Preliminary analysis of soil moisture data collected by the Fire Weather System weather station network

Preliminary analysis of soil moisture data collected by the Fire Weather System weather station network

H.G. Pearce, L. Rossignaud & S. Aguilar-Arguello

www.scionresearch.com

Fire and Emergency New Zealand Research Report Number #204
ISBN Number 978-1-92-728769-9
ISSN Number 2703-1772

This research was commissioned by Fire and Emergency New Zealand and undertaken by independent researchers. Publication does not indicate Fire and Emergency New Zealand's endorsement of the findings or recommendations.

REPORT INFORMATION SHEET

REPORT TITLE	Preliminary analysis of soil moisture data collected by the Fire Weather System weather station network
AUTHORS	H.G. Pearce, L. Rossignaud, & S. Aguilar-Arguello (Scion)
CLIENT	Fire and Emergency New Zealand
CLIENT CONTRACT NUMBER	NP2625 (Improving Predictive Services Capability)
PAD OUTPUT NUMBER	36337044
SIGNED OFF BY	Veronica Clifford
DATE	July 2021
CONFIDENTIALITY REQUIREMENT	Confidential (for client use only)
INTELLECTUAL PROPERTY	© New Zealand Forest Research Institute Limited. All rights reserved. Unless permitted by contract or law, no part of this work may be reproduced, stored or copied in any form or by any means without the express permission of the New Zealand Forest Research Institute Limited (trading as Scion).
DISCLAIMER	The information and opinions provided in the Report have been prepared for the Client and its specified purposes. Accordingly, any person other than the Client uses the information and opinions in this report entirely at its own risk. The Report has been provided in good faith and on the basis that reasonable endeavours have been made to be accurate and not misleading and to exercise reasonable care, skill and judgment in providing such information and opinions. Neither Scion, nor any of its employees, officers, contractors, agents or other persons acting on its behalf or under its control accepts any responsibility or liability in respect of any information or opinions provided in this Report.

PUBLISHED BY: Scion, Private Bag 3020, Rotorua 3046, New Zealand. www.scionresearch.com

Front cover image

Red tussock wetland looking northwest towards Cass, Slovens Stream near Lake Hawdon, Craigieburn Road, Canterbury.

Executive summary

Objective

This study sought to review data on soil moisture and soil temperature collected by Fire and Emergency New Zealand's (FENZ) network of fire weather stations, and to assess its applicability for improving determination of fire danger – in particular, dryness of sub-surface duff and soil organic layer fuels, and estimating grass fuel moisture, seasonal curing and grass fuel loads.

Background

Harvest Electronics weather stations within FENZ's national weather monitoring network began collecting data on soil moisture and soil temperature in 2016, and more comprehensively from mid-2018. However, no formal analysis has previously been undertaken of the accuracy of the data being collected, or of its usefulness for aiding the tracking of seasonal fire danger and fuel hazard conditions.

Methods

Analyses were undertaken as to the number of stations, length of record and data quality of soil moisture and temperature measurements contained within the FENZ dataset. Accuracy of the data being collected was also assessed through comparisons with alternative measurements of soil moisture for several station locations. Graphical and statistical correlations were also made against corresponding weather observations and Fire Weather Index (FWI) System components for a selection of the available stations. A literature review was also carried out on the potential for use of the collected soil moisture and temperature data in the development of predictive models for grassland fire hazard, including grass fuel moisture, seasonal curing and fuel loads.

Results

Soil moisture and temperature data were available for a total of 138 weather stations, representing over half the entire Fire Weather System (FWSYS) network, with current measurement locations being generally well spread across the country. Data records archived in the FWSYS database start in April 2018, with 125 stations beginning recording during 2018, 7 in 2019, 5 in 2020, and the remaining one associated with a newer station installation during 2021.

All Harvest stations have a high daily soil measurement frequency, with most recording every 10 minutes, and the rest slightly less frequently (every 30 mins). This would appear to be excessive given that soil moisture changes only slowly in the absence of rainfall, but is tied to the higher reporting frequency required for other weather elements (air temperature, humidity, wind speed and direction, and rainfall) being measured by the stations.

Quality of the Harvest station soil observations is very good. There were very few gaps in recording (hypothesised to be associated with communications errors) and only very minor data irregularities observed, the latter at just a small number of stations (which appear to be associated with rounding of measured values to whole numbers, as opposed to decimal places).

The range of values observed also appears reasonable, with measured soil moistures ranging from 1%-89% and soil temperatures from -4 °C to +36 °C. Accuracy also compares well against NIWA data from nearby stations, with variances found likely to be associated with different sensor types and measurement depths. The rapid response of measured soil moistures to the occurrence of rainfall observed in the FWSYS data likely reflects the shallower installation depth of the Harvest sensors (10 cm) compared to NIWA soil moisture measurements (most at 20 cm). Similarly, the high maximums for measured soil temperatures in the FWSYS data and strong correlation with air temperatures are also indicative of shallower sensor depth.

Application

The use of soil moisture data holds much promise, both in relation to validation and improvement of the accuracy of FWI System components such as the Duff Moisture Code (DMC) and Drought Code (DC), but also for assessment of grassland fire hazard including grass curing, fuel moisture and grass fuel loads. More research is required to understand whether the best option is to obtain these soil moisture estimates from direct weather station measurements such as those being collected at fire weather stations, or from remote sensing (from satellites) or Land Surface Models, or some combination of these. However, soil moisture observations obtained from soil sensors at weather stations will still be required to provide the data to underpin the research to develop these solutions for fire danger rating (as determined by DMC and DC) and for grassland fire hazard, and to validate the data obtained from other sources.

Considerable further research is required to progress each of the potential fire danger and grass fire hazard applications, with the report outlining a number of recommendations as to how they might each be achieved. In terms of priority, the potential to significantly improve grass curing assessment warrants this application being investigated first, followed by pasture fuel load modelling, then grass fuel moisture estimation. The availability of existing satellite grass curing algorithms for New Zealand, and simple pasture productivity models for predominant pasture types, suggests these can be achieved comparatively easily, whereas grass fuel moisture modelling is likely to be more complex due to the effects of grass species and seasonal variability (curing). The development of an operational platform for presenting grass curing data could also form the basis for a more comprehensive New Zealand fuel flammability system that could later incorporate grass fuel load and moisture content data as these components were developed (and potentially for other fuel types and soil moisture as well). However, key to this is the availability of accurate and regularly updated spatial data on New Zealand vegetation and associated properties (including soil types) so that grass fuel types can be distinguished from other fuel types and the appropriate models assigned. Similarly, a field sampling programme will be needed to collect data to validate the grass curing satellite methodology. Where possible, this should also include regular collection of additional samples and other required data for grass fuel moisture and fuel load, so that solutions for these applications can also be developed and tested either sooner or at some point in the future.

Preliminary analysis of soil moisture data collected by the Fire Weather System weather station network

H. Grant Pearce, Laureline Rossignaud & Samuel Aguilar-Arguello

Scion, Rural Fire Research Group, Christchurch

February 2022

Table of Contents

List of abbreviations

AFMS	Australian Flammability Monitoring System (http://anuwald.science/afms)
AWS / Aws	automatic weather station (usually MetService), lower case version is used in station names within CLIDB and FWSYS
BUI	Buildup Index component of the FWI System
CLIDB	National Climate Database, maintained by NIWA and accessed through a web app called CliFlo (https://cliflo.niwa.co.nz/)
CWS / Cws	compact weather station (NIWA), lower case version is used in station names within CLIDB
DC	Drought Code component of the FWI System
DMC	Duff Moisture Code component of the FWI System
DSR	Daily Severity Rating, a measure of the severity of daily fire weather conditions derived from the FWI value
EVI	Enhanced Vegetation Index, one of many remotely sensed spectral vegetation indices (similar to the NDVI)
EWS / Ews	environmental weather station (usually NIWA), lower case version is used in station names within CLIDB and FWSYS
FAW	fraction of available water capacity, a measure of soil moisture status relative to a soil's water retention capacity derived from soil properties (field capacity and wilting point) and measurements or remote sensing estimates of soil moisture content
FENZ	Fire and Emergency New Zealand
FFMC	Fine Fuel Moisture Code component of the FWI System
FMC	fuel moisture content
FWI System	Fire Weather Index System, a module of the Canadian and New Zealand fire danger rating systems
FWI	Fire Weather Index component of the FWI System
FWSYS	Fire Weather System, the database and associated application (EcoConnect) and website (https://fireweather.niwa.co.nz/) managed by NIWA on behalf of FENZ
GVMI	Global Vegetation Moisture Index, a remotely sensed measure of vegetation water content
Harvest	Harvest Electronics Ltd (see Harvest.com)
ISI	Initial Spread Index component of the FWI System
JULES	Joint UK Land Environment Simulator, developed in the UK Met Office and used in New Zealand by NIWA
KBDI	Keetch-Byram Drought Index, an index of soil drought status estimated from temperature and rainfall used in the U.S. and Australia (Keetch & Byram, 1968)
LM	linear models, statistical regression method that finds an equation that describes a straight-line relationship between two quantities that show a constant rate of change
LMM	linear mixed models, statistical regression method that extends simple linear models to allow both fixed and random effects, which are particularly used when there is non-independence in the data

MetService	Meteorological Service of New Zealand
NDI	Normalized Difference Index, one of many remotely sensed spectral vegetation indices (similar to the NDVI)
NDVI	Normalised Difference Vegetation Index, a remote sensing index that describes the difference between visible and near-infrared reflectance of vegetation cover
NIWA	National Institute of Water and Atmospheric Research
RAWS / Raws	remote automatic weather station (commonly used with FENZ stations), lower case version is used in station names within CLIDB and FWSYS
RVI	Ratio Vegetation Index, one of many remotely sensed spectral vegetation indices (similar to the NDVI)
SAVI	Soil Adjusted Vegetation Index, a remote sensing vegetation index that accounts for reflectance from soil
SDI	Soil Dryness Index, an index of soil dryness estimated from temperature and rainfall used in Australia (after Mount, 1972)
TDR	time domain reflectometry method of soil measurement, made using probe-type sensors
TDT	time domain transmissometry method of soil moisture measurement, made using closed loop-type sensors
VOD	Vegetation Optical Depth, a remote sensing vegetation index that accounts for vegetation moisture content and structure
VIN	Vegetation Index Number, one of many remotely sensed spectral vegetation indices (similar to the NDVI)
VPD	Vapour Pressure Deficit, a measure of the drying power of the air, similar to humidity, that specifically describes the actual pressure difference (in units of pressure) between the air in its current moisture state and when fully saturated

Introduction

Soil moisture and temperature are important factors affecting plant growth. In the case of pasture grasses especially, these soil factors play a critical role in controlling the seasonal changes occurring in grassland productivity, along with sunlight and nutrient supply. These changes can affect fire risk, with low soil moisture availability causing plant stress and wilting which reduces the moisture content of live fuels, or even death which converts live vegetation to dead fuel (curing) that is easier to ignite. On the other hand, increased soil moisture can promote vegetation growth, increasing the amount of fuel available to burn and potentially resulting in more intense fires.

Weather stations on the Fire Weather System (FWSYS) network began collecting observations of soil moisture and temperature around 2016, but it was not until mid-2018 that these data started to be recorded within the system. This began with the installation of soil moisture sensors on the (at that time) relatively new Harvest Electronics weather stations, initially in the Marlborough and South Canterbury regions, followed by Wairarapa and Southland, and now extending to most Harvest stations across the country. In total, 138 stations collected observations of soil moisture and temperature when this analysis was undertaken (May 2021).

The Harvest weather stations initially used Acclima time domain transmissometry (TDT) closed loop-type sensors (Fig. 1a; also see https://www.youtube.com/watch?v=LAknnS3411I). However, over time these have been replaced by Acclima time domain reflectometry (TDR) probe-type sensors (Fig. 1b; also see https://www.youtube.com/watch?v=e9wZchyKgoQ). The TDR probe sensors are considered more accurate and easier to install, as it can be difficult to ensure complete soil contact avoiding air gaps within the TDT sensor loop (Harvest, 2019). Both Acclima sensor types measure volumetric water content (the volume of soil water present expressed as a percentage of the total volume of water, air and soil). They also include inbuilt soil temperature measurement (°C) which, in addition to providing additional useful information in its own right, is used to correct soil moisture for soil temperatures changes. A key advantage of the TDR and TDT sensors is that they do not require calibration for different soil types (e.g. bulk density and salinity) as is the case for most other sensors (e.g. capacitance-type). Probes are typically buried at soil depths of 10-15 cm (see Fig.1).

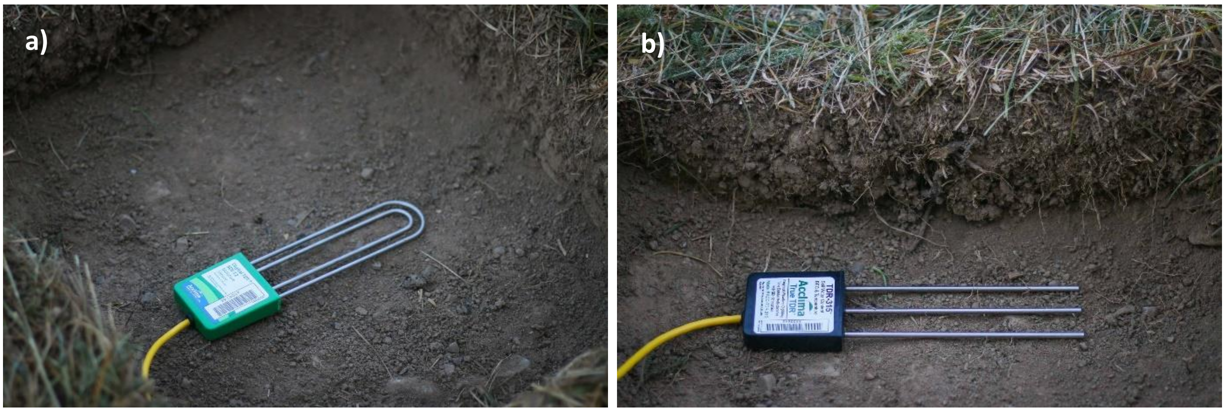


Figure 1: Soil moisture sensors used with the Harvest weather stations: **a)** Acclima SDI-12 TDT 'loop' sensor, and **b)** Acclima 310/315H TDR 'probe' sensor. (Images courtesy of Harvest Electronics, http://harvest.com/gallery/).

Project Scope

Despite the availability of soil moisture data from the FWSYS network for several years, no previous analysis has been undertaken to assess the usefulness of this information to aid fire danger monitoring. This study therefore sought to achieve the following aims:

- Review the available data on soil moisture and temperature contained within the Fire Weather System (FWSYS) database;
- Analyse the soil moisture data to determine relationships with fire danger ratings, especially dryness of sub-surface duff and soil organic layer fuels represented by the Fire Weather Index (FWI) System's Duff Moisture Code (DMC) and Drought Code (DC) components; and
- Review what options exist for use of the data to improve the New Zealand Fire Danger Rating System through the development of:
    - Grass curing prediction
    - Live fuel moisture prediction model(s)
    - Grass growth fuel load modelling

Methods

The analyses carried out consisted of six key steps:

1. Combining of FWSYS soil measurements from all available stations into a single dataset and assessment of dataset quality for further analysis (determination of observation frequency, and calculation of daily, monthly and yearly means and ranges of values for each station);
2. Updating of dataset by including station location, weather and FWI System information, and determination of the coverage of the dataset across New Zealand;
3. Identification of suitable stations for exploring correlations with FWI System values;
4. Identification of co-located NIWA soil moisture stations, and assessment of the accuracy of FWSYS soil moisture measurements against NIWA data;
5. Investigation of the correlations between measured soil moistures and temperatures and recorded weather and FWI System values;
6. Brief literature review and summary of recommendations on applicability of soil data for grass fire hazard monitoring (e.g. grass fuel moisture, seasonal curing, and grass fuel loads).

Assessment of the suitability of FWSYS soil measurements

The measurements of soil moisture and temperature contained within FWSYS have been captured by a subset of the Harvest stations that form part of the fire weather monitoring network across New Zealand. For the most part, these records date back to April-June 2018 and extend up to the present time (2021). However, measurements started to be collected at different dates and with different recording frequencies that vary through time for each station (see Appendix 2).

The records from 138 stations were used to assess the suitability of the soil measurements for further analysis. Each station provided a series of dates and observation times with associated measurements for both soil moisture (in percentage) and soil temperature (in °C). All recorded observations from all the stations with soil data were combined into a single dataset and summarised using the R software version 3.5.1 (R Development Core Team, 2018). Daily observation frequencies (e.g., every hour, 30 min or 10 min) and length of record, as well as daily and monthly averages and extremes (min and max values) were calculated for each station. Monthly averages of soil moisture and temperature were used for an initial assessment of the variability between stations, whereas daily averages were used for more detailed investigation such as the detection of anomalies or gaps within the records. However, it should be kept in mind that the variability of length and observation frequency for a particular station may influence the accuracy of the averages calculated.

A Master Sheet document was developed with key IDs for each station (i.e., id, station name, NIWA ID, type of measurement) and was combined with the soil measurements dataset using the station ID number as a reference (e.g., CliDB-ND fwsys_soil_moisture+CLIDB_39729.csv).

Weather and FWI datasets

A parallel study to this one, carried out by Scion in collaboration with FENZ, has involved the updating of fire weather datasets for stations across New Zealand. At the time this soil moisture analysis was undertaken, this fire climatology study had resulted in weather data updates to some 153 stations representative of all regions of the country, although data checking and FWI System recalculation was still ongoing. In some cases, stations have been replaced over time by alternative sources (e.g. MetService sites replaced by Harvest or NIWA stations), meaning that the resulting long-term datasets for some locations can consist of data obtained from different stations in similar or nearby locations for different time periods but with different instrumentation (e.g. sensor types or mast heights).

In order to ensure completeness of the associated weather records by location, the climatology analysis includes datasets for fire remote automatic weather stations (RAWS) retrieved from the FWSYS managed by NIWA for FENZ, together with data from additional Meteorological Service of NZ Ltd (MetService) and NIWA stations. Daily synoptic (3-hourly AWS) data for MetService stations dating back to 2011 (when the climatology dataset was last updated; Pearce et al. 2011) was provided directly by MetService. The NIWA data includes additional EWS (as well as some Regional Council and further MetService synoptic station) sites not currently contained within the FWSYS, for which data can be accessed through the National Climate Database (CLIDB; https://cliflo.niwa.co.nz/). A key part of the latest fire climatology update has therefore involved more rigorous checking of data consistency for all stations and especially where these station data amalgamations have occurred (see Pearce et al., in prep).

From the 153 stations for which weather data has been updated, 87 have had quality checking and recalculation of FWI System values completed. These all have a minimum data length of 18 years (from first day of record to 1st July 2020). Each of these datasets (stations) contain reliable and uninterrupted daily data of:

1) *Weather variables*: These are daily observations made at noon (12 pm) New Zealand Standard Time (NZST) (or 1 pm Daylight Time) of temperature (°C), relative humidity (%), wind speed (km/h), and 24-hour accumulated rainfall (mm, from 12:01pm of the previous day to 12:00pm of the current day). Station datasets have been updated to fill gaps of missing data, and to correct errors and inconsistencies.
2) *Recalculated FWI System values:* Based solely on these weather observations, the FWI System codes and indices provide numerical ratings of fuel dryness, and relative ignition and fire behaviour potential which are used to guide fire management activities (Scion & NRFA, 2014; Anderson, 2005). The FWI System outputs comprise daily values of the Fine Fuel Moisture Code (FFMC), Drought Code (DC), Duff Moisture Code (DMC), Initial Spread Index (ISI), Buildup Index (BUI), Fire Weather Index (FWI), and Daily Severity Rating (DSR) (as well as fire danger class frequencies for Forest, Grassland and Scrubland fuel types which were not used here) for each station that have been recalculated based on corrected weather inputs.

Mapping of the FWSYS soil moisture stations

To further explore the dataset suitability, several variables of interest from the weather and FWI System dataset were added to the soil moisture data. The station ID and code, location (coordinates, island, region, area), beginning and end (if not ongoing) of weather data collection, and availability of weather data and FWI System values were associated with each station. The extreme values of soil moisture and soil temperature were assessed for each region, as well as the number of stations per region (see Table 1).

