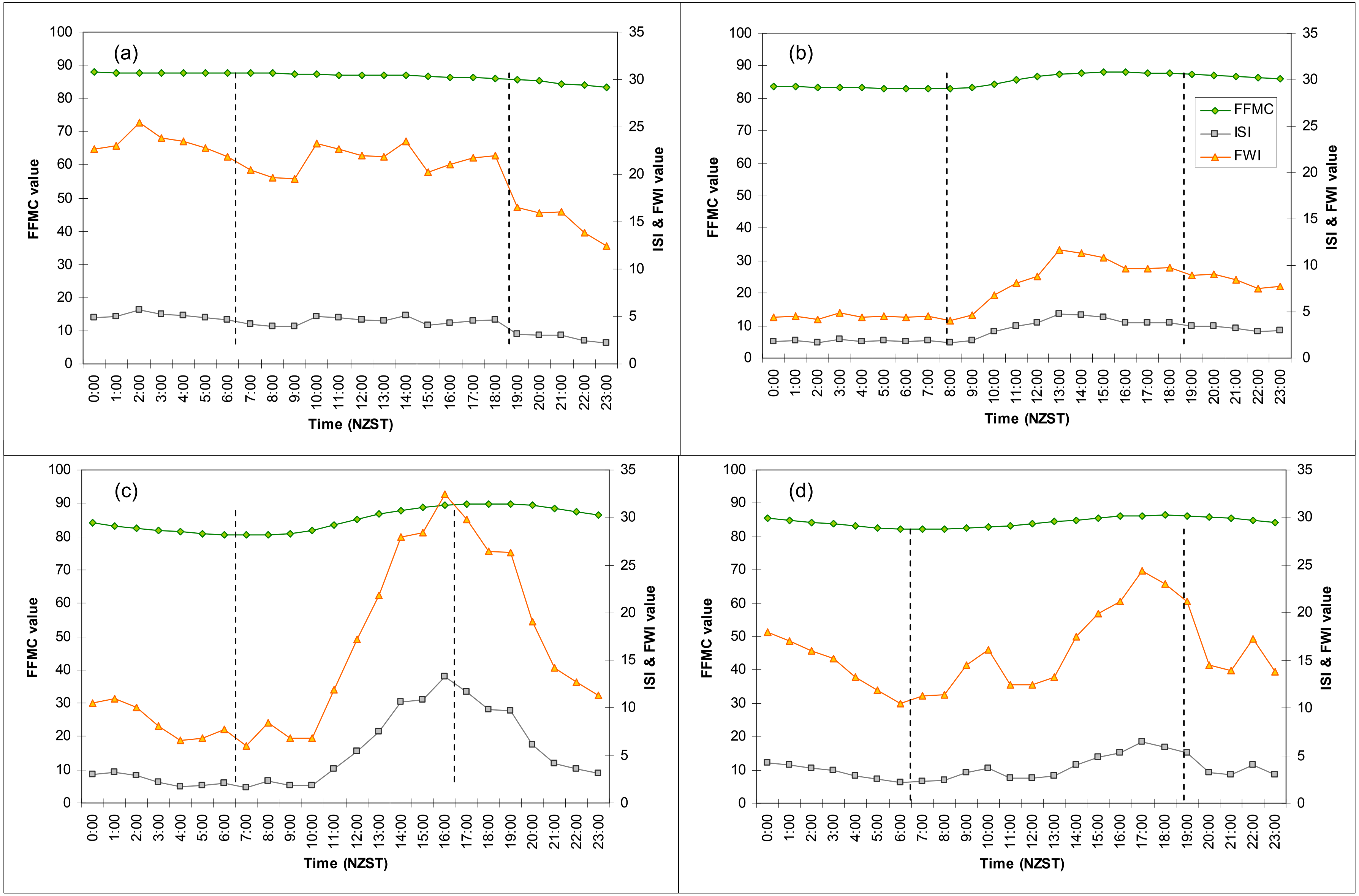


Figure 14. Hourly Fine Fuel Moisture code (FFMC), Initial Spread Index (ISI) and Fire Weather Index (FWI) from the nearest RAWS. (a) Bottle Lake Forest 10/02/09; (b) Bottle Lake Forest 19/03/09; (c) McLeans Island Forest 23/01/09; (d) McLeans Island Forest 03/02/09. (Source: NRFA & NIWA). Dotted line represents start and finish times for collecting samples.