The locations of the 138 stations with soil moisture data were projected on a map using ArcGIS Desktop version 10.6.1 (Fig. 2), with symbolism being used to show the number of observations or data length for each station (red circles indicate stations with 10-min observations for almost the full period from August 2018 to May 2021, and blue circles indicate shorter records &/or less frequent observations; see Fig. 3 for more details). From the station locations, it is apparent that stations with available soil moisture data provide reasonable coverage across the country. A focus was also put on those stations which also had available FWI System data (see Fig. 3).

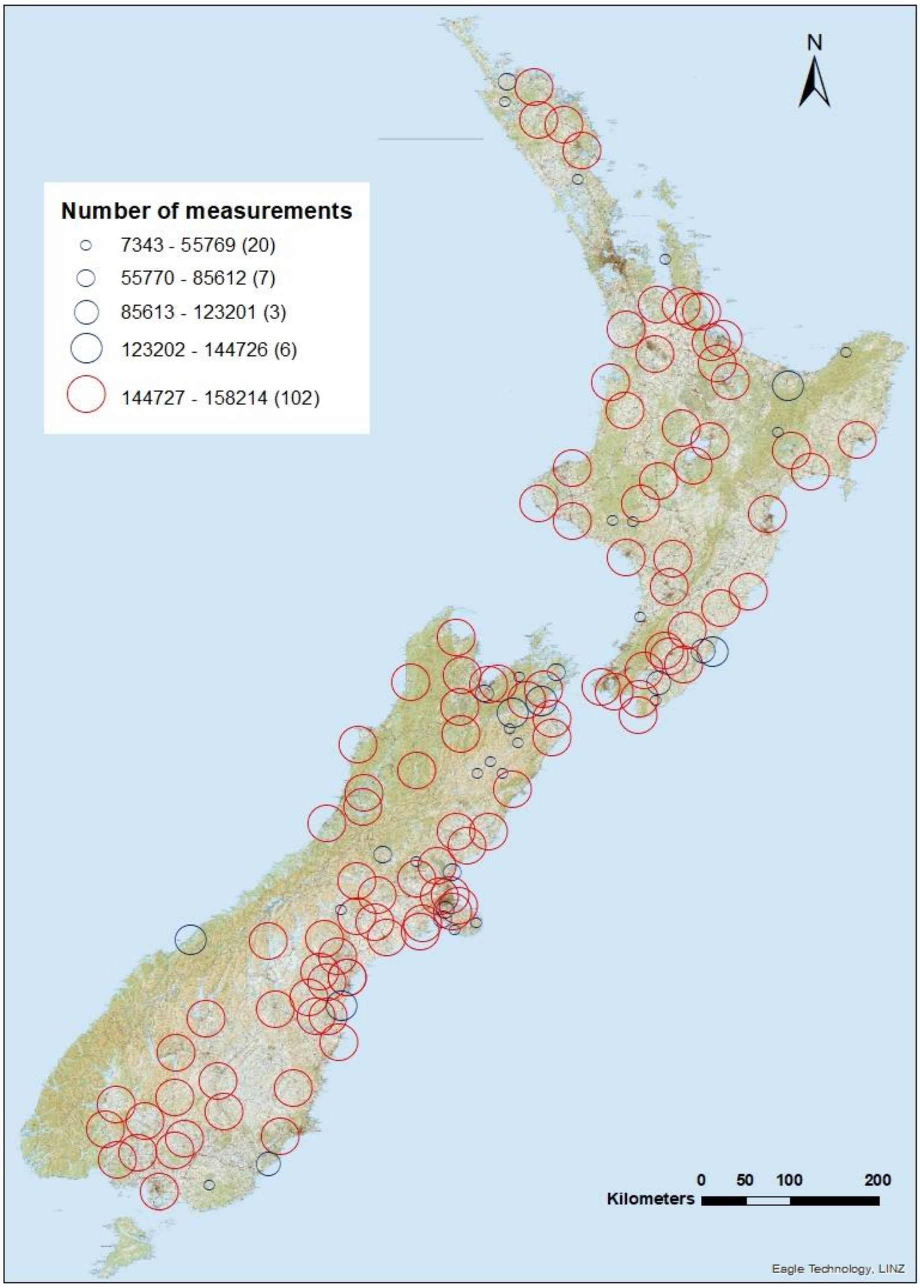


Figure 2: Locations and number of observations of soil moisture/temperature for stations from the Fire Weather System (FWSYS) monitoring network. Red circles indicate stations with 10-min observations for almost the full period from August 2018 to May 2021, and blue circles indicate shorter records &/or less frequent observations.

Correlation between soil moisture data and FWI System values

The correlation between soil moisture and FWI System or weather values at each of the 18 stations with available verified FWI data was tested using regression techniques by performing both linear models (LM) and linear mixed models (LMMs) with the “lme4” package (Bates et al., 2015) in R software. All stations with soil moisture data have corresponding FWI data, but these had not all had their weather data quality checked and FWI System values re-calculated at the time of this analysis. While the subset of stations used in this correlation modelling is relatively small (13%), it is still considered to provide representative results indicative of correlations present.

Models were run predicting daily mean soil moisture from daily rainfall, air temperature, FFMC, DMC, DC and BUI. A supplementary model was run predicting soil temperature from air temperature. For LMMs, date of measurement and station ID were included as random factors. Mixed models were checked for overdispersion using the “DHARMa” package (Hartig, 2020). The best models were selected using the Akaike Information Criterion (AIC; Sakamoto et al., 1986), model R^2 and the model selection function from the “MuMIn” package (Barton, 2020).

Figures showing the trends in monthly soil moisture and soil temperature as well as the relationships between daily soil moisture and FWI or weather values, and daily soil temperature and air temperature, were generated with R software using the “ggplo2” package (Wickham, 2016).

Accuracy of FWSYS soil moisture values

The ‘accuracy’ of the FWSYS measurements of soil moisture content obtained from the Harvest weather station sensors were assessed by comparing these with measurements made at NIWA soil moisture stations in close proximity.

Harvest stations on the FWSYS network initially used Acclima TDT closed loop-type sensors, but over time these have been replaced by TDR probe-type sensors (see Fig. 1) which are considered to be more accurate and easier to install. Both Acclima sensor types include inbuilt soil temperature measurement, with probes typically being buried at depths of 10-15 cm.

Several locations were identified where NIWA observations were made within 10 km of a Harvest station with soil moisture observations. These were typically NIWA environmental weather station (EWS) or compact weather station (CWS) types. EWS stations have typically used TDR-like Aquaflex ribbon-type sensors, which are often considered better than probe-type sensors because they measure soil moisture content across a larger volume and depth of soil (see https://www.aquaflex.co.nz/applications). CWS stations, on the other hand, are more likely to use TDT closed loop-type sensors. In both cases, hourly measurements are indicative of soil moisture at a depth of about 20 cm. However, more recently NIWA have been changing to multi-depth capacitive sensors (EnviroPro, see https://enviroprosoilprobes.com/).[1]

Data from the NIWA and Harvest stations were compared both graphically and using correlation statistics.

---

[1] Graham Elley & Andrew Harper, NIWA, pers. comm.

Review of applicability of soil measurements for grassland fire hazard prediction

A brief literature review was also conducted to assess the potential for improvements to be made in the monitoring of grassland fire hazard using the additional information provided by soil moisture and temperature observations. This focussed on three key areas:

1) Seasonal grass curing assessment;
2) Grass fuel moisture prediction; and
3) Prediction of pasture growth, especially estimation of changes in grass fuel loads.

The starting point for this review was the previous evaluation of grass curing assessment methods undertaken for FENZ by Clifford et al. (2018).

Results and Discussion

FWSYS soil observation dataset description

The dataset obtained from FWSYS contains information on soil moisture content (%) and soil temperature (°C) for stations located across all regions of New Zealand (see Fig. 2). Of the 141 stations, 138 stations have substantial soil measurement data, with the remaining 3 only being installed more recently and therefore having only very short records (of just a month or so) (see Appendix 2). From the 138 datasets for those stations with longer term records, 125 stations have data starting in 2018 up until present (May 2021), and the rest start in 2019 (7), 2020 (5) or early 2021 (1) through until present (see Fig. 3). Of these, 121 stations have a length of record capturing three complete fire seasons[2] (from June 2018 to May 2021), 7 contain data for two complete fire seasons (June 2019 to May 2021), and 10 stations have one fire season (June 2020 to May 2021) or less. However, in terms of full calendar years[3], 125 stations have data for two full years (2019-2020) and 7 stations one full year (2020), with the remaining 6 having less than one full year of data.

The observation frequency at which this data has been captured varies greatly within a station, as well as among the different stations. Data has been collected at different observation intervals from every 1 min to 10 min, 30 min or 60 min (hourly) and, as a result, datasets are inconsistent due to gaps (intervals without measurements) or changes in interval length (interval often changes more than once within a station's data). For example, 24 stations have two different interval lengths, and one station (Haast Junction Raws, CLIDB 43205) has the four different intervals within its dataset. Thus, the frequency of the records (interval length) and the length of the record directly affects the number of observations per station (see Fig. 2, and Appendix 2). Despite these inconsistencies, the datasets contain enough data to represent daily, or even hourly, values. Some 18 stations have at least 100 days of consistent recorded data on a 30 min interval, and 113 stations have at least 100 days of consistent 10 min data.

Stations with soil moisture and temperature data show good coverage across most areas of the country, with the exceptions of the Auckland and southern West Coast regions, and mountain regions of the eastern North Island and inland North Canterbury (see Figs. 2 & 3). By region, Canterbury (north and central) has the greatest number of stations, followed by Mid-South Canterbury, Marlborough, Southland and Wairarapa (see Table 1). Incidentally, these regions were the first to change to the Harvest weather stations, as well as being some of the largest by area, so these regions having the most stations is not surprising.

Observed range of FWSYS soil moisture and temperature data

Table 1 contains a summary of the ranges in observed values for both soil moisture and soil temperature at stations in each region of the country. These show that soil temperatures range from just below zero (-4 °C in Taranaki, and -0.5 °C in Mid-South Canterbury) to over 30 °C (33.3 °C in Nelson, and 35.7 °C in Marlborough). Measured soil moisture values range from over 50% in all regions and almost 90% for Otago and Southland, to practically completely dry (just 1%).

---

[2] One fire season in New Zealand includes data from October 1st of a specific year to April 30th of the following year.

[3] A full calendar year includes data capturing the full period from January 1st to December 31st of the same year.

Table 1: Summary of ranges in observed soil moisture (%) and soil temperature (^{o}C) values for stations by region of the country.

		Soil Moisture (%)		Soil Temperature (^{o}C)		No. of
Island	**Region**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**stations**
North Island	Northland	65	1	30	0	7
	Waikato	57	7	31.6	0	8
	Bay of Plenty	60	4	29	0	7
	Central North Island	63	5	27.9	0	4
	Taranaki	68	15	30	-4	4
	Wanganui-Manawatu	71	6	30	0	9
	East Coast/Hawkes Bay	61	6	30	0	5
	Wairarapa	75	4	26.1	0	10
	Wellington	50	14	21.8	0	2
South Island	Nelson	53	3	33.3	0	7
	Marlborough	54	1	35.7	0	14
	Canterbury	60	1	30	0	19
	Mid-South Canterbury	85	1	30.1	-0.5	16
	West Coast	61	6	26.5	0	7
	Otago	88	1	32.7	0	9
	Southland	89	1	25.8	1	10
All of New Zealand		**89**	**1**	**35.7**	**-4.0**	**138**

Weather and FWI datasets

While assessing FWI System datasets available from the fire climatology update study for comparison with the soil moisture and temperature datasets being analysed here, we found a low number of compatible weather stations (just 18). This was due to the fact that despite fire weather data being available for all Harvest stations for which soil measurements were available, the majority had not yet had their fire weather data quality checked and FWI values re-calculated at the time this analysis was carried out. Of those that had been through this process, only this subset had at least three full fire seasons of soil moisture data for comparison with verified FWI values.

Despite comparative data only being available for just a small subset of the weather stations (18 of 138, or 13%), these stations are latitudinally well spread across New Zealand. However, they are dominated by southern and eastern South Island locations, with only three stations in the North Island (Fig. 3). However, for the purposes of this initial scoping analysis, this subset of stations is considered large enough to observe trends between soil values and fire weather data.

Fire weather variables considered for correlations with observed soil moisture and temperature were Rainfall, Temperature, FFMC, DC, DMC, and BUI.

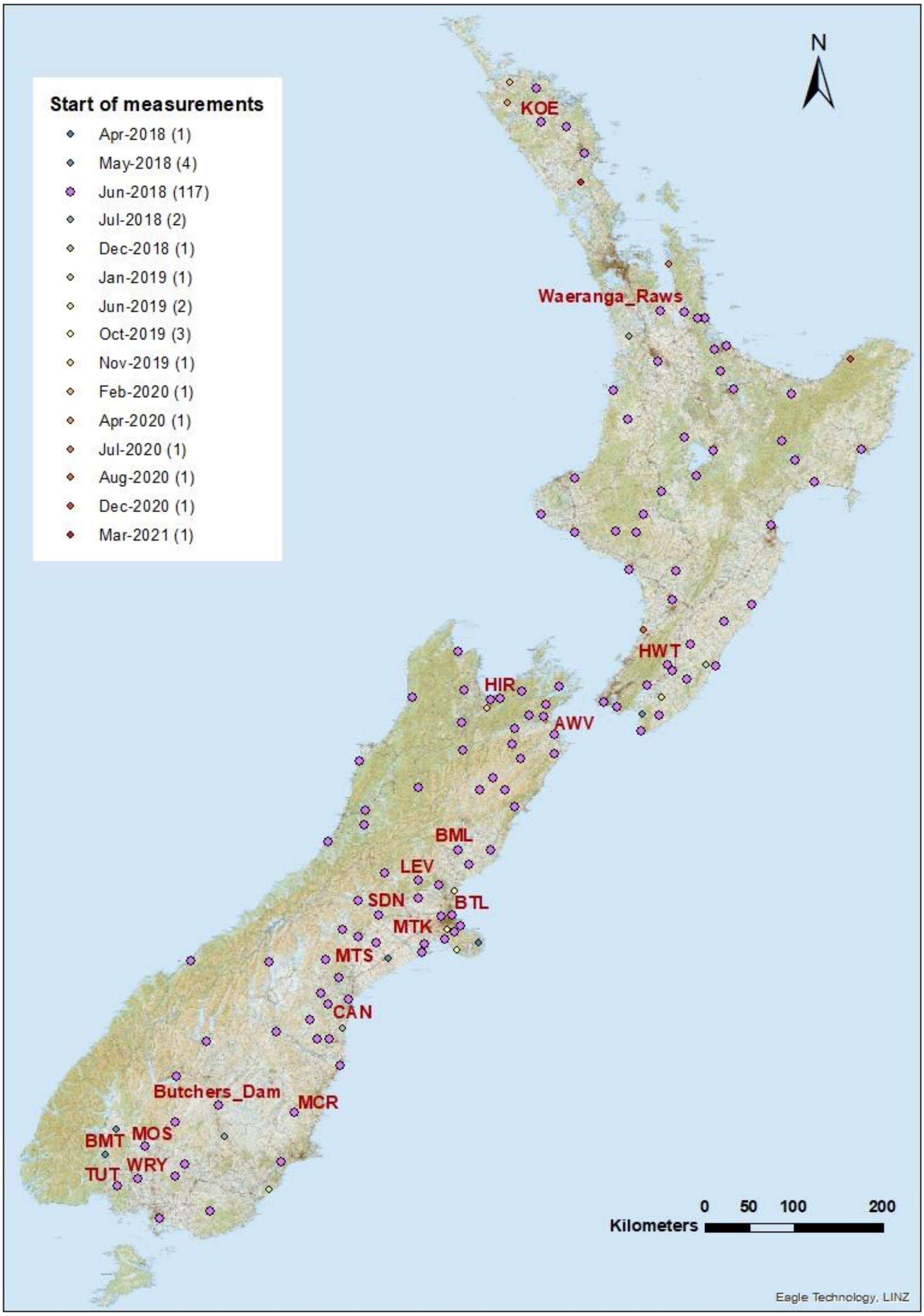


Figure 3: Locations of stations with soil moisture and soil temperature measurements available (N = 138). Start of measurements for each station are grouped and colour coded by month of the year. Stations with verified FWI data available are shown by their name or station code in red (KOE: Kaikohe, Waeranga Raws, HWT: Holdsworth Station, HIR: Hira, AWV: Awatere Valley, BML: Balmoral, LEV: Lees Valley, BTL: Bottle Lake Forest, MTK: Motukarara, SDN: Snowdon, MTS: Mount Somers, CAN: Cannington, MCR: Macrae's, Butchers Dam, MOS: Barnhill, BMT: Blackmount, TUT: Tuatapere, WRY: Wreys Bush).

Quality of FWSYS soil measurement data

To gain a general view of data reliability in terms of accuracy and consistency (such as gaps in data), graph plots of monthly average values of soil temperature and soil moisture were prepared (see Figs. 4 & 5). Grouping stations by region shows that stations exhibit similar seasonal trends in both soil moisture and soil temperature, with each of these showing inverse relationships. Specifically, soil moisture reaches its maximum values during the June-August period (winter) and lowest values during January-March (summer). In contrast, soil temperatures reach their peak during January-March, and lowest values in June-August. This trend is uniform throughout the three years of record (mid-2018 to mid-2021) and shows no significant outliers or periods without records across all 138 stations, although these will be less apparent in monthly averages (Figs. 4-5, also see Appendix 1, Figs. A1-A4) compared to the daily or continuous data plots.

Overall, data quality for the majority of stations was very good, with few apparent issues seen in plots of daily values. However, breaks in the continuous observations were seen in some cases as a result of both missing values and potentially erroneous data.

Example of likely data quality issues from the Nelson Raws station

As an example of potentially erroneous data, a specific case is presented for the Nelson Raws station showing an odd trend in the daily data record. The case occurred between January and March of 2019 (Fig. 6A). This station and observation period is of particular interest as it coincides with the Pigeon Valley wildfire (which began on 5th February 2019), a significant fire event for the region and nationally (also see Fig. 10 for timeseries plots of relevant FWI System values).

The irregular behaviour of the soil moisture trend over this period is characterised by an abrupt decrease in recorded soil moisture content which is followed by a period of constant values over time, then a further abrupt decrease followed by an abrupt increase in moisture content (see Fig. 6A). Comparisons with other stations in the region (Hira Raws and Big Pokororo Raws, Figs. 6B-C) show similar trends in soil moisture values, although the rates of change through time are smoother than observed for the Nelson Raws. Moreover, analysing the observed values in more detail, by plotting the moisture values over a shorter interval of 48 hrs and comparing them with five other stations from the same region (Fig. 7), shows that the abrupt decrease of 10% in soil moisture observed on the 8th February 2019 for the Nelson Raws happens in minutes (a single 10-min measurement period) whereas values at the rest of the stations were either constant or showed only minor variations (see Fig. 7A). At the time of the abrupt increase of soil moisture content (of ~6%) at the Nelson Raws on 8th March 2019, similar increases (with even greater rates of change) are also observed at the other stations (see Fig. 7B). In contrast to these erratic changes in soil moisture, soil temperatures do not show any irregularities throughout either period.

The behaviour of the soil moisture trend observed at the Nelson Raws and other stations for the latter period (see Fig. 7B) can be explained by the occurrence of significant rainfall across the region during those dates (50mm of rain recorded in 24 hrs at the Nelson Raws on 8th March 2019), which produced the dramatic increases in soil moisture observed (up to 25-30% in the case of St Arnaud and Western Boundary).

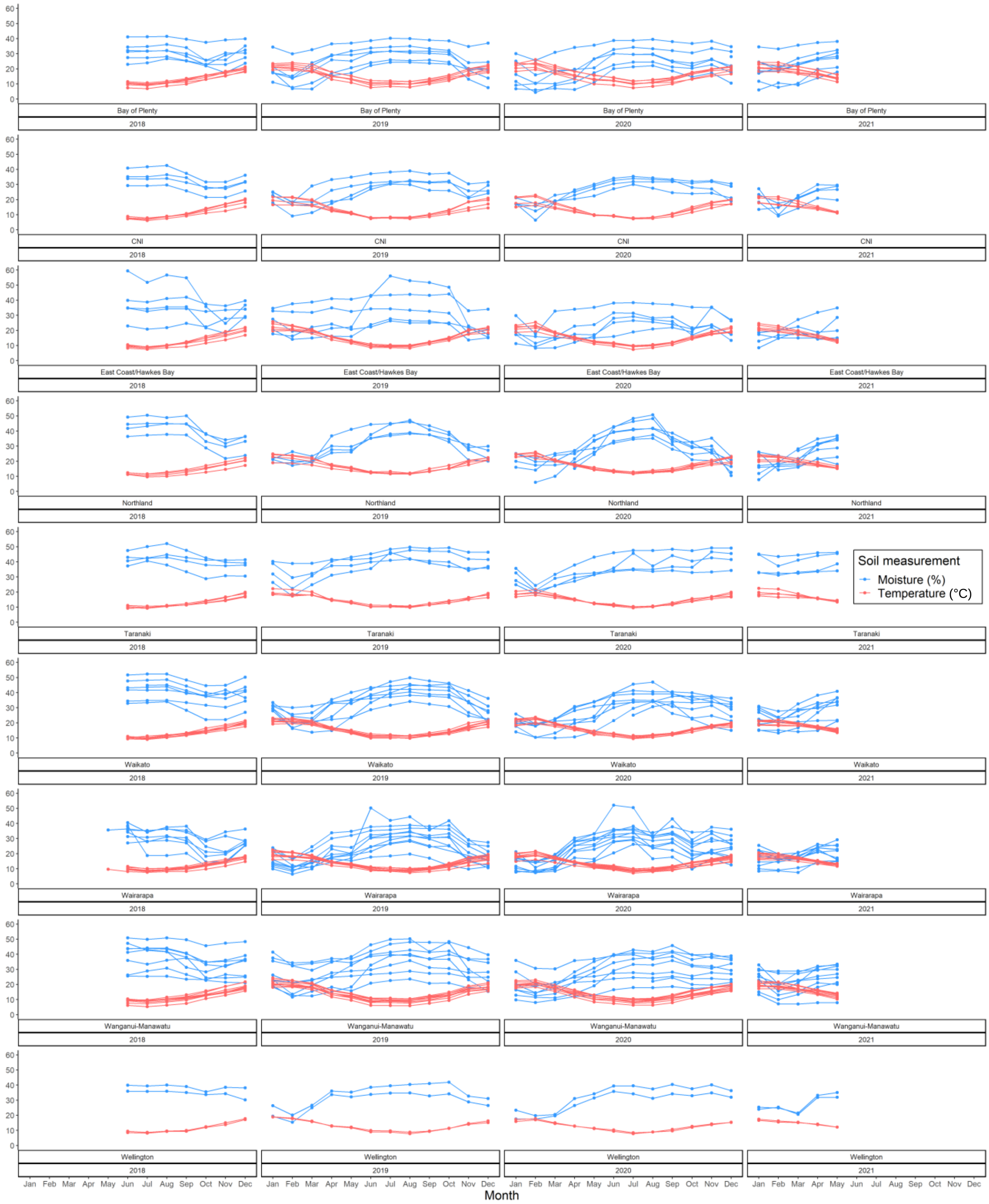


Figure 4: Monthly mean soil moisture content as a % (blue) and mean soil temperature in °C (red) from mid-2018 to mid-2021 for FWSYS stations by region of the North Island.

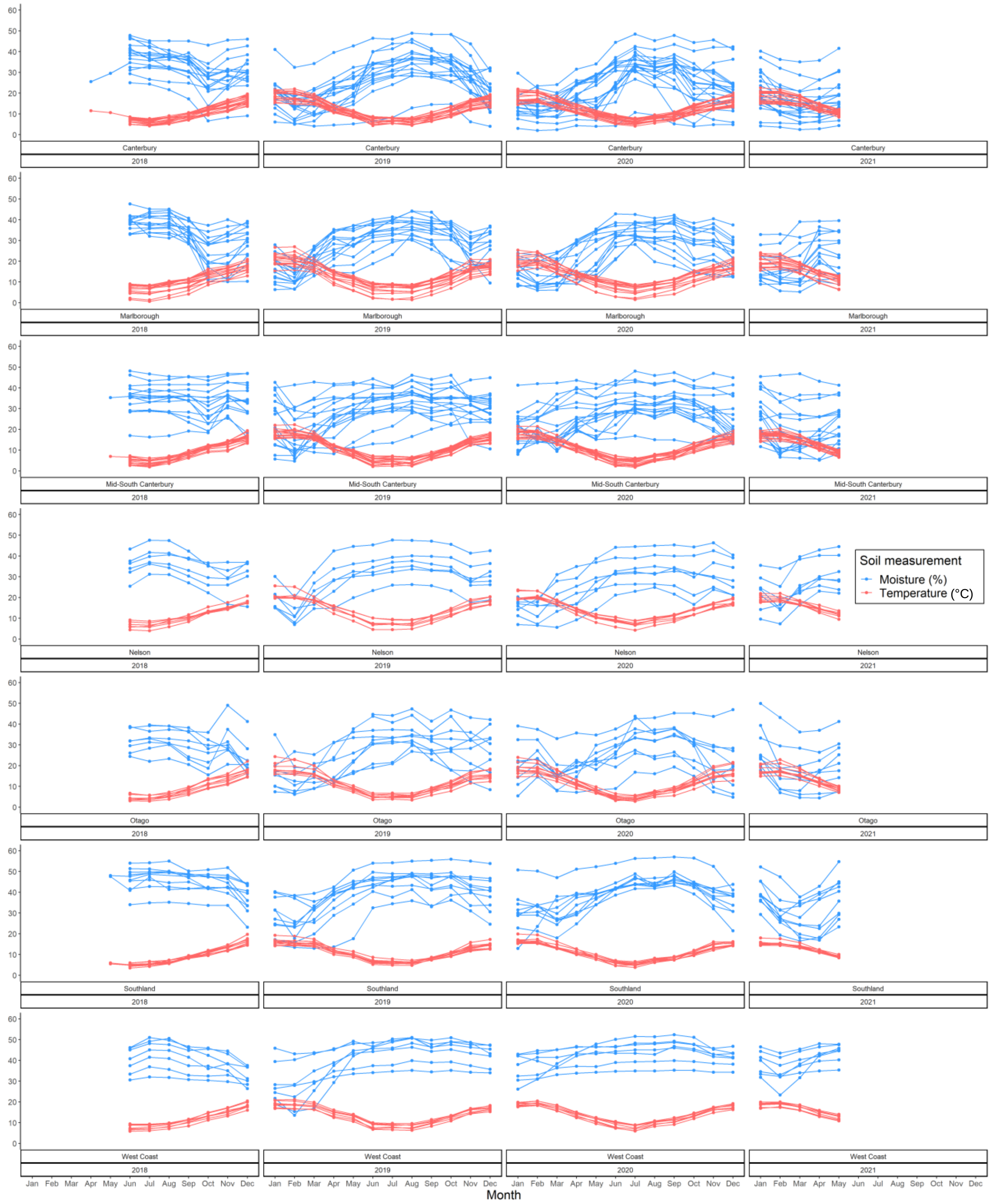


Figure 5: Monthly mean soil moisture content as a % (blue) and mean soil temperature in °C (red) from mid-2018 to mid-2021 for FWSYS stations by region of the South Island

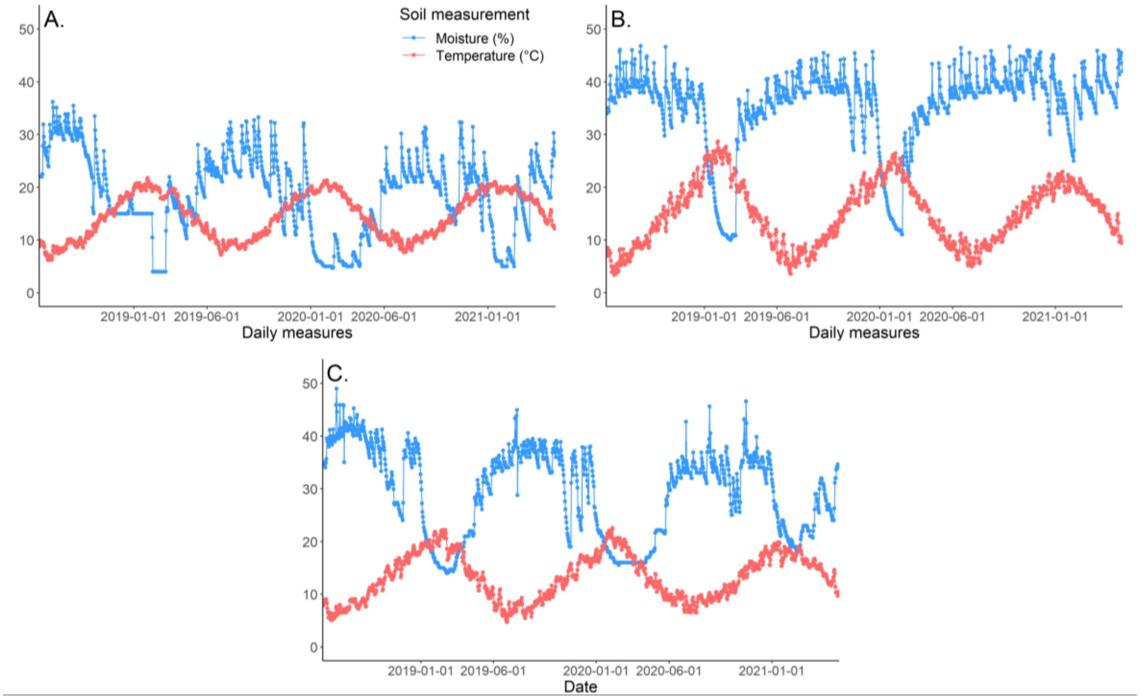


Figure 6: Trends in daily mean soil moisture as a % (blue) and soil temperature in °C (red) from FWSYS observations recorded at the: **A)** Nelson Raws, **B)** Hira Raws, and **C)** Big Pokororo Raws stations.

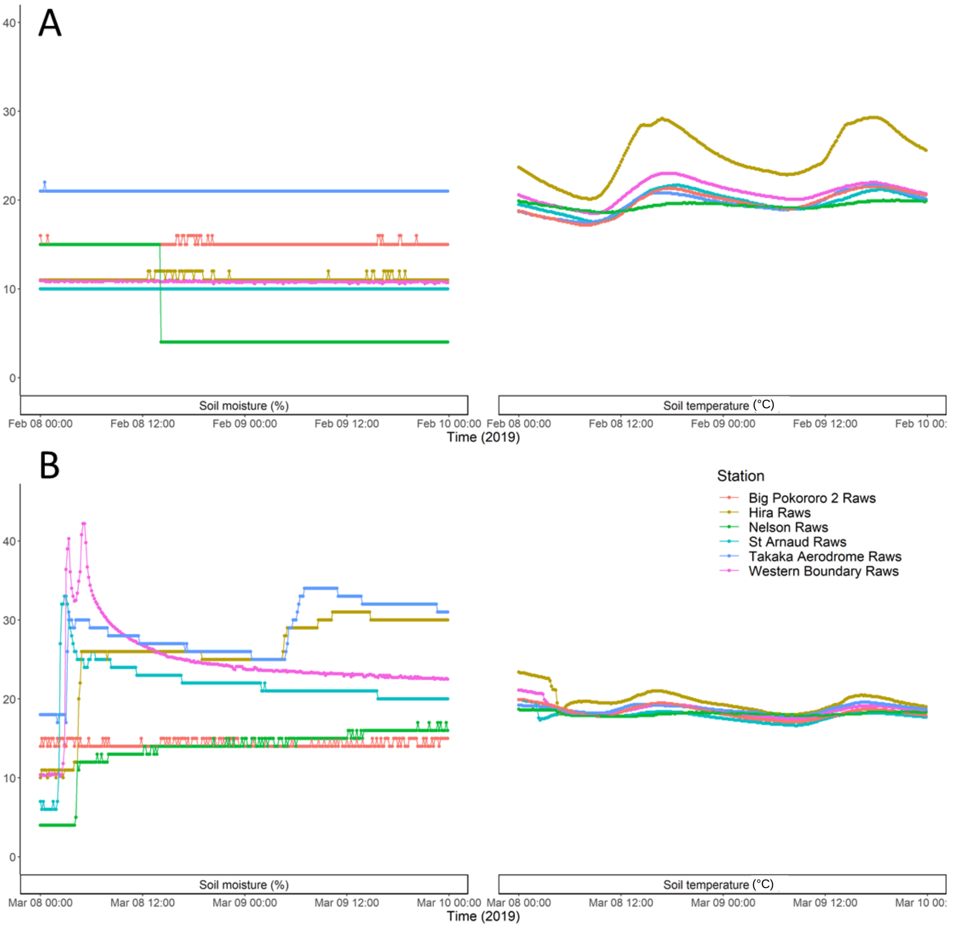


Figure 7: Detailed trends in soil moisture as a % (left) and soil temperature in °C (right) for FWSYS stations in the Nelson area for the periods: **A)** 8-10 February 2019, and **B)** 8-10 March 2019.

However, the abrupt decrease (of 10%) in soil moisture seen in the first period (on 8th February 2019; see Fig. 7A) is more problematic. While this did occur in the absence of rain prior to and at the time of occurrence, there is no particular reason why the soil moisture values should drop so significantly for Nelson Raws, especially when no similar changes are seen for other nearby stations. In this case, the observations demonstrate a possible problem with the sensitivity of the soil moisture sensor, possibly resulting from poor installation (e.g. air gaps around the sensor resulting in poor contact between it and the soil) or with its calibration. Observations of soil moisture from these and other periods for the Nelson Raws as well as other stations (as seen for example in Figs. 7A-B), especially during the early part of their records, also show the possibility of recorded values being affected by rounding or 'binning" to the nearest whole number (%), as opposed to continuous decimal values.

Nevertheless, these soil moisture values still seem sufficiently reliable as these react accordingly with the incidence of rainfall as well as drying periods, and are generally comparable with the records of nearby stations at equivalent times (see next section). They also have little to no affect in the subsequent analyses where values are averaged at the daily level for comparison with noon daily weather and FWI values.

Comparison of FWSYS and NIWA soil moisture observations

The accuracy of the measurements of soil moisture content obtained from the Harvest weather station sensors were assessed by comparing these with measurements made at NIWA soil moisture station locations in close proximity (Table 2). Four stations (Cheviot Ews/Raws, Tauranga Cws/Raws, Diamond Harbour Ews/Raws, and Hokitika Ews/Raws) were identified with NIWA observations made within 3 km of a Harvest station with soil moisture data, and another three stations (Wairau Valley Cws/Landsdowne Raws, Napier Ews/Raws and Whangarei Ews/Raws) within 5 km. A further nine stations were identified within a range of 5-25 km of Harvest stations with soil moisture observations but were not used in the comparison here due to being considered too distant and the potential for soil types to be different.

Comparisons for the seven NIWA stations identified within 5 km of the adjacent Harvest stations are shown in Figs. 8 & 9. Soil moisture information for these seven NIWA weather stations was retrieved from CLIDB for comparable timelines. Here, the earliest data acquired was for 11th June 2018 to coincide with the beginning of the FWSYS soil dataset previously acquired, and the latest was the end date of the Climatology database update (1st July 2020).

In order to have compatible datasets, apart from selecting identical timelines for each pair of stations (e.g. Napier Raws and Napier Ews), we also calculated average daily values of soil moisture data for the NIWA stations. This allowed production of values from identical timelines for pairs of stations with different observation frequencies, thereby providing the flexibility to perform paired tests or mixed model analyses, depending on the nature of the data.

With the exception of Napier, where NIWA's Napier Ews station showed very little measurement variability (and to a lesser extent, also Whangarei Ews), station pairs showed very similar trends with soil moisture measurements following comparable patterns over time (see Fig. 8). Data from the Tauranga stations are visually the most similar. However, in the majority of cases, NIWA station values tended to be higher (moister) than the FWSYS values by around 10%-15%, apart from Whangarei where the FWSYS values were generally higher (and except Napier as per above).

Table 2. NIWA stations located in close proximity to FWSYS stations with soil moisture observations suitable for use in comparing FWSYS data accuracy.

NIWA agent no.	NIWA Station Name	Lat	Long	Start Date	FWSYS Station ID	FWSYS Station Name	Lat	Long	Start Date	Distance (km)
41322	Hokitika Ews	-42.7123	170.9843	8-Jan-16	42930	Hokitika Raws	-42.7138	170.984	27-Jul-17	0.2
40985	Diamond Harbour Ews	-43.6331	172.7281	17-Sep-15	42926	Diamond Harbour Raws	-43.642	172.7212	22-Jul-17	1.1
31832	Cheviot Ews	-42.8272	173.2241	18-Jul-07	42989	Cheviot Raws	-42.8123	173.2221	27-Oct-17	1.7
41428	Tauranga Cws	-37.6741	176.163	5-May-16	41549	Tauranga Raws	-37.677	176.1978	11-Oct-16	2.7
36106	Wairau Valley, Mill Road Cws	-41.572	173.497	21-Sep-08	40416	Landsdowne Raws	-41.5872	173.5313	12-Dec-13	3.2
40980	Whangarei Ews	-35.7444	174.3287	20-Aug-15	42503	Whangarei Raws	-35.7684	174.3594	9-Mar-17	3.6
41330	Napier Ews	-39.4985	176.9119	12-May-16	42533	Napier Raws	-39.4696	176.8638	21-Mar-17	5.0
23849	Takaka Ews	-40.8636	172.8057	30-Apr-02	41196	Takaka Aerodrome Raws	-40.8153	172.7765	29-Jan-16	5.9
24976	Gisborne Ews	-38.6275	177.9218	12-Jun-03	42532	Gisborne Raws	-38.6592	177.983	21-Mar-17	6.0
41077	Rotorua Ews	-38.1464	176.2578	24-Sep-15	41547	Rotorua Raws	-38.1059	176.3146	24-Aug-16	6.4
41429	Taupo Cws	-38.6781	176.0796	22-Apr-16	41548	Taupo Raws	-38.7426	176.0809	11-Oct-16	7.3
26117	Hamilton, Ruakura 2 Ews	-37.7739	175.3052	9-Nov-05	42501	Hamilton Raws	-37.8608	175.3315	8-Mar-17	10.0
36914	Waimate Cws	-44.7413	171.0631	6-Apr-09	40849	Waimate Forest Raws	-44.7063	170.9399	25-Dec-14	10.4
40986	Oamaru Ews	-45.0568	171.0226	11-Sep-15	42935	Oamaru North Raws	-44.9718	171.0819	27-Jul-17	10.6
35703	Timaru Ews	-44.4105	171.2543	16-Jun-08	40847	Timaru Coastal Raws	-44.3049	171.2216	30-Sep-13	12.1
15752	Dunedin, Musselburgh Ews	-45.9013	170.5147	26-May-00	43315	Dunedin Raws	-45.9291	170.197	17-Feb-18	25.0

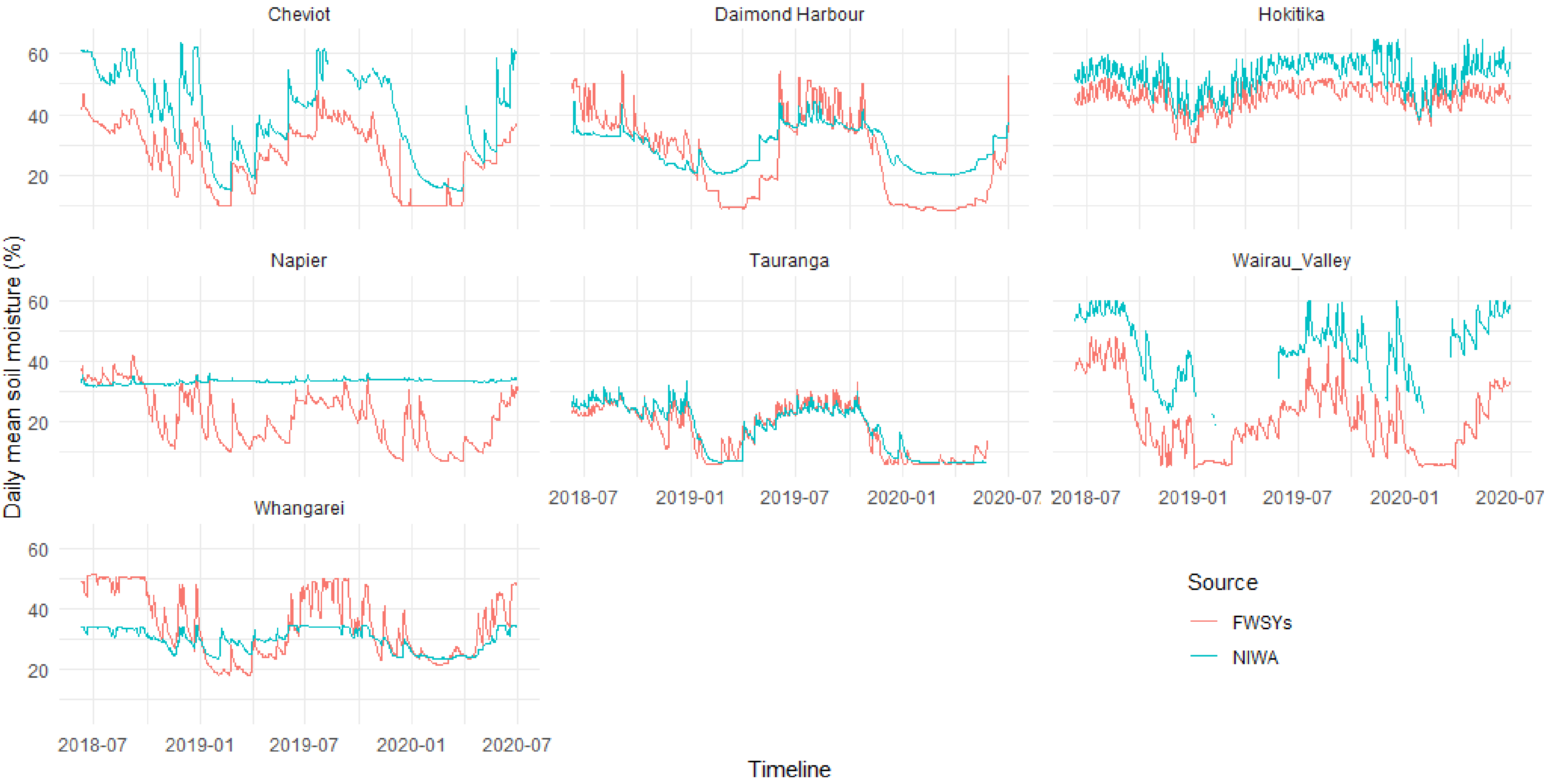


Figure 8: Comparisons of observed daily mean soil moisture for seven locations across the country, depicting corresponding data from FWSYS (red lines) and NIWA (blue lines) weather stations for the same period (July 2018 to June 2020).