Hourly fuel moisture content

Time-series plots of hourly elevated and surface fuel moisture contents are contained in Figure 15 (raw moisture content data is located in Appendix 5.3, Tables 27 - 30 and Appendix 5.4 Figures 53 - 56). For each of the four sampling days, there were slight differences in moisture content between surface and elevated fuels.

Bottle Lake Forest

The moisture content of both the elevated and surface fuels varied little over the sampling time between the hours of 0700 and 1700 on the 10 of February 2009 (Figure 15a). Initially the elevated fuels were dryer (about 2% difference) than the surface fuels, but during the day elevated fuels increased in moisture due to the weather conditions. The little change in moisture content was a result of the weather conditions on the day. Sampling occurred on a cool and overcast day with temperature varying only by two degrees and relative humidity steadily increasing (Figure 12a).

On 19 March 2009, there was a 10% difference in fuel moisture content between the elevated and surface fuels (Figure 15b). Elevated fuels reached a minimum moisture content of 12% at 1700 hours. Surface fuels reached a minimum moisture content of 20% at 1600 hours. There was a much greater change in fuel moisture contents on this day due to the greater change in the diurnal cycle in temperature and relative humidity (Figure 12b) and warm westerly winds (Figure 13b).

McLeans Island Forest

On 23 January 2009, there was generally about 5% difference in fuel moisture content between elevated and surface fuels (Figure 15 c). The elevated fuels were initially higher at the start of sampling, but dried more quickly to be lower in moisture content than surface litter for most of the day. The elevated layer reached a minimum of 8% at 1600 hours. The surface layer reached a minimum moisture content of 11% at 1600 hours. There was a lesser dramatic change in temperature and relative humidity on this day compared to Bottle Lake Forest on the 19 March 2009 (Figure 12c). However, fuels would continue to loose moisture during sampling due to the relatively strong winds around 20km/h (Figure 13c).

On 3 February 2009, moisture content between surface and elevated fuels was very similar during sampling (1-2% difference). At the start of sampling, elevated fuels were initially higher in moisture content, but dried more quickly during the day before increasing again in the evening (Figure 15d). The elevated layer reached a minimum moisture content of 12% at 1500 hours. The surface layer reached a minimum of 13% by 1700 hours. Both surface and elevated fuels lost moisture content as a response to the changes in the diurnal pattern in temperature and relative humidity (Figure 12d).

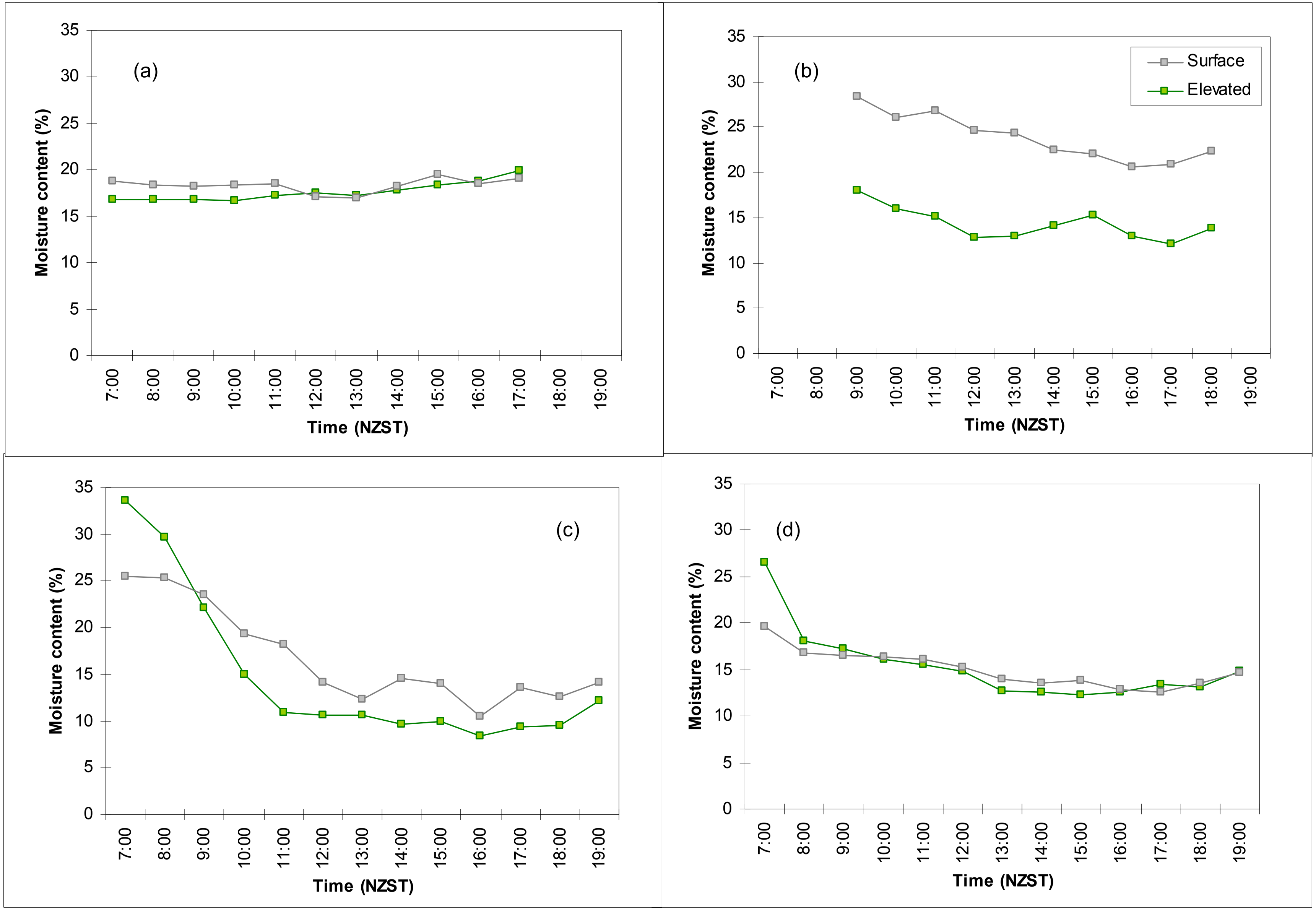


Figure 15. Elevated (green) and surface (grey) fuel moisture content sampled on the hour from: (a) Bottle Lake Forest 10/02/09; (b) Bottle Lake Forest 19/03/09; (c) McLeans Island 23/01/09 (d) McLeans Island 03/02/09. Fuel moisture values represent an average of 5 replicate samples.

Actual versus predicted hourly moisture contents

Plots of actual versus predicted moisture content for the elevated and surface fuel layers are shown in Figures 16 and 17. A summary of statistics for the comparisons of observed versus predicted moisture contents for the two fuel layers are provided in Table 12. Individual plots and statistics for each site are located in Appendix 5.6 (Figures 59 – 62 Tables 31 & 32).

The time-series plots of actual moisture content versus that predicted using both the FF- and FX-scales of the FFMC for both elevated and surface fuel layers are contained in Appendix 5.5 (Figures 57 & 58). These plots clearly show that the FX-scale was unsuitable for predicting moisture content for elevated and surface fuel layers. Therefore, discussion of results and further analyses presented here was restricted to the use of the FF-scale of the FFMC only.

Elevated fuel layer

Elevated moisture content was also predicted relatively poorly using the FF-scale of the FFMC calculated from weather observations from the nearest RAWS and was even worse using weather observations under the canopy (Figure 16 a & b, Table 10). Elevated moisture content was over-predicted when using weather observations from under the canopy. Predicted moisture content was marginally better at Bottle Lake Forest than McLeans Island.