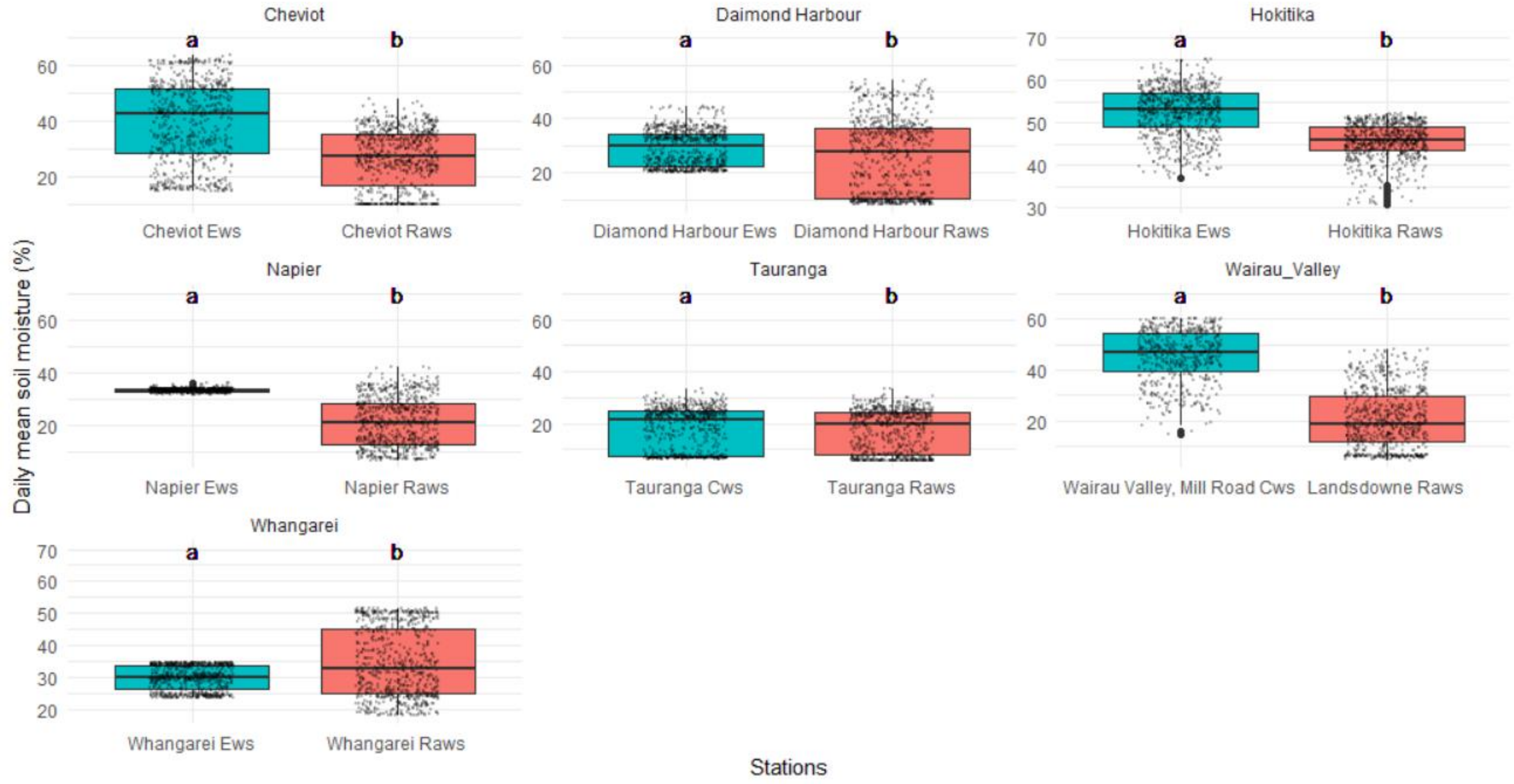


Figure 9: Daily mean soil moisture per pair of stations. Notice high variability in data for some FWSYS stations (e.g. Diamond Harbour Raws, Napier Raws, Whangarei Raws), whereas data variability is narrower for some NIWA stations (e.g. Napier Ews, Whangarei Ews).

These relationships between station pairs are further evidenced by Figure 9, which shows the distribution of values for each station within the pair. NIWA's Napier Ews is again the anomaly, where there is almost no variation in values observed. The distribution of observations for each of the Tauranga stations is again almost identical, with comparable average (median) values and data ranges. Median values for the Diamond Harbour and Whangarei station pairs are similar, although the data ranges for the FWSYS stations are much greater than for the corresponding NIWA stations. Both median values and observation ranges vary more widely for the remaining four stations, with observations for Cheviot, Hokitika, Wairau Valley and Napier NIWA stations being higher (moister) than their FWSYS station pairs.

Efforts to test differences between each paired station dataset statistically using T-tests were unsuccessful, as the soil moisture data did not comply with the assumption of normally distributed residuals (Shapiro-Wilk normality test, $P < 0.05$) for any of the station pairs, or with regard to data independency of recorded values (here data is dependent as it was recorded through time). Therefore, comparisons were made using Linear Mixed Models (Table 3), a more suitable analysis to handle dependent data (repeated measures). The results show differences in all comparisons, with the average daily soil moisture values almost always (with the exception of Whangarei) being higher for the NIWA stations (with Confidence Intervals (CI) in Table 3 not including zero).

Table 3: Results of the Linear Mixed Models comparing daily average soil moisture values for FWSYS stations with respect to the corresponding NIWA station. In this model the response variable was the average daily soil moisture, the fixed effect was the station, and the mixed factor was the corresponding date of the response variable. Negative values indicate FWSYS values being lower than NIWA station values, and positive values indicate higher values. AIC = Akaike Information Criterion, CI = Confidence interval at 95%, df = degrees of freedom.

NIWA station	FWSYS station	AIC	Estimate	CI	t	df	P-value
Hokitika Ews	Hokitika Raws	7865.0	-6.868	-7.026 – -6.710	-85.11	1	<0.0001
Diamond Harbour Ews	Diamond Harbour Raws	11005.7	-3.119	-3.751 – -2.488	-9.698	1	<0.0001
Cheviot Ews	Cheviot Raws	10682.7	-13.584	-14.0.86 – -13.081	-53.09	1	<0.0001
Tauranga Cws	Tauranga Raws	8533.6	-0.758	-0.976 – -0.54	-6.795	1	<0.0001
Wairau Valley, Mill Road Cws	Landsdowne Raws	9216.6	-21.930	-22.418 – -21.447	-89.57	1	<0.0001
Whangarei Ews	Whangarei Raws	10312.6	4.673	4.104 – 5.242	16.12	1	<0.0001
Napier Ews	Napier Raws	9840.8	-12.068	-12.711 – -11.424	-36.8	1	<0.0001

Differences seen between station pairs are likely to be associated with different sensor types and measurement depths. NIWA uses a range of sensors depending on station type (Ews vs Cws), including Aquaflex ribbon, Acclima TDT loop and, more recently, Enviropro capacitive sensors, whereas FWSYS stations have used either Acclima TDT loop or TDR probe types. The rapid response of measured soil moistures to the occurrence of rainfall observed in the FWSYS data (as observed in the Nelson example, see Fig. 7B) likely reflects the shallower installation depth of the Harvest sensors (10 cm) compared to NIWA soil moisture measurements (most at 20 cm). Depth measurement differences may also help explain the generally higher soil moistures measured at NIWA stations, with soil moistures typically higher (wetter) deeper in the soil than closer to the surface. Similarly, the high maximums for measured soil temperatures in the FWSYS data (see Table 1) and strong correlation with air temperatures (see Figs. 10F & 12D) are also indicative of likely shallower sensor depth.

Relationships with weather and FWI System values

Relationships between average daily soil moisture and soil temperature values and daily weather and FWI values are illustrated graphically for the 18 FWSYS stations in Appendix 1, Figs. A5-A10. An example, for the Hira Raws from the Nelson region, is also shown in Figure 10.

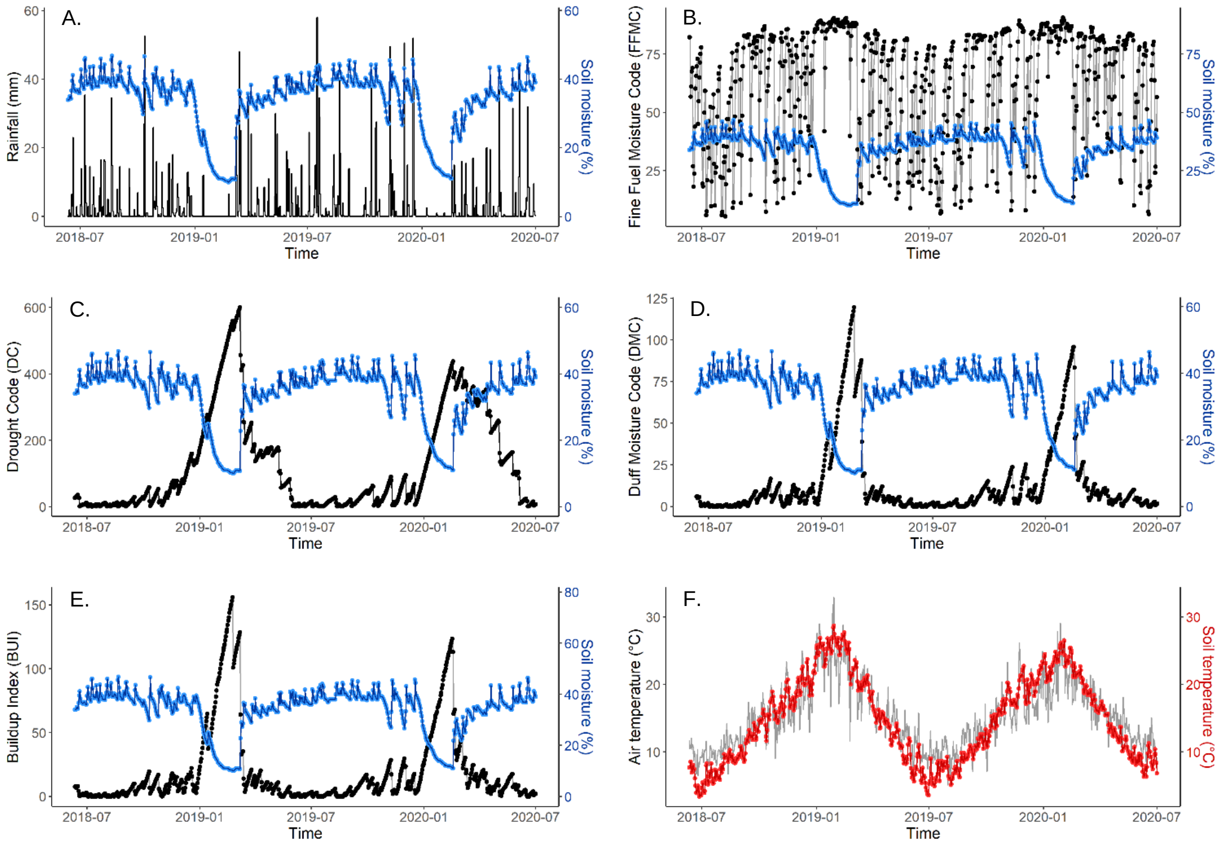


Figure 10: Relationship between mean daily soil moisture (blue line with observations shown as points) and: **A)** 24-hr total rainfall (black), **B)** Fine Fuel Moisture Code (FFMC, grey with observations shown as black points), **C)** Drought Code (DC, black), **D)** Duff Moisture Code (DMC, black), **E)** Buildup Index (BUI, black); and **F)** between mean daily soil temperature (red) and daily noon air temperature (grey), for the Hira Raws station from the Nelson region over the period April 2018 to June 2020.

Plotting the behaviour of trends between soil moisture and rainfall highlights obvious relationships (Fig. 10A; also see Appendix 1, Fig. A5). Here, the occurrence of rainfall is accompanied by increases in soil moisture content, while rainfall absences are linked to decreases in moisture values (see Fig. 10A; also see Fig. 12A). In contrast, when comparing fluctuations in soil moisture and FWI moisture codes and indices (FFMC, DC, DMC and BUI), a decrease in soil moisture corresponds with an increase of the codes/indices, and vice versa (see Fig. 10 and Fig. 12B-C; also see Appendix 1, Figs. A6-A9). Additionally, we found that fluctuations in average daily soil temperature correspond strongly with similar fluctuations in daily air temperature (see Fig. 12D; and Appendix 1, Fig. A10), although observations for soil temperature are less variable (see Fig. 10F). This suggests that the temperature in the soil is more stable than air temperature, with the latter likely also dependent on other variables (e.g. wind speed and direction).

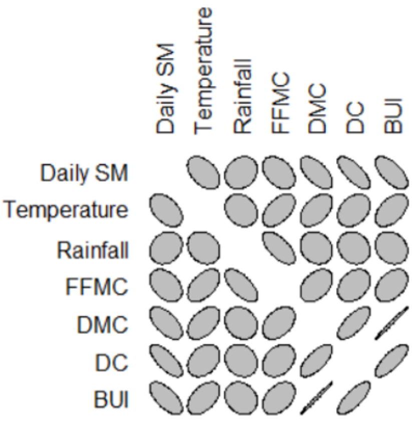
When applying Linear Mixed Models, we observed significant negative relationships for DC, BUI, DMC, FFMC and air temperature with soil moisture content ($P < 0.001$), but a significant positive relationship between rainfall and soil moisture (see Table 4). The strength of these correlations for soil moisture is also indicated in Figure 11, where the direction of the ellipse indicates the sign of the relationship (upward = positive, down = negative), and the shape of the data ellipse indicates the strength of the correlation (long and narrow = stronger, wider = weaker).

According to the linear mixed models (Table 4), DC is the factor that explains the biggest change in soil moisture. When averaged across all 18 stations used here, for each one point increase in DC value there is a 20% decrease in soil moisture content (see Fig. 12C). In this specific case, the data distribution for DC (see Fig. 12C) suggests a logistic relationship rather than a linear one, but this would require more advanced statistical modelling (i.e. use of non-linear models) than employed here to better define the exact nature of this relationship.

Weaker, but still statistically significant relationships were also found between soil moisture and BUI, DMC, FFMC and air temperature (Table 4). A strong positive relationship was also found between soil temperature and air temperature, where air temperature explained 3% of the increase of soil temperature values (Fig. 12D).

Table 4: R analysis outputs testing the relationships between mean daily soil moisture (%) and weather and FWI System values (Rainfall: total 24-hr rainfall, Air Temp.: Air temperature, DC: Drought Code, BUI: Buildup Index, DMC: Duff Moisture Code, FFMC: Fine Fuel Moisture Code), and relationship between mean daily soil temperature (°C) and air temperature, using linear mixed models with date and station ID as random factors. Number of stations = 18, R^2 in percentage.

Measurement	**Fixed effect**	**AIC**	**ΔAIC**	**Model R^2**	**Fixed effect R^2**	**Trend**	**P-value**
Soil moisture	DC	83988.7	0	74.77	21.01	negative	<0.001
	BUI	84455.6	466.91	76.20	9.83	negative	<0.001
	DMC	84712.4	723.73	76.71	7.58	negative	<0.001
	FFMC	85321.5	1332.84	78.63	3.55	negative	<0.001
	Rainfall	85920.1	1931.41	79.12	1.11	positive	<0.001
	Air Temp.	85959.9	1971.24	76.63	4.01	negative	<0.001
Soil temperature	Air Temp.	44091.4	-	94.27	3.08	positive	<0.001



	Temp	Rain	FFMC	DMC	DC	BUI
Daily SM	-0.4585	0.2026	-0.3927	-0.6102	-0.7366	-0.6527
Temp	1	-0.2235	0.5271	0.4961	0.3278	0.4981
Rain	-0.2235	1	-0.6497	-0.1832	-0.1657	-0.187
FFMC	0.5271	-0.6497	1	0.4124	0.3196	0.4171
DMC	0.4961	-0.1832	0.4124	1	0.7093	0.9916
DC	0.3278	-0.1657	0.3196	0.7093	1	0.7748
BUI	0.4981	-0.187	0.4171	0.9916	0.7748	1

Figure 11. Correlation plot (left) and correlation table (right) between variables of interest for soil moisture (Daily SM: mean daily soil moisture, Temp: daily air temperature, Rain: 24-hr total rainfall, FFMC: Fine Fuel Moisture Code, DMC: Duff Moisture Code, DC: Drought Code, BUI: Buildup Index). Notice that BUI and DMC are highly correlated with average daily soil moisture content (the data ellipse is very narrow) compared to Rain and DMC (wider ellipses).

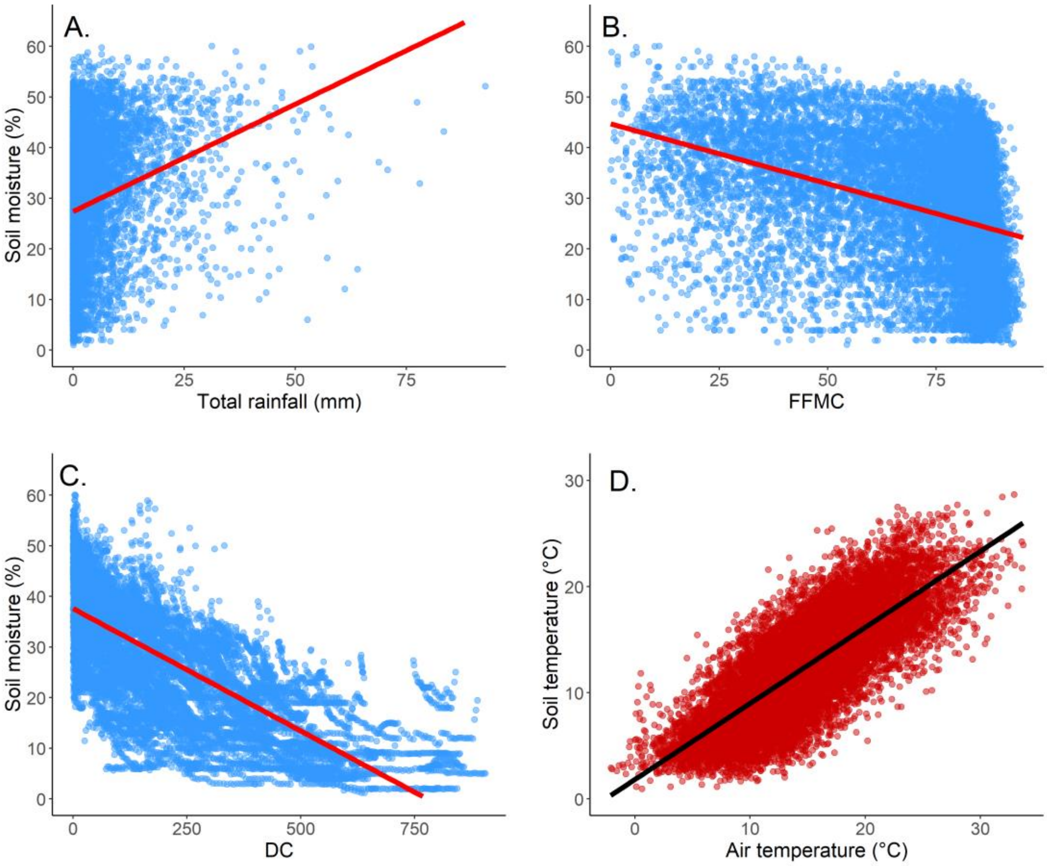


Figure 12: Subset of linear relationships between mean daily soil moisture contents (%) and: **A)** total daily rainfall, **B)** daily values of Fine Fuel Moisture Code (FFMC), **C)** Drought Code (DC); and between **D)** daily mean soil temperature (°C) and air temperature, using data for all 18 stations combined.

Application of soil moisture data for improving fire danger rating

Soil moisture, or at least analogues for soil dryness in the form of drought indices, have long been used as inputs into fire danger rating systems. For example, the fuel moisture codes of the FWI System – the FFMC, DMC and DC – which estimate the relative moisture contents of different layers of the soil profile, also provide fire managers with useful information on the relative dryness of vegetation fuels and associated fire control difficulty. This includes indications of ease of ignition and involvement of different fuel layers and sizes in combustion, potential fuel consumption, depth of burning, and extinguishment (mop up) requirements.

The reasoning behind the use of soil moisture in inferring wildfire danger is associated with the relationship between soil moisture and other environmental factors such as temperature, wind, vapor pressure deficit (VPD), and rainfall. High temperature, wind, high VPD (which equates with low relative humidity) and low rainfall increase the evaporative demands, which drain moisture directly from the soil and indirectly via plants into the atmosphere, leading to drier soil and vegetation and therefore increased wildfire risk.

However, while the FWI System moisture codes in particular provide very useful indicators of these drying processes, from time to time fire managers have questioned the validity of the code values and their representativeness to the range of soil and fuel types found across New Zealand (e.g. Pearce & Whitmore, 2009). These concerns are especially relevant given the FWI moisture codes were developed for a specific reference fuel type in Canada (deep forest floor layers beneath mature jack and lodgepole pine forest).

The FWI System moisture codes each apply to different layers of the soil profile beneath a mature pine stand with distinct drying rates. The FFMC represents the moisture content of the fast-drying pine needle litter and other dead fine fuels on the surface, present as a shallow layer of 1-2 cm deep with a dry weight of ~0.25 kg/m^2 (Van Wagner, 1987). The moisture content of the fuels represented by the FFMC ranges up to about 250% at an FFMC of zero, decreasing to a theoretical minimum of 0% at the FFMC's maximum value of 101.

The DMC represents the moisture content of loosely compacted, decomposing organic material (duff) in the forest floor beneath the litter layer (Van Wagner, 1987). About 3-10 cm deep and weighing ~5 kg/m^2 when dry, this layer has an upper moisture content limit of 300% at a DMC of zero and a lower limit of 20% above DMC values of 200 (and 0% at a DMC of 300).

The DC relates to the compacted duff layers which generally lie 10-20 cm below the surface, with a nominal fuel load of about 25 kg/m^2 (Van Wagner, 1987). The "standard" DC fuel layer with these properties has a theoretical maximum moisture content of 400% when fully saturated (at a DC of zero), decreasing to less than 50% moisture content at DC values greater than 800[4]. Although the water capacity of this "standard" DC layer referenced by Van Wagner (1987) is 100 mm[5], it is generally considered that more than 200 mm[6] (8 inches or 800 points) of precipitation is required to "re-set" the DC (Lawson 1977, McAlpine 1990).

---

[4] This value equates to the theoretical maximum for the DC of 800, although values in excess of 1000 have been recorded in New Zealand (Pearce & Whitmore, 2009) and internationally (e.g. Alexander & Pearce, 1993).

[5] A forest floor layer weighing 25 kg/m^2 on an oven-dry basis, if saturated at 400% moisture content, would hold 100 kg/m^2 of water, which is equivalent to 100 mm depth of water.

[6] The predecessor to the DC, the Stored Moisture Index (SMI) of Turner (1972), in fact referred to a "water reservoir" with a capacity of 200 mm; however, this was subsequently revised to 100 mm for the "standard" forest floor layer defined by Van Wagner (1987).

In the case of the DC in particular, studies have shown it to be a useful indicator of daily moisture change in the deeper layers of the forest floor and, consequently, a good indicator of fire-conducive droughts. Predicting moisture variations at depth in the forest floor, the DC can provide warning of moisture reversals with depth (Muraro & Lawson, 1970), where lower layers of deep duff may be drier than upper layers, resulting in persistent deep smouldering even though fire behaviour at the surface may not be severe (Lawson & Armitage, 2008)

Despite being based on only simple water balance assumptions, studies have shown that the moisture codes track moisture variations in soil organic layers reasonably well, although actual moisture content relationships vary across forest stands with different structures, and soil types and depths (Muraro and Lawson, 1970; Lawson et al. ,1996, 1997; Wilmore, 2001; Wotton et al., 2005; Abbott et al., 2007; Otway et al., 2007). No allowances for different soil types are made in the FWI System, with the exception of the overwintering adjustments of the DC undertaken in Canada to restart calculations again in spring following winter snowfall which differentiate between poorly drained and moderately or well-drained soils (Lawson & Dalrymple, 1996; Lawson & Armitage, 2008). However, these overwintering adjustments are not used in New Zealand as code calculations are continued all year round. The FWI System moisture codes each have specific rainfall thresholds which account for differences in the amount of forest canopy interception and rates of moisture absorption by each layer (0.5, 1.5 and 2.8 mm respectively for FFMC, DMC and DC; Lawson & Armitage, 2008), but the effect of canopy interception on soil moisture content has been shown to be more highly variable across the landscape (Wotton et al., 2005; Raaflaub & Valeo, 2008; Keith et al., 2010a,b).

Previous New Zealand studies (around grass curing) have shown evidence of very strong relationships between the DMC or DC and measured soil moisture (Baxter & Woodward, 1999; NZ Fire Research, 2002a,b; Anderson & Pearce, 2003). However, the most promising relationship with the DC component was found to vary between sites and from season to season (Anderson & Pearce, 2003).

A key factor in the differences observed between sites was likely to have been due to soil types. Water which enters the soil is stored on the surface of the soil particles, as well as in the holes or gaps (pores) between individual soil particles. Soils with coarse sand particles have less surface area for water to attach to, but also a greater proportion of larger pores, so these sandy soils are more free draining allowing easier passage of water through the profile. Conversely, in silt and clay soils, most of the pores are very small, and the larger surface area associated with these many smaller particles allows them to hold more water. Soils high in organic matter (peat) can also absorb more water. These differences in texture and organic matter content result in different soils having varying water-holding capacities. Generally, soil moisture contents range from about 10% to 60%, but it can be higher during and after rainfall.

The FWI moisture codes are just simple water balance models that add moisture after rain and subtract some for each day's drying. They independently track the movement of water in the soil profiles of increasing depth through a “bookkeeping” system in which today’s code values are built on yesterday’s values. Moisture losses follow simple exponential drying relationships driven by simplistic assumptions of evapotranspiration, and moisture absorption is a function of rainfall amount and the moisture content of the forest floor before rainfall. With respect to the DC, in particular, Yang et al. (2015) highlighted that the evaporation is assumed to be in a simple linear relationship with the moisture content and potential evaporation, where this potential evaporation is calculated using only air temperature and day-length factor. It does not consider the wind speed, air stability or humidity, nor the effects of different vegetation types or soil texture.

Another key limitation is that the water balances used for each moisture code are not coupled, and so respond independently to changes in rainfall and atmospheric conditions (Johnson et al., 2013). They also don’t account for the vertical movement of moisture from one layer to another, either from the top down due to inputs from rainfall and by gravity, or upward from deeper in the soil during dry periods. The DMC and DC are not water budgets, in that they do not measure the fluxes of water into and out of fuel, nor do they incorporate process equations responsible for these fluxes. Johnson et al. (2013) compared FWI System moisture code calculations with estimates from a multi-layer water budget model and showed that this lack of coupling can result in both the underestimation and overestimation of the measured water content of each layer.

All of the relationships contained in the FWI System moisture codes are empirically derived and require only easily measured weather variables for their calculation. It is therefore not surprising that they do not reflect moisture contents for all soil or forest types, let alone other vegetation types such as grasslands, nor should they be expected to. The FWI System was developed to provide general indicators of fire danger potential without the need for detailed inputs, and for broad areas rather than site-specific fuel type or terrain situations. The FWI moisture codes were also developed at a time when the physical understanding of the processes involved and computational requirements needed to fully account for these were limited (Johnson et al., 2013; Miller, 2020).

Johnson et al. (2013) stated that to improve predictions of soil moisture content based on the fuel moisture codes would require use of coupled water and heat budgets along with information on the hydrologic properties of the relevant soil layers. A better understanding now exists of how the processes of wetting and drying occur in the organic fuel in soils and how the water content of the organic fuels affect and are affected by their surrounding fuels, atmosphere, and soil (Johnson et al., 2013).

This increasing knowledge is now available in coupled atmosphere-land surface models that capture the physical linkages between different environmental components, including soil, vegetation, water bodies and the atmosphere above. Land Surface Models, like the Joint UK Land Environment Simulator (JULES) used by NIWA, produce estimates of soil moisture for a range of depths in the soil profile as one of the many outputs from these complex models. They can simulate changes associated with a range of soil types and, more importantly, vegetation types, based on modelled atmospheric conditions. A study by Yang et al. (2015) focussing on the DC showed that the use of modelled soil moisture estimates from JULES could improve the accuracy of the FWI System moisture codes. However, the practicality of using Land Surface Models for improving estimates of grass fire hazard such as grass curing, fuel moisture contents or grass fuel loads is potentially limited by the current resolution and computing requirements of these models, as well as limited availability of required inputs (soil parameters and, to a lesser extent, meteorological observations) (Yang et al., 2014).

Yang et al. (2015) also showed that use of direct soil moisture measurements, such as provided by weather stations with soil moisture sensors, could also improve the accuracy of the FWI System’s moisture codes. For example, Clifford et al. (2018) suggested that an enhanced soil moisture observation network could help in validating the FWI System moisture code values (especially for DC) during the fire season, by “nudging” calculations where necessary, such as at the beginning of the fire season when early spring fire danger conditions are elevated due to below normal over-winter rain (Anderson & Pearce, 2003). This potential for improved accuracy, combined with the strong relationships observed between the DMC / DC and soil moisture both here and previously (e.g. NZ Fire Research, 2002b), mean that this topic warrants further investigation. A more detailed analysis of fuel moisture contents versus FWI System moisture codes will be possible once verified FWI data (and longer-term soil moisture measurements) are available from the Climatology update project. These analyses should include investigation of the effects of other variables, such as soil type, latitude, elevation, aspect, and distance from the coast, in the identification of possible relationships for different regions of the country.

Consultation should also be undertaken with NIWA around standardising the measurement of soil moisture. As a priority, this should include confirmation of the best measurement depth(s), and consideration of whether monitoring should be undertaken at multiple soil depths to better capture soil water movement within different soil layers representative of the FWI System moisture codes. Procedures should be developed to ensure that the installation depth of soil moisture probes is standardised across the network, especially for new sensor installs.

Investigations should also be made into the availability and potential of soil moisture estimates from other sources, such as land surface models (e.g. JULES, used by NIWA) or satellite-derived indices.

Review of applicability of soil measurements for grassland fire hazard prediction

A brief literature review was undertaken to assess the potential to utilise soil moisture and soil temperature measurements to improve predictions of grass fire risk. This included considering:

- Use of soil moisture data for estimating grass curing;
- Use of soil moisture data for predicting fuel moisture content (FMC), especially of live grass vegetation; and
- Use of soil moisture and soil temperature data for predicting pasture grass growth.

The Scion review of potential methods for monitoring grass curing undertaken for FENZ (Clifford et al., 2018) provided a useful starting point for this expanded evaluation.

Soil moisture and soil temperature are important factors affecting plant growth. In the case of pasture grasses especially, along with sunlight and nutrient supply, these soil factors play a critical role in controlling the seasonal changes occurring in grassland productivity. These changes can affect fire risk, with low soil moisture availability causing plant stress which can reduce the moisture content of live fuels, causing wilting or even death which converts live vegetation to dead fuel (curing) that is easier to ignite. On the other hand, increased soil moisture can promote vegetation growth, increasing the amount of fuel available to burn when conditions dry out and potentially resulting in more intense fires.

Temperature also impacts plant growth. When temperatures, of either the air or the soil, are too cool, growth slows or ceases altogether. Conversely, high air temperatures can also induce plant stress, causing wilting or, under extreme conditions, the plant to lose the ability to control moisture loss through its stomata therefore resulting in excessive transpiration.

Grass curing prediction

Pasture grasses go through an annual cycle of growth and seasonal die-off driven by both plant physiology (flowering and seeding) and environmental factors, with these being more evident in annual grasses but also present in perennial grass species. Temperature as well as soil moisture, which reflects the water availability associated with rainfall versus evapotranspiration losses (in turn driven by temperature, humidity and wind speed), are key components of these environmental factors.

Grass curing describes this seasonal cycle of plant senescence where grasses die and dry out following flowering. The ‘degree of curing’ refers to the proportion of dead (cured) material present, expressed as a percentage of the total grassland fuel complex (live and dead material), ranging from zero (completely live/green) to 100% (fully dead/cured) (Alexander, 2008).

Annual grasses that complete their life cycle over a period of three to six months from spring through summer die when they reach maturity and dry out rapidly when their roots cease drawing moisture from the soil. This curing process is related to physiological changes which take place in the plant associated with the development of seed heads, yellowing of stalks and leaf blades through reduction of chlorophyll, and eventual death (Garvie & Millie, 2000; Country Fire Authority, 2014). The rate of curing varies among grass species, seasons, and geographical location. Late spring or early summer rains can delay the maturing process until the onset of hotter, drier weather conditions, when curing will proceed rapidly. Conversely, lack of spring rains and early commencement of summer will cause grasslands to cure early, but less rapidly. Below 60% curing, rainfall can prolong grass growth and slow curing. However, once the degree of curing has reached about 60%, completion of the process is generally irreversible and, above 80% cured, fuel moisture content is significantly influenced by temperature and humidity (through adsorption and desorption processes) as opposed to surface soil moisture availability.

Perennial grasses also go through an annual cycle of curing related to the die-off of grass growth and production and yellowing of seed heads and stalks, although they are more deeply rooted so better able to take advantage of increases in soil moisture associated with summer rainfall that can delay curing.

Tussock grasslands go through a somewhat different annual cycle of curing, due to the drivers and timing involved being different. Here temperature is the key factor, with the die-off of tussock tillers being driven by overwinter frost curing, followed by replacement of dead tillers by new green growth in late spring and summer as conditions become warmer. Tussocks can retain a significant proportion of dead material, which can accumulate within the elevated tussock tillers and tussock clump base, which is further compounded by discarded tiller litter on the surrounding ground. Rather than annually, flowering and seeding in tussock also only occur every few years. This is generally following warmer than average summer temperatures during the previous summer (Mark, 1965; Rees et al. 2002), and these “mast years” can result in a significantly increased proportion of dead (cured) material as well as greater fuel loads than normal.

Curing in mixed tussock/pasture grasslands is even more complicated, with the cycle of curing of tussock being offset by the opposite cycle of the annual pasture grasses. When tussock curing is highest at the end of winter/early spring, inter-tussock pasture grasses are generally green; and in summer when the inter-tussock grasses typically have highest curing, tussocks are sprouting new green growth.

For pasture grasses, the degree of curing has generally been monitored using visual assessments or satellite remote sensing; however both these methods have associated problems (Anderson & Pearce, 2003; Anderson et al., 2011; Martin et al, 2009; Newnham et al., 2010; Clifford et al., 2018). Current remote sensing methods employed internationally typically use the Normalized Difference Vegetation Index (NDVI) (Partridge & Barber, 1988; Dilley et al., 2004; Martin et al., 2009; Newnham et al., 2010, 2011), sometimes together with other satellite derived indices to account for soil reflectance (e.g. Soil Adjusted Vegetation Index (SAVI); Newnham et al., 2010) or vegetation moisture. Examples of the latter include the Global Vegetation Moisture Index (GVMI) developed by Ceccato et al. (2002), and used in the Victorian Country Fire Authority system (Martin et al., 2015); or the Vegetation Optical Density (VOD), which was found by Chaivaranont et al. (2018) to improve accuracy of grass curing estimates.

Often these satellite data are also used in combination with visual assessments from a network of field observers (Martin et al., 2015; Wright et al., 2016). Algorithms for application of satellite indices appropriate to New Zealand grasses have been developed (Newnham et al., 2010, 2015), although these are still to be implemented, either on their own or in combination with field observations or additional measurements (see Clifford et al., 2018).

Chladil and Nunez (1995) used grass curing (derived from the Mount Soil Dryness Index (SDI), similar to the Drought Code) and NDVI to predict soil and fuel moisture content. They found stronger relationships between grass curing and measured soil moisture content compared to estimates based on the SDI, but NDVI proved a good predictor of soil moisture content (and fuel moisture). A recent study by Sharma et al. (2020) looked at the use of satellite-derived soil moisture to predict grass curing (and FMC, see below). They found that curing increased with declining soil moisture, expressed as a fraction of available water capacity (FAW) derived from reflectometry sensor measurements. Curing rate increased linearly as the FAW declined below 0.30. They found though that NDVI readings failed to adequately respond to rapid drying and curing of the grass fuel-bed.

As curing can be affected by rainfall, especially at levels below 60%, some attempts have been made to predict curing for New Zealand grass types using either measured soil moisture or surrogates of soil dryness such as the FWI System's DMC and DC components (Baxter & Woodward, 1999; NZ Fire Research, 2002a,b; Anderson & Pearce, 2003). This showed much promise, although soil moisture measurements at that time were scarce, and relationships with the better-performing DC component were found to vary between sites and from season to season. More recently, and building on the earlier work of Chladil & Nunez (1995) above, Kidnie et al. (2015) also had some success modelling curing of Australian grasses using drought indexes, including both the Mount SDI and Keetch-Byram Drought Index (KBDI), especially when the overall grass FMC was included, although again there was some evidence of site effects.

Good reviews of soil moisture measurement methods, including the wide range of remotely sensed soil moisture products now available globally, are provided by Vinodkumar & Dharssi (2015) and Babaeian et al. (2019). The new Australian Flammability Monitoring System (AFMS, http://anuwald.science/afms; Yebra et al., 2018; Vinodkumar et al., 2021) also includes several soil moisture estimates for layers of different depths. The role of soil moisture, and strong relationships found in the studies highlighted here between measured soil moisture and DC, as well as with satellite-derived soil moisture (and fuel moisture) products, mean that this line of study definitely warrants further investigation for predicting grass curing.

Grass fuel moisture

Due to its importance in fire ignition and spread, many relationships exist for predicting dead fuel moisture content (FMC) in various vegetation types, including grasslands. For example, from temperature and humidity with or without curing (e.g. Cruz et al., 2016), and even from an hourly version of the FWI System's FFMC component developed specifically for grasslands (Wotton, 2009). Dead FMC varies rapidly with changing weather conditions, as well as spatially due to soil and terrain changes, especially aspect. In dead grassland fuels, the rate of FMC change also varies for different grass species due to differences in fuel properties such as stalk diameter and wall thickness which affect moisture absorption and desorption processes.