The one-way ANOVA confirmed a significant difference between the actual and predicted moisture content ($p < 0.0001$). The Tukey test indicated a non significant difference using weather observation from RAWS, but a significant difference using weather observations under the canopy (Appendix 5.7). This difference between actual and predicted moisture content is also highlighted in the time-series graphs located in Appendix 5.5 (Figures 57).

Surface fuel layer

Surface moisture content was also predicted poorly by the FF-scae of the FFMC calculated using weather observations from both the nearest RAWS and under the canopy (Figure 17 a & b, Table 10). Moisture content was largely under-predicted at Bottle Lake (Figure 16 a) and over-predicted at McLeans Island (Figure 17 b). Surface fuel moisture content was predicted better at McLeans Island than Bottle Lake using the RAWS weather observations (Figure 17 a).

The one way ANOVA and subsequent Tukey test confirmed that there was a significant difference ($p < 0.0001$) between the actual and predicted surface moisture content using weather observations from the nearest RAWS and under the canopy (Appendix 5.7). This difference between actual and predicted moisture content is also highlighted in the time series graphs located in Appendix 5.5 (Figure 58).

Table 10. Statistical comparison of the actual moisture content of the elevated and surface layers against that predicted by the FFMC (FF- and FX- scales), using weather observations from the nearest RAWS and under the canopy. Data were combined from both sites into a single dataset (in all cases, n = 47).

	RAWS		Under-canopy	
	FF-scale	FX-scale	FF-scale	FX-scale
Elevated				
RMSE	3.76	11.31	7.59	9.17
ME	0.13	10.45	-6.40	8.24
R^2	0.41	0.42	0.40	0.41
Surface				
RMSE	5.46	13.95	6.45	11.89
ME	2.92	13.24	-3.61	11.02
R^2	0.09	0.09	0.11	0.07

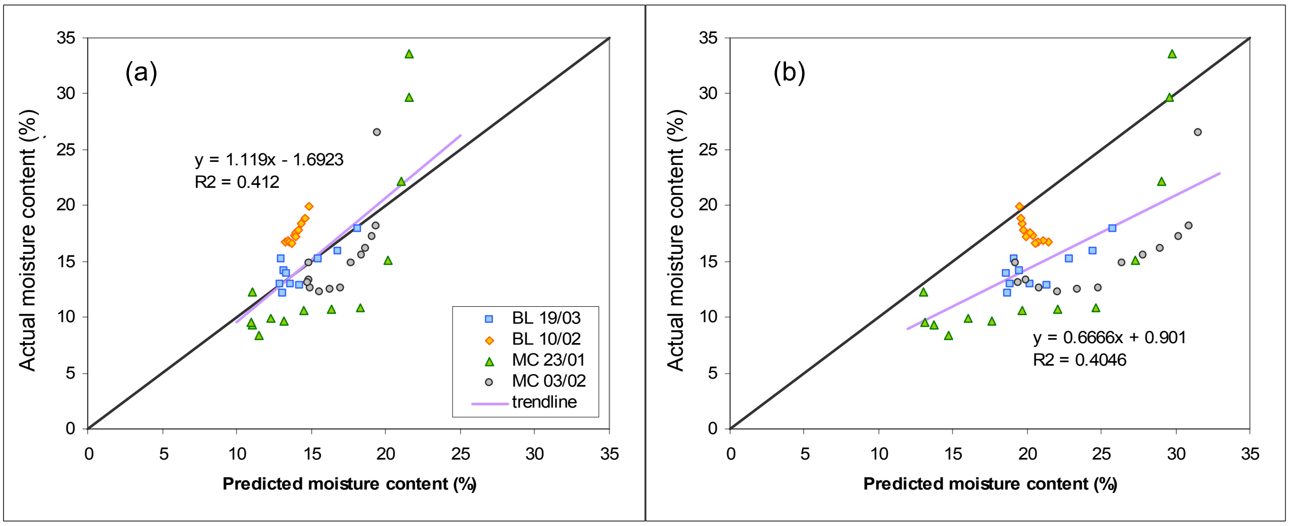


Figure 16. Combined actual versus predicted **elevated** moisture content for the four hourly sampling days from both sites (Bottle Lake 10 February and 19 March; McLeans Island 23 January and 3 February 2009). Predicted moisture content was calculated from the FF-scale of the FFMC using weather observations from: (a) the nearest RAWS; (b) under the canopy.