The moisture content of live vegetation is controlled by species physiology and time of year, and has very little to do directly with weather conditions, although short-term variations can be brought about by extreme weather conditions, such as very high air temperatures and/or prolonged drought (i.e. when the plant is under water "stress"). Rainfall can also have an obvious impact on live fuels, directly wetting the surface for short periods, or through increased soil moisture being taken up over longer time periods. Moisture content of all new vegetation is highest at the time of emergence, and moisture contents two or three times the organic dry weight (i.e. 200-300%) are common. However, on a day-to-day and hour-to-hour basis, the moisture content of living fuels generally varies proportionally much less than that of dead fuels, with changes in live fuels of a single species over these time scales usually being less than 10%.

There is a lack of clarity in the literature about which herbaceous (grassland) fuels are considered ‘live’ at any time and exactly how to objectively separate and measure the live and dead herbaceous fuels (Sharma et al., 2020). It is also difficult to define and to operationally determine when grass fuel is ‘dead’, and representing these fuels as either live or dead may be too simplistic for fire behaviour prediction (Kidnie et al., 2015). Visual estimation of live and dead fuels in the field is highly subjective, and manual separation is prohibitively time-consuming for studies of grassland fuel dynamics.

Estimating live FMC in grass fuels is especially complex, as it varies by part of the plant and stage of growth through the season, as well as by grass species. As a result, it can vary much more widely, with an analysis by Andrews et al. (2006) (using data from the Australasian Bushfire Cooperative Research Centre study; Newnham et al., 2010) showing live grass FMC values ranging from near 90% to over 330%. Andrews et al. (2006) also reported significant differences between native grasses and improved pasture species, with native grasses often having lower FMCs for the same conditions (125% versus 250% for the same date and location in the example they cite).

In their study of curing dynamics, Kidnie et al. (2015) therefore expanded the fuel component groups present in grasslands undergoing curing from two (live and dead) to four (green, senescing, new dead and old dead fuel). They found that all these components had significant FMC differences. Overall, green fuels had the highest FMC and widest range, followed by senescing fuels, new dead and finally old dead. There were statistically significant differences in the FMC between the green and senescing fuels, between senescing and new dead fuels, and between new and old dead fuel. Moisture content of senescing fuel components was, on average, three times higher than new dead fuels; similarly, new dead grass components had, on average, a moisture content threefold higher than that of old dead grass fuel. These differences make it all the more difficult to predict the moisture content of grass fuels.

In spite of these issues, as noted above, predictive relationships for grass fuel moisture do exist. The grass FFMC relationship from Wotton (2009) has had some uptake in Canada (Kidnie et al., 2010; Kidnie & Wotton, 2015), but has not been tested in New Zealand and warrants further investigation as a means of estimating dead grass FMC. Similarly, the Australian temperature-humidity relationships (e.g. Cheney et al., 1989; Noble et al., 1980; Cruz et al., 2016) also warrant further study for New Zealand grasses, including for applicability to tussock grasslands (e.g. using the buttongrass moorland FMC relationship from Marsden-Smedley & Catchpole, 2001).

In relation to tussock grasslands, Everson et al. (1988) successfully modelled fuel moisture for a South African low tussock grass (Highland Sourveld) that has a dormant period during the dry winter season. Once the above-ground parts of the grasses are killed by the first winter frosts, the herbage gradually dries. They developed a simple model to estimate overall FMC from easily measured atmospheric variables (temperature, humidity and wind speed) for different age grasses (1, 2 and 3-year old) and time of day (with a very impressive R^2 of 0.94), although this had different equations for different periods of the year (relative to the curing of the grass, along the same lines as Kidnie et al. (2015) above). Temperature was the most significant factor, followed by age and time of day, with age thought to relate to increased accumulation of dead material, and therefore lower overall FMC. Interestingly, humidity was not found to be significant for this grass type and environment (highlands 1890m above sea level). Rain was also not considered, as rainfall mainly occurs in summer and is negligible during the winter curing period.

Andrews et al. (2006) found that live fuel moisture was not an indicator of the level of grass curing, so conversely it could be implied that curing cannot be used to predict live fuel moisture, at least not without estimates of the relative proportions of dead versus live, and both the dead and composite fuel moisture contents; i.e. live FMC could be estimated from the dead and combined FMCs and ratio of live vs dead fuel (curing). Chladil & Nunez (1995) considered that grass FMC was best modelled by including grass curing (in their case, estimated from the Mount SDI as a surrogate for soil moisture) together with the NDVI, reducing the unexplained variation in FMC to under 30%. Kidnie et al. (2015) found that the moisture content of green grass could not be predicted from curing; however, the decrease in moisture content with increased curing was significant for the senescent fuel component. They found that moisture content dropped by approximately 6% for every 10% increase in degree of curing (although the R^2 value for the model fit was just 0.41).

Curing studies have previously shown however that indices derived through remote sensing used to predict curing, such as NDVI and GVMI, are also reasonable predictors of composite grass FMC (Partridge & Barber, 1988; Chladil & Nunez, 1995; Chuvieco et al., 2002). Dilley et al. (2004) identified good relationships between grass FMC and NDVI at three separate sites in Victoria, Australia, but found accuracy decreased markedly if the relationship appropriate to one site was used to derive estimates of FMC at other sites. García et al. (2008) were able to develop a predictive model for live FMC in Spanish grassland fuels by incorporating day of year and remotely sensed surface temperature along with NDVI. Similarly, Sharma et al. (2018) were able to successfully predict FMC in Oklahoma tallgrass prairies using day of year, NDVI and grass canopy height.

The latter study was further extended by Sharma et al. (2020) who, in addition to curing (see above), found that FMC of the mixed live and dead herbaceous fuels also clearly tracked soil moisture, expressed as FAW (obtained in their case using data from onsite reflectometry sensor measurements). Grass FMC decreased with decreasing soil moisture below a FAW threshold of 0.59 and fell below 30% only when FAW fell below 0.30. McGranahan et al. (2016) also compared seasonal trends in fuel moisture of common rangeland grasses at two locations in South Africa, and found positive linear relationships between fuel moisture and soil moisture at their two sites over four sampling events capturing different stages of grass curing; however, the relationship was spatially variable and potentially soil-type dependent.

A good perspective on the potential to utilise soil moisture data to better estimate fire danger, including in grasslands, is provided by Sharma & Dhakal (2021). They suggest that the combination of field-based soil moisture measurements with remotely sensed data offers the most potential, but note that sensors capable of acquiring higher spectral information and radiometry across large spatiotemporal domains are still lacking. This has not stopped the development of automated fuel moisture monitoring systems using current data sources and remote sensing relationships, including in Australia (via the AFMS; Yebra et al., 2018; Vinodkumar et al., 2021), and global fuel moisture systems (Yebra et al., 2013, 2019; Quan et al., 2021). However, a key requirement of such systems is an accurate, up-to-date spatial representation of vegetation cover, so that fuel moisture models (and other associated vegetation and soil properties) can be assigned correctly to provide meaningful information.

Grass growth and fuel load

In addition to light and nutrients, the key factors influencing the growth of plants are temperature and moisture availability. Plants, including grasses, react to temperature by speeding up or slowing down all of their life processes. Warmth, as indicated by both air and soil temperatures, encourages germination and growth. Warmer temperatures trigger chemical reactions inside the plant's cells which speed up the processes of water loss (transpiration), exchange of oxygen and carbon dioxide (respiration) and transformation of light into chemical energy needed for growth (photosynthesis). Plants grow more quickly during warm periods and slow down or even become dormant during cool or colder periods. For pasture grasses, commonly cited minimum air temperature thresholds for growth are 5 °C for temperate grasses and 9-10 °C for white clover, although considerable growth of temperate grasses has also been reported at 5 °C or less (Hutchinson et al., 2000).

Plants need water to survive, and without it, they become stressed and die. Water nourishes the plant and hydrates it, with water and humidity in the air encouraging plant growth. Water in the soil breaks down and dissolves minerals and critical elements in the soil, and as the plant absorbs water through its roots, it also transports nutrients into its cells. However, too much water can kill plants, and it is therefore important that plants have access to the right amount of water for their needs. In terms of soil moisture, plant available water is the difference between field capacity (the maximum amount of water the soil can hold) and the wilting point (where the plant can no longer extract water from the soil). As noted earlier (p. 24), different soils have different plant available water capacities. The large variation in the maximum rooting depth of different crops and the tolerance of plant species to different soil conditions, in addition to depth of soil, determines the capacity of a plant to access available water on many soils. For pasture grasses, which obviously have shallower rooting systems than trees and shrubs, the available water content in the top 10-20 cm of the soil profile is most important, although both annual and perennial grass species have been shown to extract soil water from depths of 100 cm or more (Parry et al., 1992) .

The importance of temperature and soil moisture for grass growth has meant that a number of pasture growth models have been developed, ranging from very simple indexes based around only few inputs to increasingly complex ‘productivity’ models that capture the influences of many additional factors. These are relatively well described in the previous report by Clifford et al. (2018).

Simple pasture growth models, such as the Pasture Growth Forecaster (DairyNZ, 2021) and NZ Pasture Growth Index (NZX, 2020), provide forecast predictions of relative grass growth (change in kilograms of dry matter per hectare, kg DM/ha) to aid in livestock grazing management and estimating meat and milk production. As such, they do not directly provide estimates of total grass biomass present that could be used to quantify fuel load; however, it is possible that with some minor modifications they could provide this. They use climate and soil data to estimate the amount of water in the soil, soil productivity and resulting potential for pasture growth via short (14-day) and longer term (3-month and annual) growth forecasts as well as comparisons against typical growth rates for districts or individual farm sites.

Clifford et al. (2018) identified a number of New Zealand and Australian pasture productivity models that had potential for use in estimating grass curing, but that might also have potential to estimate grass fuel loadings due to producing estimates of the biomass of the live and dead grass components (from which degree of curing could be derived). Of these, the AgResearch pasture quality model (of Woodward, see below) and GrazPlan system (CSIRO, 2007) appeared the most promising. These modelling systems incorporate a series of submodels, including water balance models that estimate soil moisture and evapotranspiration, pasture models that predict grass growth as well as seeding, death and litter fall and, in some cases, ruminant models that estimate animal feed requirements and grazing effects (see https://grazplan.csiro.au/grassgro/models/).

Scion previously investigated use of the AgResearch model for predicting curing (Baxter & Woodward, 1999), noting that the model can calculate the amount of grass, cover and dead matter present, as well as the amount of live (green) material (Woodward et al., 1998; Woodward, 2001). All the required inputs – mean daily temperature, daily rainfall (mm) and daily radiation receipt (MJ/m^2) (and/or number of sunshine hours per day) – are readily available, although further work is likely required to extend the model to grassland types other than the ryegrass/clover mixes it was developed for. However, it would be very worthwhile finding out what the current status of this and any other AgResearch pasture growth models is.

Similarly, the GrassGro model from within the GrazPlan decision support tool (CSIRO, 2007) would likely require significant additional work to accommodate New Zealand grass types, although it already includes the phenology, growth, death and decay of a number of Australian annual and perennial pasture species (Donnelly et al., 1997; Moore et al., 1997), and has also been used in Canada demonstrating its flexibility for transferral to a new environment. A key advantage of the GrassGro model is that it includes the effects of grazing, and outputs total live/dead biomass as dry weight as well as curing from dead standing and litter vs total biomass as a percentage (%). The potential of the GrazPlan model to aid grassland fire danger rating was shown by Gill et al. (2010), who successfully calculated retrospective daily grassland fire danger and potential fire intensity for a 54-year weather station record for three contrasting pasture types (exotic annual, exotic perennial and native perennial). King et al. (2012) also used GrazPlan to assess implications for grass fire risk with climate change, including the effects of daily grass curing and fuel load dynamics.

Alternative approaches to estimating fuel loads in grasslands (as well as other fuel types), especially across broad areas, rely on remote sensing methods. Destructive (clipping and weighing) and non-destructive (point-contact and falling plate) measurement methods are time consuming and point-specific, meaning a large number of samples need to be collected.

Primary remotely-sensed vegetation indices such as the NDVI have been widely used for estimating above-ground grass biomass (Griffith et al., 2001; Xie et al., 2009); however these indices can be affected by saturation, soil background reflectance, and coarse spatial resolution which limits application in areas with different grass management treatments (Sibanda et al., 2017). Like Xie et al. (2009), whose models used topographical aspect as well as NDVI to successfully predict typical grassland biomass in Inner Mongolia, Sharma et al. (2018) used day of year (DOY), canopy height and NDVI as predictors of standing crop biomass in Oklahoma tallgrass prairies (in addition to curing and moisture content – see above). Both these studies also found that artificial neural network models based on machine learning algorithms provided better prediction accuracy than multiple linear regression models.

A number of possible alternatives to the NDVI exist, including the Soil Adjusted Vegetation Index (SAVI) and Enhanced Vegetation Index (EVI) trialled for estimating grass curing (see Newnham et al., 2010), plus a range of others such as the Normalized Difference Index (NDI), Vegetation Index Number (VIN) and Ratio Vegetation Index (RVI) (Zumo et al., 2021). Of these, the VIN appears to have been the most successfully used to estimate grassland biomass (Jiang et al., 2014; Zumo et al., 2021). In an effort to overcome the limitations of vegetation indices, other studies have investigated the use of red-edge wavebands between red and the near infra-red bands used in the NDVI (Delegido et al., 2015) and optical texture models (Sarker & Nichol, 2011). Literature shows that the red-edge is sensitive to chlorophyll as well as leaf structure reflection (i.e., leaf area index, leaf angle distribution), thereby providing more information for the characterization of vegetation. Optical texture models which can provide information on vegetation structure (e.g. height, density, cover), especially when combined with synthetic aperture radar or LiDAR measurements, have also been shown to better predict field measured above-ground vegetation biomass when compared with vegetation indices. Studies by Sibanda et al. (2017) and Shoko et al. (2018, 2019) have shown that the combination of these spectral approaches has led to improved estimates of grassland biomass, especially with complex pasture management.

Conclusions and Recommendations

This study sought to review data on soil moisture and soil temperature collected by Fire and Emergency New Zealand's (FENZ) network of fire weather stations, and to assess its applicability for improving determination of fire danger – in particular, dryness of sub-surface duff and soil organic layer fuels, and estimating factors relating to grassland fire hazard, including grass fuel moisture, seasonal curing and grass fuel loads.

This research confirms the validity of the data being collected, and endorses continuation of commissioning soil moisture sensors on FENZ weather stations to collect this soil moisture and soil temperature data on an ongoing basis. However, due to the range of grass species covered by the international studies reviewed, wide variety of potential methods and validation of these required, it was not possible to provide any specific equations or models that could be directly adopted for estimating grass curing, grass fuel moisture or grass fuel loads in New Zealand. But it does identify several options for further research and investigation of these applications.

The use of soil moisture data holds much promise, both in relation to validation and improvement of the accuracy of FWI System components such as the Duff Moisture Code (DMC) and Drought Code (DC), but also for assessment of grassland fire hazard including grass curing, fuel moisture and grass fuel loads. However, more research is required to understand whether the best option is to obtain these soil moisture estimates from direct weather station measurements, remote sensing or Land Surface Models, or some combination of these. However, soil moisture observations obtained from soil sensors at weather stations will still be required to provide the data to underpin the research to develop these solutions, and to validate the data obtained from other sources.

Considerable further research is required to progress each of these potential areas of application, with a number of recommendations outlined below as to how they might each be achieved. In terms of prioritisation for further investigation, the potential to significantly improve grass curing assessment warrants this application being looked at first, followed by pasture fuel load modelling, then grass fuel moisture estimation. The availability of existing grass curing algorithms for New Zealand from the previous Bushfire CRC research, and simple pasture productivity models for predominant pasture types, suggests these could be achieved relatively easily, whereas fuel moisture modelling is likely to be more complex. The development of an operational platform for presenting grass curing data could also form the basis for a more comprehensive New Zealand fuel flammability system that could later incorporate grass fuel load and moisture content data as these components are developed. However, key to this is the availability of accurate and regularly updated spatial data on New Zealand vegetation and associated properties (including soil types) so that non-grass fuel types can be masked out and the appropriate models assigned.

Recommendations

Soil moisture measurement

- The value of soil moisture (and soil temperature) measurements identified here, along with their use for a range of possible applications, warrant continuation of the present data collection and inclusion of soil moisture sensors on future weather station installations.
- However, consultation should be undertaken with NIWA on the different soil moisture sensor types available, their accuracy and which soil moisture layer(s) they should be representative of.

- As a priority, this discussion should include confirmation of the best measurement depth(s), and development of procedures to ensure that the installation depth of soil moisture probes is standardised across the network, especially for new installs.
- These discussions should also include consideration of monitoring soil moisture at multiple soil depths to better capture soil water movement within different soil layers of the plant root zone and/or applicable to the FWI System moisture codes (DMC and DC), either through use of a second Acclima TDR probe sensor or via use of multi-depth sensors (such as EnviroPro).
- Investigations should be made into the availability and potential utilisation of soil moisture estimates from other sources, such as satellite-derived indices and land surface models (e.g. JULES, used by NIWA).

FWI System moisture codes

- Once a more comprehensive dataset of both verified FWI System data and longer-term soil moisture measurements are available from a greater number of Harvest and NIWA weather stations, further statistical modelling analyses should be undertaken into relationships between observed soil moisture and the DC, DMC and BUI components of the FWI System.
- These analyses should include identifying more stations for comparison, using noon soil moisture and temperature observations (as opposed to daily averages) and using non-linear statistical models, as suggested from the analyses undertaken here. It should also include investigation of the effects of other variables, such as latitude, elevation, aspect, distance from the coast and soil type, in the identification of possible relationships for different regions of the country.
- Where possible (e.g. for NIWA stations with appropriate sensors), analyses should also include observations of soil moisture at different depths relative to the fuel-layer dryness measures indicated by the DMC versus the DC.
- If available, analyses should also investigate the use of soil moisture estimates from other sources, such as satellite remote sensing and/or Land Surface Models, for use in improving FWI System moisture code calculations.

Grass curing

- As a first step in developing an automated grass curing monitoring system, the NZ-specific satellite algorithms identified by Newnham et al. (2015), based on the Map Victoria method, should be implemented in New Zealand. A platform (likely web-based) to deliver the resulting curing information will also be required. It is understood this work may already be underway.
- The value of including additional satellite-derived soil moisture products (or other soil or vegetation characteristics) to potentially improve the currently recommended satellite-derived grass curing methods (as above), as identified by research overseas, means that this area warrants further investigation. The latest knowledge in this regard from Australia should be identified as a first step in this process.
- Similarly, the importance of soil moisture in grass curing, and strong relationships found here and in previous studies between measured soil moisture and DC, also warrant further research as a possible means of predicting grass curing directly from RAWS data.
- A regular field-based seasonal curing data collection programme is required to enable the validation or extension of automated satellite grass curing estimates, and also to support potential future improvements (derived from satellite methods, soil moisture or FWI System relationships). This will require a network of trained observers and sampling sites to be established.

- Pasture growth models also hold some potential for determining seasonal grass curing levels (and fuel loads), but further investigation is required to determine what local and international pasture growth models are available and their potential for application to common New Zealand pasture grass species.
- The identification of key grassland types and species for which seasonal curing is important will be needed to inform the selection of sites for field validation, as well as to enable evaluation of the potential to use remote sensing or local or international pasture growth modelling approaches. For example, present methods are unlikely to be appropriate for tussock grasslands, where alternative approaches are likely to be needed.

Fuel moisture

- Empirical models for predicting dead grass fuel moisture currently available from overseas should be tested for New Zealand grass species. These include the Canadian grass FFMC model, as well as the Australian temperature/humidity models of Cheney, Cruz et al. and Kidnie et al., plus the Marsden-Smedley model for tussock grasslands.
- Here, again, a regular sampling programme would be needed to test these models. Potentially this could utilise the same field sampling collection network as for grass curing validation. Alternatively, this model testing for different grass species would make ideal student projects.
- Fewer empirical models are available for predicting the moisture content of live (green) grass fuels, although the relationships of Kidnie et al. could be tested, including those for the transitional senescing and new dead curing stages they identified.
- Remote sensing approaches should also be investigated, including use of the NDVI on its own or with other vegetation (e.g. GVMI) and/or soil moisture (e.g. FAW) indices and surface properties (such as surface temperature). Remote sensing methods have the advantage of generally characterising changes in moisture content across several grass types and curing stages. As a starting point, the existing grassland moisture models from the Australian Flammability Monitoring System (AFMS) should be investigated.
- Once a data set of grass fuel moisture contents is available from a field sampling programme, relationships between grass fuel moisture and soil moisture could also be investigated. Where possible, this should utilise soil moisture measurements from the RAWS network, but could also extend to investigating potential relationships between grass fuel moisture and soil moisture estimates from the FWI System moisture codes (e.g. DC) or other sources (e.g. soil moisture estimates from satellite data, or Land Surface Models such as JULES).