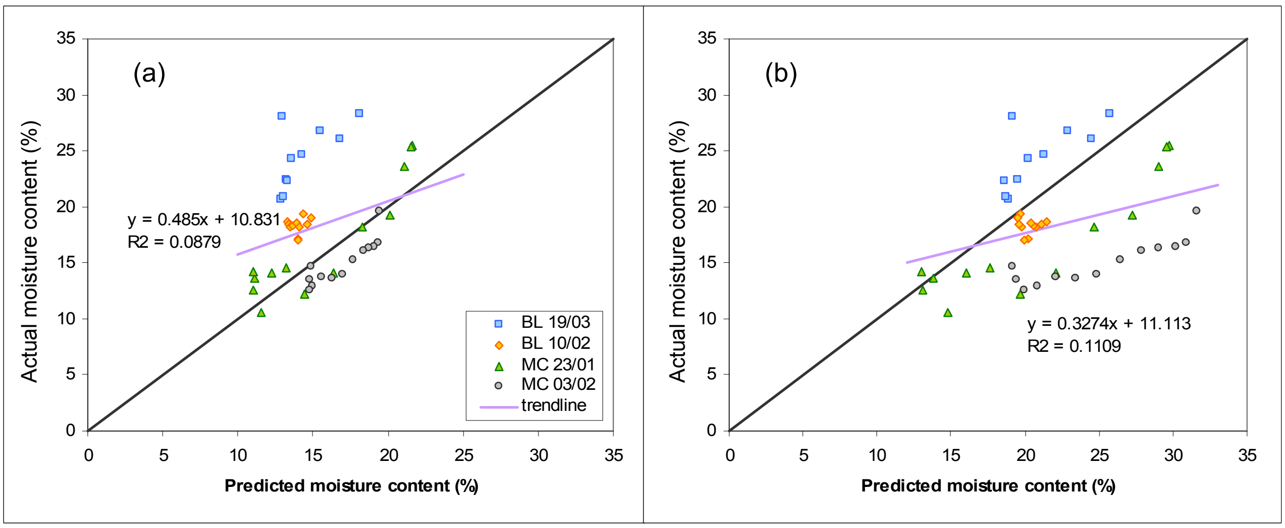


Figure 17. Combined actual versus predicted **surface** moisture content for the four hourly sampling days from both sites (Bottle Lake 10 February and 19 March; McLeans Island 23 January and 3 February 2009). Predicted moisture content was calculated from the FF-scale of the FFMC using weather observations from: (a) the nearest RAWS; (b) under the canopy.

DISCUSSION AND CONCLUSION

For the two Canterbury sites, the FFMC calculated at noon (NZST) did not generally reflect the actual moisture content of the fine elevated and surface fuels around 1600 hours. Elevated and surface fuel moisture contents were under-predicted using the FF-scale of the FFMC, with predictions using the FX-scale of the FFMC even less accurate, significantly under-predicting moisture content. More accurate predictions were obtained when calculating the FFMC (FF-scale) at the actual time of sampling (1600 hours) using weather observations from the nearest RAWS, rather than using the FFMC value calculated at noon. However, over-prediction was observed following rainfall events. This was particularly evident at McLeans Island following two heavy rainfall events (9.8 mm on 19 January 2009 and 2.4 mm on 4 February 2009).