Grass growth and fuel load

- Discussions should be held with NIWA and MetService to determine the status of their pasture growth modelling/forecasting. Use or adaptation of the existing pasture growth indexes may provide an easy pathway to estimating gross fuel loads.
- As an alternative means of estimating fuel loads, and in conjunction with potentially providing grass curing estimates, the use of pasture growth models should be further investigated. The first step in this should be determining the present status of the AgResearch (Woodward) pasture quality model. Australian models such as GrazPlan should also be further investigated.
- Remote sensing approaches, such as use of NDVI or other spectral indices, could also be investigated. However, this would likely require a more formal research project involving regional sample collection to allow model validation.
- Again, key New Zealand grass species will need to be identified as the priority for validation of any of these pasture growth model or remote sensing approaches.

- The potential to obtain additional grass vegetation characteristics, such as height and cover, from satellite data or LiDAR surveys (e.g. optical depth or texture) for different grass types, areas of the country and time of year should also be investigated. This data could improve fuel load estimation based on existing simple height/cover models, or from remote sensing approaches.

General issues

- A key issue associated with all the above areas is having accurate, up-to-date data to underpin the application of any models or predictive relationships developed.
- This particularly applies to maps for New Zealand vegetation cover, even at the generic fuel-type level (forests, grassland and scrublands), but preferably for subsidiary fuel types; i.e. by forest type/species and age, grass types/species (esp. pasture vs tussock), and scrub type/species. Additional vegetation properties (e.g. height, cover) will also likely be required, as will regular updating to ensure the data is current.
- Similarly, accurate data on soil types and properties will be required to underpin soil moisture estimation, as well as vegetation modelling.
- Access will also be required to the necessary satellite data required for input into the various models. In some cases, as currently for some of the Australian approaches to grass curing, this may require combining data from different sources or satellites (e.g. MODIS and SPOT) which may have different overpass frequencies, spatial coverage or resolutions.
- A platform, such as a new stand-alone application or online web interface, along with the underpinning data storage, programming and mapping capabilities (like the Australian Flammability Monitoring System), will likely also be required to calculate and display modelled properties. This will need to be able to transfer data to and from other systems (such as the Fire Weather System).
- Field validation of the outputs will also need to be undertaken to ensure that any information provided is accurate. This is probably best achieved through a network of trained field observers, such as has been suggested for a new grass curing monitoring system. Field assessment procedures would also need to be developed to support these observers and to ensure consistency. Policies around how any field observations are utilised in the system may also need to be determined.
- Any new models implemented are also likely to need further and, in some cases, ongoing research to refine and improve them for the highly variable New Zealand environment, especially where they have been adopted from overseas.

Acknowledgments

The use of soil moisture data from the NIWA Climate Database, CliFlo (https://cliflo.niwa.co.nz/) is acknowledged. Funding for this research was provided by Fire and Emergency New Zealand (FENZ). Thanks are also extended to Darrin Woods (National Wildfire Specialist, FENZ) for feedback during the project and review of this report.

References

Abbott, K.N., Alexander, M.E., MacLean, D.A., Leblon, B., Beck, J.A., & Staples, G.C. (2007). Predicting forest floor moisture for burned and unburned Pinus banksiana forests in the Canadian Northwest Territories. International Journal of Wildland Fire, 16, 71-80.

Alexander, M.E. (2008). Proposed revision of fire danger class criteria for forest and rural areas of New Zealand, 2nd edition. National Rural Fire Authority, Wellington, in association with the Scion Rural Fire Research Group, Christchurch, New Zealand.

Alexander, M.E., & Pearce, H.G. (1993). The Canadian fire danger ratings associated with the 1991 Oakland/Berkeley Hills Fire. Wildfire News and Notes 7(2): 1,5.

Anderson, S. (2005). Forest and rural fire danger rating in New Zealand. In: Colley, M. (ed.). Forestry Handbook. New Zealand Institute of Forestry, Christchurch. pp 214-244.

Anderson, S.A.J., & Pearce, H.G. (2003). Improved methods for the assessment of grassland curing. In: Proceedings, 3rd International Wildland Fire Conference, Sydney, Australia.

Anderson, S.A.J., Anderson, W.R., Hollis, J.J., & Botha, E.J. (2011). A simple method for field-based grassland curing assessment. International Journal of Wildland Fire, 20, 804-814.

Andrews, P.L., Anderson, S.A.J., & Anderson, W.R. (2006). Evaluation of a dynamic load transfer function using grassland curing data. In: Andrews, P.L. & Butler, B.W. (comps.). Fuels Management – How to Measure Success: Conference Proceedings, Fuels & Fire Behaviour Conference, 28-30 March 2006, Portland, OR. Proceedings RMRS-P-41. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Babaeian, E., Sadeghi, M., Jones, S.B., Montzka, C., Vereecken, H., & Tuller, M. (2019). Ground, proximal, and satellite remote sensing of soil moisture. Reviews of Geophysics, 57, 530-616.

Barton, K. (2020). MuMIn: multi-model inference, R package version 1.43.17. https://CRAN.R-project.org/package=MuMIn.

Bates, D., Maechler, M., Bolker, B. & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48.

Baxter, G.J., & Woodward, S.J.R. (1999). Estimating grassland curing using soil moisture indicators and a pasture quality model. In: Proceedings, Australian Bushfire 99 Conference, Albury, NSW, 7-9 July 1999. pp 33-38.

Ceccato, P., Gobron, N., Flasse, S., Pinty, B., & Tarantola, S. (2002). Designing a spectral index to estimate vegetation water content from remote sensing data: Part 1: Theoretical approach. Remote Sensing of Environment, 82, 188-197.

Chaivaranont, W., Evans, J.P, Liu, Y.Y., & Sharples, J.J. (2018). Estimating grassland curing with remotely sensed data. Natural Hazards & Earth System Science, 18, 1535-1554.

Cheney, N.P., Gould, J.S., & Hutchings, P.T. (1989). Prediction of fire spread in grassland. Report distributed to collaborators, CSIRO National Bushfire Research Unit, Canberra, ACT.

Chladil, M., & Nunez, M. (1995). Assessing grassland moisture and biomass in Tasmania – the application of remote-sensing and empirical-models for a cloudy environment. International Journal of Wildland Fire, 5(3), 165-171.

Chuvieco, E., Riaño, D., Aguado, I., & Cocero, D. (2002). Estimation of fuel moisture content from multitemporal analysis of Landsat thematic mapper reflectance data: applications in fire danger assessment. International Journal of Remote Sensing, 23, 2145-2162.

Clifford, V., Pearce, G., Wallace, H., Steel, D., & Moller, D. (2018). Evaluation of grass curing assessment methods for application in New Zealand. Fire and Emergency New Zealand, Wellington. Fire and Emergency New Zealand Research Report Number 165. https://fireandemergency.nz/assets/Documents/Files/Report-165-Evaluation-of-grass-curing-assessment-methods-for-application.pdf

Country Fire Authority. (2014). Grassland Curing Guide. Country Fire Authority, Melbourne, Vic.

Cruz, M.G., Kidnie, S., Matthews, S., Hurley, R.J., Slijepcevic, A., Nichols, D., & Gould, J.S. (2016). Evaluation of the predictive capacity of dead fuel moisture models for eastern Australia grasslands. International Journal of Wildland Fire, 25, 995-1001.

CSIRO (2007). Grassgro brochure. Produced by CSIRO Plant Industry Communication Group. http://www.GRAZPLAN.csiro.au/files/brchr_grassgro.pdf

DairyNZ. (2021). Pasture Growth Forecaster. Dairy New Zealand. http://pasture-growth-forecaster.dairynz.co.nz/

Delegido, J., Verrelst, J., Rivera, J.P., Ruiz-Verdú, A., Moreno, J. (2015). Brown and green LAI mapping through spectral indices. International Journal of Applied Earth Observation & Geoinformation, 35(B), 350-358.

Dilley, A.C., Millie, S., O'Brien, D. M., & Edwards, M. (2004). The relation between Normalized Difference Vegetation Index and vegetation moisture content at three grassland locations in Victoria, Australia. International Journal of Remote Sensing, 25, 3913-3930.

Donnelly, J.R., Moore, A.D., & Freer, M. (1997). GRAZPLAN: Decision support systems for Australian grazing enterprises. I. Overview of the GRAZPLAN project, and a description of the MetAccess and LambAlive DSS. Agricultural Systems, 54(1), 57-76.

Everson, T.M., Everson, C.S., Dicks, H.M., & Poulter, A.G. (1988). Curing rates in the grass sward of the Highland Sourveld in the Natal Drakensberg. African Forestry Journal, 145(1), 1-8.

García, M., Chuvieco, E., Nieto, H., & Aguado, I. (2008). Combining AVHRR and meteorological data for estimating live fuel moisture content. Remote Sensing of Environment, 112, 3618-3627.

Garvey, M., & Millie, S. (2000). Grassland Curing Guide. Country Fire Authority, Community Safety Department, Melbourne.

Gill, A.M., King, K.J., & Moore, A.D. (2010). Australian grassland fire danger using inputs from the GRAZPLAN grassland simulation model. International Journal of Wildland Fire, 19(3), 338-345.

Griffith, J.A., Price, K.P., & Martinko, E.A. (2001). A multivariate analysis of biophysical parameters of tallgrass prairie among land management practices and years. Environmental Monitoring & Assessment, 68, 249-271.

Hartig, F. (2020). DHARMa: residual diagnostics for hierarchical (multi-level/mixed). Regression models. R package version 0.3.2.0. https://CRAN.R-project.org/package=DHARMa.

Harvest (2019). Soil moisture monitoring. Harvest Electronics Ltd, June 2019. 6 p. http://harvest.com/assets/Brochures/Soil-Moisture-White-Paper.pdf

Hutchinson, G.K., Richards, K., & Risk, W.H. (2000). Aspects of accumulated heat patterns (growing degree days) and pasture growth in Southland. Proceedings of the New Zealand Grassland Association, 62, 81-85.

Jiang, Y., Tao, J., Huang, Y., Zhu, J., Tian, L., & Zhang, Y. (2014). The spatial pattern of grassland aboveground biomass on Xizang Plateau and its climatic controls. Journal of Plant Ecology, 8(1): 30-40.

Johnson, E., Keith, D. & Martin, Y. (2013). Comparing measured duff moisture with a water budget model and the duff and drought codes of the Canadian Fire Weather Index. For. Sci. 2013, 59, 78-92.

Keetch, J.J., & Byram, G.M. (1968). A drought index for forest fire control. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina. Research Paper SE-38.

Keith, D.M., Johnson, E.A., & Valeo, C. (2010a). A hillslope forest floor (duff) water budget and the transition to local control. Hydrological Processes, 24(19): 2738-2751.

Keith, D.M., Johnson, E.A., & Valeo, C. (2010b). Moisture cycles of the forest floor organic layer (F and H layers) during drying. Water Resources Research, 46(7): W07529.

Kidnie, S., Cruz, M.G., Gould, J., Nichols, D., Anderson, W., & Bessell, R. (2015). Effects of curing on grassfires: I. Fuel dynamics in a senescing grassland. International Journal of Wildland Fire, 24, 828-837.

Kidnie, S., & Wotton, B.M. (2015). Characterisation of the fuel and fire environment in southern Ontario’s tallgrass prairie. International Journal of Wildland Fire, 24, 1118-1128.

Kidnie, S.K., Wotton, B.M., & Droog, W.N. (2010). Field guide for predicting fire behaviour in Ontario’s tallgrass prairie. Ontario Ministry of Natural Resources, Aylmer, Ontario, Canada.

King, K.J., Cary, G.J., Gill, A.M., & Moore, A.D. (2012). Implications of changing climate and atmospheric CO2 for grassland fire in south-east Australia: insights using the GRAZPLAN grassland simulation model. International Journal of Wildland Fire, 21(6), 695-708.

Lawson, B.D. (1977). Fire Weather Index - the basis for fire danger rating in British Columbia. Canadian Forestry Service, Pacific Forestry Research Centre, Victoria, British Columbia. Report BC-P-17. 24 p

Lawson, B.D., & Armitage, O.B. (2008). Weather guide for the Canadian Forest Fire Danger Rating System. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB. 73 p.

Lawson, B.D., Armitage, O.B., & Hoskins, W.D. (1996). Diurnal variation in the Fine Fuel Moisture Code: Tables and computer source code. Natural Resources Canada, Canadian Forest Service and British Columbia Ministry of Forests, Pacific Forestry Centre and Research Branch, Victoria, BC, Canada. FRDA Report 245, 20 p.

Lawson, B.D., & Dalrymple, G.N. (1996). Ground-truthing the Drought Code: Field verification of overwinter recharge of forest floor moisture. Canada-British Columbia Partnership Agreement on Forest Resources Development, Pacific Forestry Centre and Research Branch, Victoria, BC, Canada. FRDA Rep. 268, 21 p.

Lawson, B.D., Dalrymple, G.N., & Hawkes, B.C. (1997). Predicting forest floor moisture contents from duff moisture code values. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Forest Research Applications Technology. Transfer Note 6.

Mark, A.F. (1965). Flowering, seeding, and seedling establishment of narrow-leaved snow tussock, Chionochloa rigida. New Zealand Journal of Botany, 3, 180-193.

Marsden-Smedley, J.B, & Catchpole, W.R. (2001). Fire modelling in Tasmanian buttongrass moorlands. III. Dead fuel moisture. International Journal of Wildland Fire, 10, 241-253.

Martin, D., Chen, T., Nichols, D., Bessell, R., Kidnie, S., & Alexander, J. (2015). Integrating ground and satellite-based observations to determine the degree of grassland curing. International Journal of Wildland Fire, 24, 329–339.

Martin, D., Grant, I., Jones, S., & Anderson, S. (2009). Development of satellite vegetation indices to assess grassland curing across Australia and New Zealand. In: Jones, S. & Reinke, K. (Eds.) Innovations in Remote Sensing and Photogrammetry. Springer-Verlag, Berlin, Germany. pp 211–227.

McAlpine, R.S. (1990). Seasonal trends in the Drought Code component of the Canadian Forest Fire Weather Index System. Forestry Canada, Petawawa National Forestry Institute, Chalk River, Ontario. Information Report PI-X-97E/F. 36 p.

McGranahan, D.A., Ramaano, R., Tedder, M.J., & Kirkman, K.P. (2016). Variation in grassland fuel curing in South Africa. Fire Ecology, 12, 40-52.

Miller, E.A. (2020). A conceptual interpretation of the Drought Code of the Canadian Forest Fire Weather Index System. Fire, 3, 23.

Moore, A.D., Donnelly, J.R., & Freer, M. (1997). GRAZPLAN: Decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS. Agricultural Systems, 55(4), 535-582.

Mount, A.B. (1972). The derivation and testing of a soil dryness index using runoff data. Forestry Commission of Tasmania, Hobart. Bulletin No. 4.

Muraro, S.J., & Lawson, B.D. (1970). Prediction of duff moisture distribution for prescribed burning. Canadian Forestry Service, Dept. of Fisheries and Forestry. Information Report BC-X-46, 13 p.

Newnham, G., Clifford, V.R., Pearce, G., Grant, I., Wood, S., & Uddstrom, M. (2015). New Zealand grassland curing satellite algorithms development and mapping system implementation. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No. 22828.

Newnham, G.J., Grant, I.F., Martin, D.N., & Anderson, S.A.J. (2010). Improved methods for assessment and prediction of grassland curing: Satellite based curing methods and mapping - Final Report: Project A1.4. Bushfire Cooperative Research Centre, Melbourne, Australia. Report No. A.11.10.

Newnham, G.J., Verbesselt, J., Grant, I.F., & Anderson, S.A.J. (2011). Relative greenness index for assessing curing of grassland fuel. Remote Sensing and Environment, 115, 1456-1463.

Noble, I.R., Bary, G.A.V., & Gill, A.M. (1980). McArthur's fire-danger meters expressed as equations. Australian Journal of Ecology, 5, 201-203.

NZ Fire Research. (2002a). Fire Research Update. Newsletter of the forest and rural fire research Programme, New Zealand Forest Research Institute, Rotorua. (March 2002).

NZ Fire Research. (2002b). Fire Research Update. Newsletter of the forest and rural fire research Programme, New Zealand Forest Research Institute, Rotorua. (June 2002).

NZX. (2020). NZ Pasture Growth Index – A leading indicator of NZ dairy production. NZX and Dairy Futures. http://nzx-prod-s7fsd7f98s.s3-website-ap-southeast-2.amazonaws.com/attachments/NZX/202391/130033.pdf

Otway, S.G., Bork, E.W., Anderson, K.R., & Alexander, M.E. (2007). Predicting sustained smouldering combustion in trembling aspen duff in Elk Island National Park, Canada. International Journal of Wildland Fire, 16, 690-701.

Parry, F.J., McKenzie, B.A. & Lucas, R.J. (1992). Productivity and water use of five pasture grasses in Canterbury. Proceedings of the New Zealand Grassland Association, 54, 135-138.

Partridge, G.W., & Barber, J.R. (1988). Monitoring grassland dryness and fire potential in Australia with NOAA / AVHRR data. Remote Sensing and Environment, 25, 381-394.

Pearce, H.G., Aguilar-Arguello, S. & Gogoski, D. (in prep.). Updated fire danger climatology for New Zealand − 2021 update. Scion, Christchurch. Scion Client Report, in preparation.

Pearce, H.G., Kerr, J.L., Clifford, V.R. & Wakelin, H.M. (2011). Fire climate severity across New Zealand. New Zealand Fire Service Commission, Wellington. New Zealand Fire Service Commission Research Report No. 116. 78 p.

Pearce, H.G., & Whitmore, M.A. (2009). Analysis of seasonal trends in the Drought Code in New Zealand. Scion, Rural Fire Research Group, Christchurch. Scion Client Report No. 12788. 59 p.

Quan, X., Yebra, M., Riaño, D., He, B., Lai, G., & Liu, X. (2021). Global fuel moisture content mapping from MODIS. International Journal of Applied Earth Observation and Geoinformation, 101, 102354.

R Development Core Team (2018). R: A Language and Environment for Statistical Computing.

Raaflaub, L.D., & Valeo, C. (2008). Assessing factors that influence spatial variations in duff moisture. Hydrological Processes, 22(15): 2874-2883.

Rees, M., Kelly, D., & Bjørnstad, O.N. (2002). Snow tussocks, chaos, and the evolution of mast seeding. American Naturalist, 160, 44-59.

Sakamoto, Y., Ishiguro, M. & Kitagawa, G. (1986). Akaike information criterion statistics. D Reidel Publishing Company.

Sarker, L.R., & Nichol, J.E. (2011). Improved forest biomass estimates using ALOS AVNIR-2 texture indices. Remote Sensing of Environment, 115, 968-977.

Scion & NRFA (2014). Fire Weather Index System Tables for New Zealand. Scion Rural Fire Research Group, Christchurch, in association with the National Rural Fire Authority, Wellington, New Zealand.

Sharma, S., Carlson, J.D., Krueger, E.S., Engle, D.M., Twidwell, D., Fuhlendorf, S.D., Patrignani, A., Feng, L., & Ochsner, T.E. (2020). Soil moisture as an indicator of growing-season herbaceous fuel moisture and curing rate in grasslands. International Journal of Wildland Fire, 30(1), 57-69.

Sharma, S.; & Dhakal, K. (2021). Boots on the ground and eyes in the sky: A perspective on estimating fire danger from soil moisture content. Fire, 4, 45.

Sharma, S., Ochsner, T.E., Twidwell, D., Carlson, J., Krueger, E.S., Engle, D.M., & Fuhlendorf, S.D. (2018). Non-destructive estimation of standing crop and fuel moisture content in tallgrass prairie. Rangeland Ecology and Management, 71, 356-362.

Shoko, C., Mutanga, O., & Dube, T. (2019). Remotely sensed C3 and C4 grass species aboveground biomass variability in response to seasonal climate and topography. African Journal of Ecology, 57(4), 477-489.

Shoko, C., Mutanga, O., Dube, T., & Slotow, R. (2018). Characterizing the spatio-temporal variations of C3 and C4 dominated grasslands aboveground biomass in the Drakensberg, South Africa. International Journal of Applied Earth Observation & Geoinformation, 68, 51-60.