Predictions using the faster responding FX-scale of the FFMC were universally poor for both the 1200 and 1600 hour data, with consistent under-predictions of moisture content. This is probably due to the fact that this scale was designed and intended for hotter and drier climates than those characteristic of the study sites (Lawson *et al.* 1996). Surface fuel moisture content was also generally better predicted than the elevated fuel moisture content. This likely reflects the fact that the FFMC is designed to represent the moisture content of the surface layer in a conifer forest, and not the elevated dead fuels (Van Wagner, 1987). The elevated fuels were more exposed and aerated, and probably responded quicker to changes in the surrounding atmosphere than the surface fuels on the ground.

It therefore appears that the FFMC calculated at noon may be unreliable for determining the moisture content of surface fuels in pine plantations around 1600 hours. This has significant implications for assessment of fire danger and fire behaviour potential. It may be more appropriate at 12 noon to use an hourly calculation of the FFMC based on weather forecasts for 1600 hours. It also seems that the FX-scale of the FFMC is not suited to pine plantations in New Zealand.

Hourly sampling of the elevated and surface fuel layers indicated that the FFMC, calculated hourly as per Alexander *et al.* (1984), generally predicted fuel moisture content poorly throughout the day. Both scales of the FFMC performed poorly, with predictions even worse when weather observations under the canopy were used to calculate FFMC. Moisture content was again significantly under-predicted by the FX-scale of the FFMC, and was less accurate than the FF-scale. The hourly elevated fuel moisture content at Bottle Lake Forest was predicted marginally better using the FF-scale of the FFMC, with surface fuel moisture content better predicted at McLeans Island.

The poor prediction of moisture content using the hourly FFMC is possibly because of different response times for these fuels compared to those calculated by the hourly FFMC. Fuel particles will strive to reach their equilibrium moisture content (EMC), which is the moisture content that the fuel particle will approach if exposed to constant temperature and relative humidity (Pyne *et al.* 1996). The response time is the time taken for a fuel particle to achieve approximately 63% of the difference between its initial moisture content and the EMC. The FFMC determines response time using pre-defined coefficients (refer Van Wagner 1987; Alexander *et al.* 1984). It is possible that the fuels at these sites had different response rates to wetting and drying than those that the hourly FFMC equations determined. These equations are based on empirical data from Canadian conifer forests, which could be very different to these Canterbury forests.

The FFMC, DMC and DC all provided poor predictions of the moisture content of the duff (loose and compact) and soil layers at both sites. The FFMC (using both scales) significantly under-predicted duff and soil moisture content, whereas the DMC and DC significantly over-predicted moisture content for both duff and soil layers. The FF-scale of the FFMC provided the closest predictions of moisture content for the loose and compact duff fuels, but with significant under-prediction.

Poor prediction of the moisture content of the duff layers by the DMC and DC is probably due to the significant differences between the duff layers at these two Canterbury sites and those of the Canadian reference fuel type that forms the basis of the FWI System. The duff layers were very shallow and, in some places, sparse with no deep organic layers (the duff layers ranged from 1 – 4 cm deep). The loose and compact duff layers defined in Van Wagner (1987) are typically 7 and 8 cm deep respectively. There was also no deep organic layer, representative of the DC, present at either site. The soil type at both of the study sites was sandy and free-draining, and explains the very low soil moisture contents observed throughout the study (ranging from 2 to 8 %). The very shallow duff layers therefore meant that little rainfall and moisture was retained in these fuels. In addition, the sandy and free-draining soils provided little (if any) moisture to the duff layers above the soil (through absorption), as would be expected with more organic soil types that would retain more moisture. The effects of soil type and the nature of the duff layers on the DMC and DC require further research.

A further explanation for the poor performance of all of the FWI system moisture codes could be due to poor quantification of rainfall interception by the forest canopy. The FFMC assumes a rainfall threshold of 0.6 mm (Van Wagner, 1987), suggesting that the forest canopy intercepts this amount of rainfall before any reaches the surface litter on the forest floor. Following rainfall events, the FFMC (FF-scale) over-predicted elevated fuel moisture content at both sites using both 1200 and 1600 hour weather observations. Surface fuel moisture content was under-predicted following rainfall of 2 mm on 2 December 2008 at Bottle Lake, using both 1200 and 1600 hour weather observations. However, surface fuel moisture content at McLeans Island was over-predicted using the 1600 hour weather observations and was accurate using the 1200 hour observations following two rainfall events (9.8 mm on 19 January 2009 and 2.4 mm on 4 February 2009). It is therefore possible that elevated dead fuels received less moisture from rainfall than the FFMC predicted due to the more porous nature of the forest canopy compared to the reference Canadian forest type. More rainfall would be likely to pass through the canopy and collect on (or penetrate) the surface layer. This may explain the overprediction of moisture content in the surface layer by the FFMC. However, further research is required to determine appropriate rainfall interception rates by forest canopies for New Zealand forests.

Further sources of error in predictions of moisture content by these FWI System codes could be from site differences between these Canterbury forests and those of the reference Canadian fuel type. As already mentioned the soils at both sites were sandy and retained little moisture. Duff layers were also very thin at both sites and, combined with a sandy and dry soil layer, their moisture retention was poor. The Canterbury sites were also both in managed plantation forests, subjected to thinning and pruning. The reference fuel type in Canada reflects native conifer forests that generally would not be subjected to intensive forest management. These two sites were therefore probably more open and exposed to air flow and solar radiation than the reference Canadian forest fuel type.

The representivity of the RAWS to the two sampling sites could also have been a source of error, particularly at McLeans Island, where the sample site was 9 km from the location of the Christchurch Airport RAWS (used for FWI System calculations). It is possible that McLeans Island Forest may be more exposed to wind events (particularly from the NW) than Christchurch Airport. However, calculations of moisture content using under-canopy weather observations (for the hourly sampling) were less accurate than those derived from the nearest RAWS. As discussed, this could be due to inadequate calculation of response rates for these fuels.

RECOMMENDATIONS

From a fire management perspective, these results indicate that the standard FWI System codes and indices calculated at noon most likely do not reflect actual conditions within New Zealand pine forests around 1600 hours, as the system is designed to do. It would probably be more appropriate to use forecasted weather conditions to calculate an hourly FFMC output for 1600 hours each day. The FX-scale of the FFMC is quite clearly not appropriate for plantation forests in Canterbury.

Further research is required to improve the applicability of the FWI System to New Zealand pine plantations. This is because the study was only based on two forest sites in Canterbury, and the results found may not be applicable to the entire country. However, the findings suggest that the fuel moisture codes of the FWI System may not be performing adequately for accurate fire danger assessment in New Zealand plantation forests. Recommendations are presented below to ensure that the FWI System can be applied reliably to this fuel type in New Zealand.

- Extend this study to include a broader range of plantation forests across New Zealand. This could include plantations of species other than *Pinus radiata*, and should include a range of soil types, fire climate zones and plantation management practices (i.e., pruning, thinning, stocking rates, etc.). This would also allow the effect of soil type on the DC and DMC to be explored, as previously recommended by Pearce and Whitmore (2009).
- Determine the response times (drying and wetting rates) of fine fuels in pine plantations, using experiments under controlled conditions in an environmental chamber and through extensive field data collection. This will indicate whether the FFMC equations require adjustment to more accurately model drying and wetting of these fuels. This adjustment could be carried out for both surface and elevated fuels.
- Review existing literature to determine the rainfall interception rates by forest canopies under different silvicultural regimes and different age classes. If sufficient knowledge of rainfall interception cannot be gained from existing work, then a comprehensive field study to explore these interception rates should be considered.
- Studies could also be undertaken to compare weather conditions under the forest canopy to those observed in the open (and as currently measured by RAWS on the fire weather network). Developing models to accurately predict under-canopy weather from RAWS observations in the open may result in more accurate assessments of fire danger conditions in forest fuels.
- Physical modelling of moisture content in forest fuels (e.g. using the process-based model of Matthews, 2006) could also be explored as an alternative to the current FWI System.

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