Sibanda, M., Mutanga, O., Rouget, M., & Kumar, L. (2017). Estimating biomass of native grass grown under complex management treatments using WorldView-3 spectral derivatives. Remote Sensing, 9, 55.

Turner, J.A. (1972). The Drought Code component of the Canadian Forest Fire Behaviour System. Environment Canada, Forestry Service, Ottawa. Publication 1316. 13 p.

Van Wagner, C.E. (1987). Development and structure of the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ontario. Forestry Technical Report 35. 37 p.

Vinodkumar, & Dharssi, I. (2015). Sources of soil dryness measures and forecasts for fire danger rating. Bureau of Meteorology, Melbourne, Vic. Bureau Research Report No. 009 (December 2015).

Vinodkumar, Dharssi, I., Yebra, M., & Fox-Hughes, P. (2021). Continental-scale prediction of live fuel moisture content using soil moisture information. Agricultural and Forest Meteorology, 307, 108503.

Wickham, H. (2016). Ggplot2: Elegrant Graphics for Data Analysis. Springer-Verlag, New York.

Wilmore, B. (2001). Duff moisture dynamics in black spruce–feather moss stands and their relation to the Canadian Forest Fire Danger Rating System. M.S. thesis, School of Natural Resources and Extension, University of Alaska Fairbanks, 84 p.

Woodward, S. (2001). Validating a model that predicts daily growth and feed quality of New Zealand dairy pastures. Environment International, 27, 133-137.

Woodward, S.J.R., McCall, D.G., & Barker, D.J. (1998). Pasture Quality model summary - 16 December 1998. AgResearch Unpublished Report.

Wotton, B.M. (2009). A grass moisture model for the Canadian Forest Fire Danger Rating System. In: Eighth Symposium on Fire and Forest Meteorology, 13-15 October 2009, Kalispell, MT. American Meteorological Society, Boston, MA.

Wotton, B.M, Stocks, B.J., & Martell, D.L. (2005). An index for tracking sheltered forest floor moisture within the Canadian Forest Fire Weather Index System. International Journal of Wildland Fire, 14, 169-182.

Wright, D., Chen, A., Bessell, R., Kidnie, S., Nichols, D., & Slijepcevic, A. (2016). Reducing inconsistencies of grassland curing assessment between multiple jurisdictions across Australia. Proceedings of the 5th International Fire Behaviour and Fuels Conference, April 11-15, 2016, Melbourne, Australia.

Xie, Y., Sha, Z., Yu, M., Bai, Y., & Zhang, L. (2009). A comparison of two models with Landsat data for estimating above ground grassland biomass in Inner Mongolia, China. Ecological Modelling, 220(15), 1810-1818.

Yang, Y., Uddstrom, M., Pearce, G., & Revell, M. (2015). Reformulation of the Drought Code in the Canadian Fire Weather Index System implemented in New Zealand. Journal of Applied Meteorology and Climatology, 54(7), 1523-1537.

Yang, Y., Uddstrom, M., Revell, M., & Moore, S. (2014). Soil moisture simulation by JULES in New Zealand: Verification and sensitivity tests. Meteorological Applications, 21, 888-897.

Yebra, M., Dennison, P.E., Chuvieco, E., Riano, D., Zylstra, P., Hunt Jr., E.R., Danson, F.M., Qi, Y., & Jurdao, S. (2013). A global review of remote sensing of live fuel moisture content for fire danger assessment: Moving towards operational products, Remote Sensing of Environment, 136, 455-468.

Yebra, M., Quan, X., Riano, D., Rozas-Larraondo, P., van Dijk, A., Cary, G. (2018). A fuel moisture content and flammability monitoring methodology for continental Australia based on optical remote sensing. Remote Sensing of Environment, 212, 260-272.

Yebra, M., Scortechini, G., Badi, A., Beget, M.E., Boer, M.M., Bradstock, R., Chuvieco, E., Danson, F.M., Dennison, P., Resco de Dios, V., et al. (2019). Globe-LFMC, a global plant water status database for vegetation ecophysiology and wildfire applications. Scientific Data, 6, 155.

Zumo, I.M., Hashim, M., & Hassan, N.D. (2021). Mapping and estimation of above-ground grass biomass using Sentinel 2A satellite data. International Journal of Built Environment and Sustainability, 8(3), 9-15.

Appendix 1. Graphs of soil moisture and temperature for each station by region

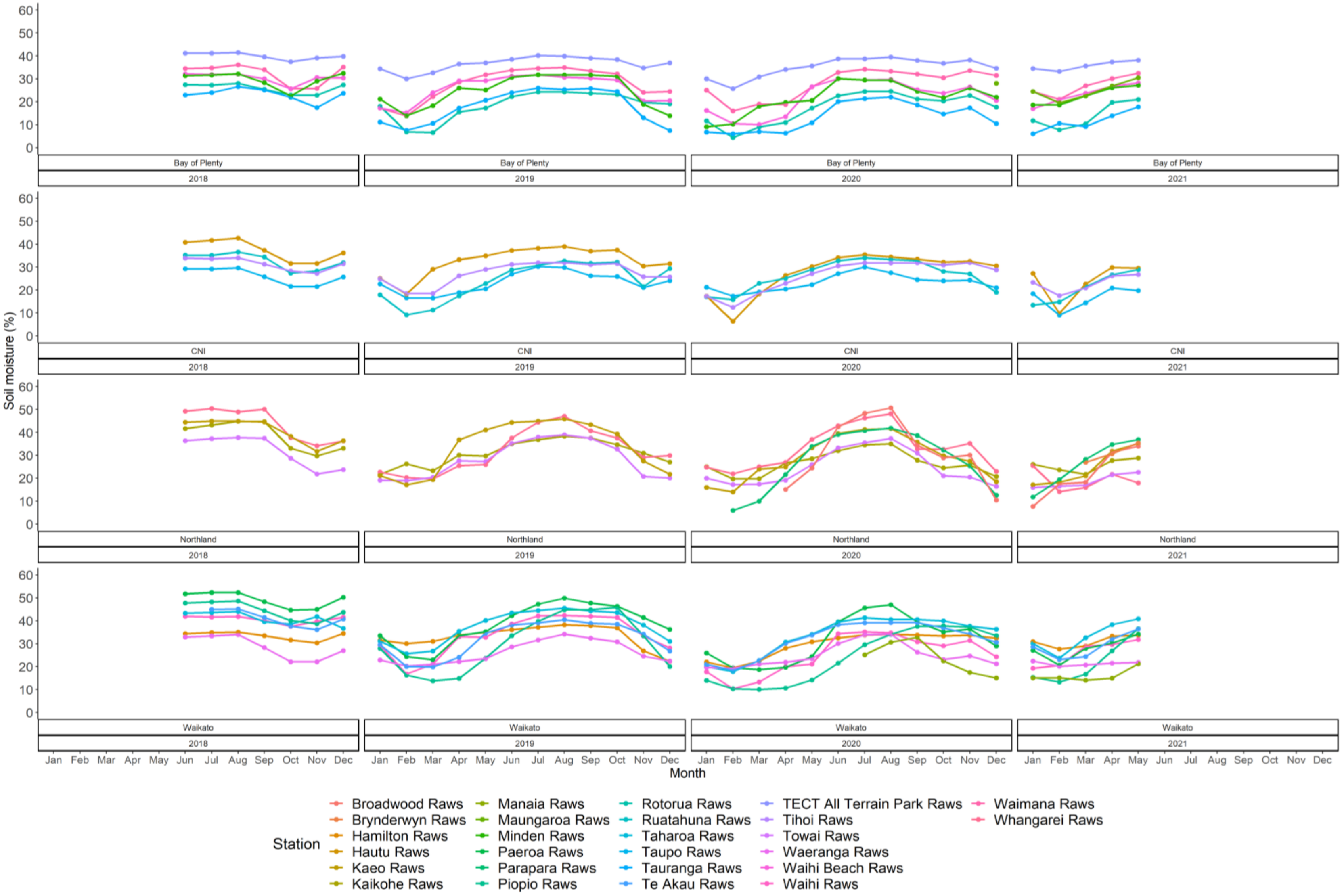


Figure A1: Monthly mean soil moisture contents (as %) from 2018 to 2021 for individual FWSYS stations by region of the North Island (Bay of Plenty, Central North Island (CNI), Northland, and Waikato).

Figure A2: Monthly mean soil moisture contents (as %) from 2018 to 2021 for individual FWSYS stations by region of the North Island (Taranaki, Wairarapa, Wanganui-Manawatu, and Wellington).

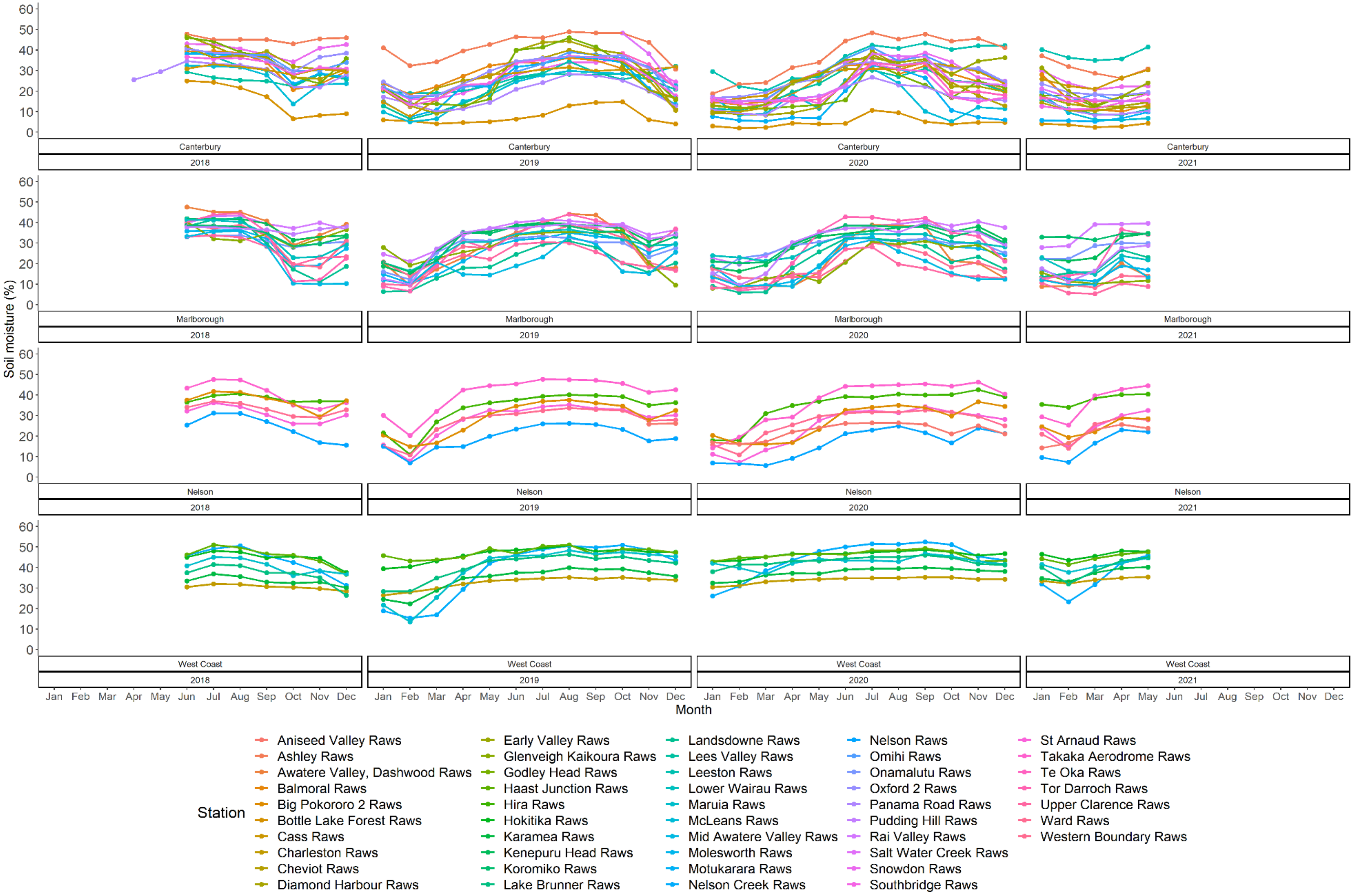


Figure A3: Monthly mean soil moisture contents (as %) from 2018 to 2021 for individual FWSYS stations by region of the South Island (Canterbury, Marlborough, Nelson, and West Coast).

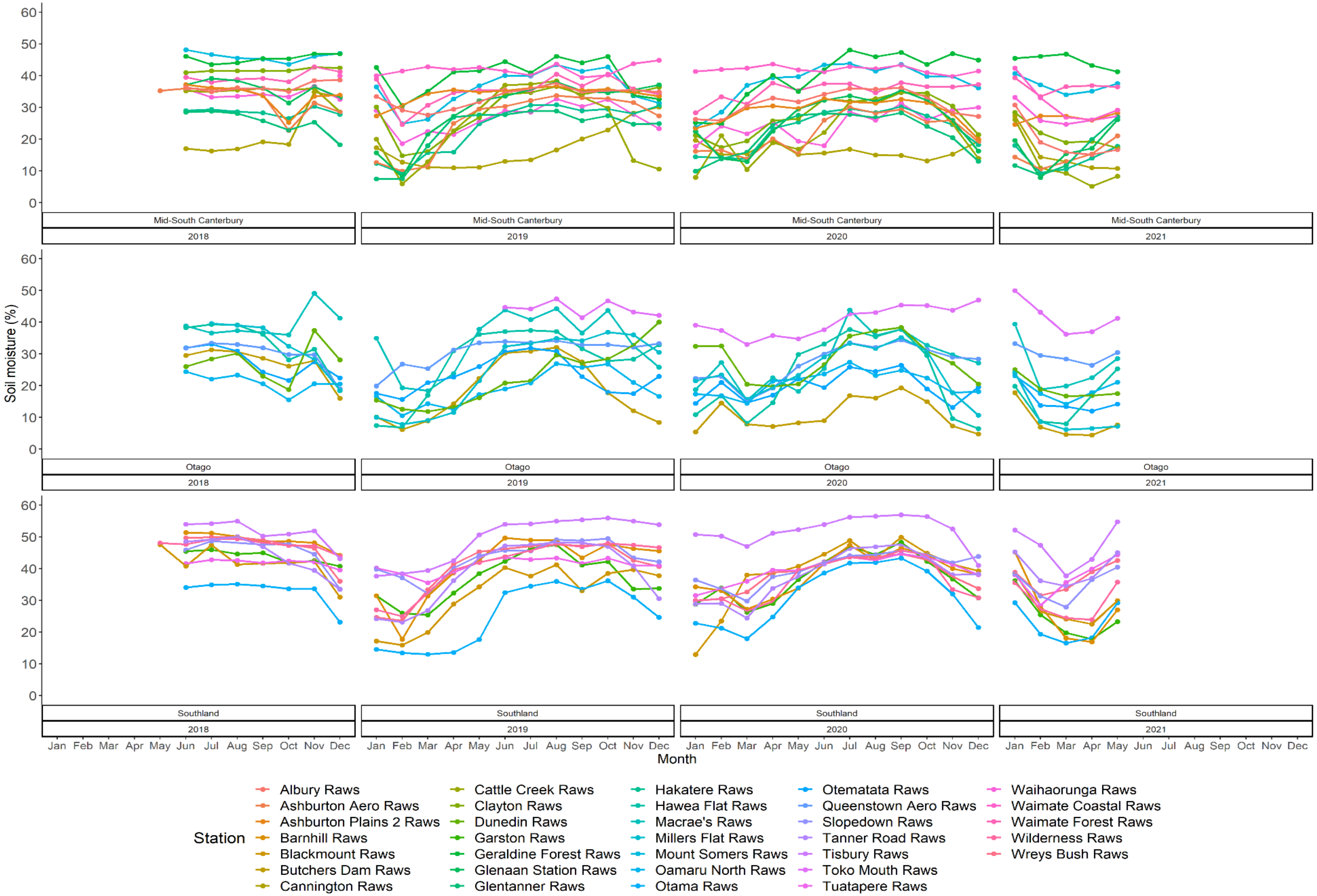


Figure A4: Monthly mean soil moisture contents (as %) from 2018 to 2021 for individual FWSYS stations by region of the South Island (Mid-South Canterbury, Otago, and Southland).

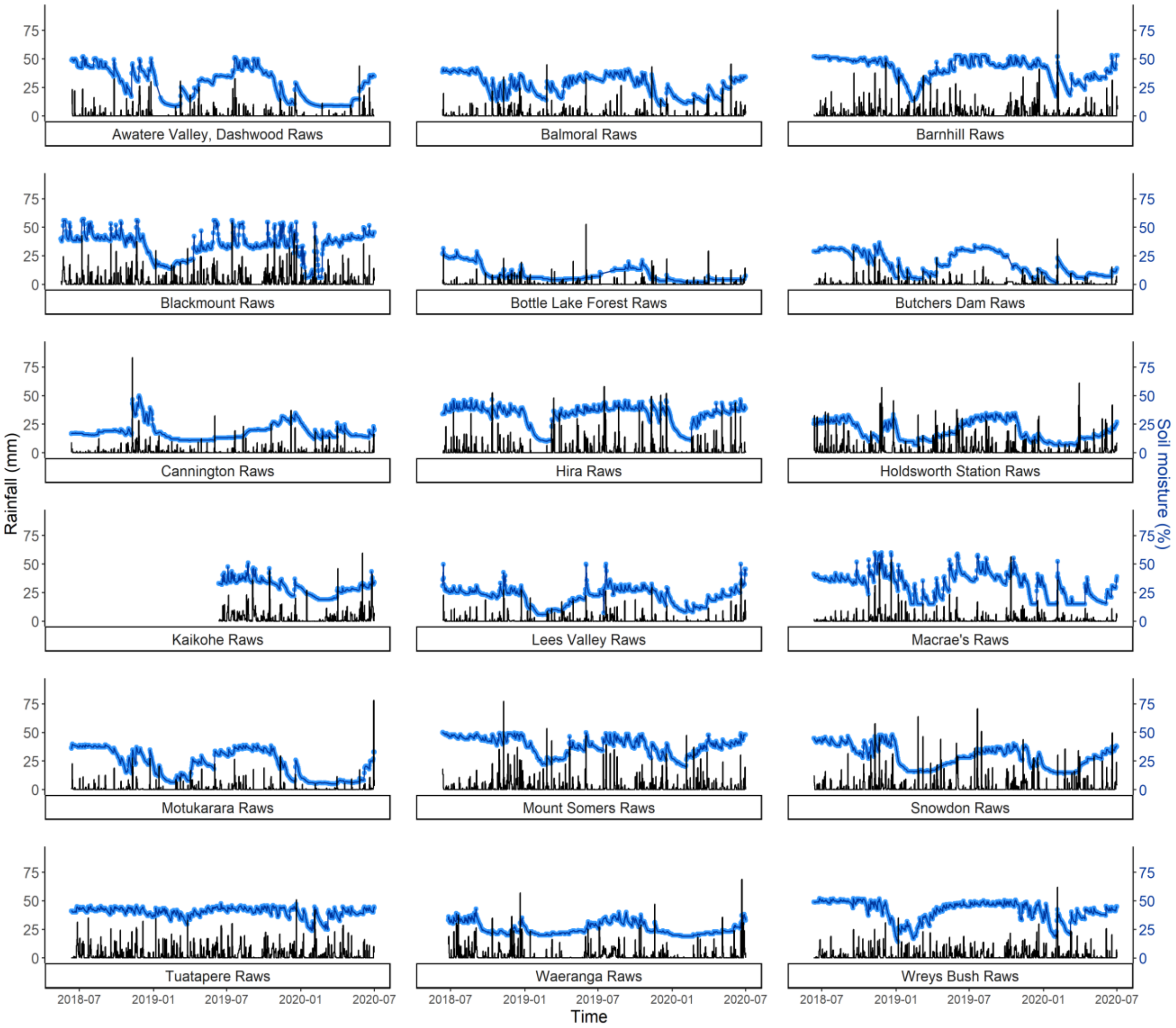


Figure A5: Relationship between mean daily soil moisture contents (blue lines with observations shown as points) and total daily (24-hr) rainfall (black bars) for the period April 2018 to July 2020 for 18 stations spread across New Zealand. Peaks in soil moisture are strongly associated with the occurrence of significant rainfall.

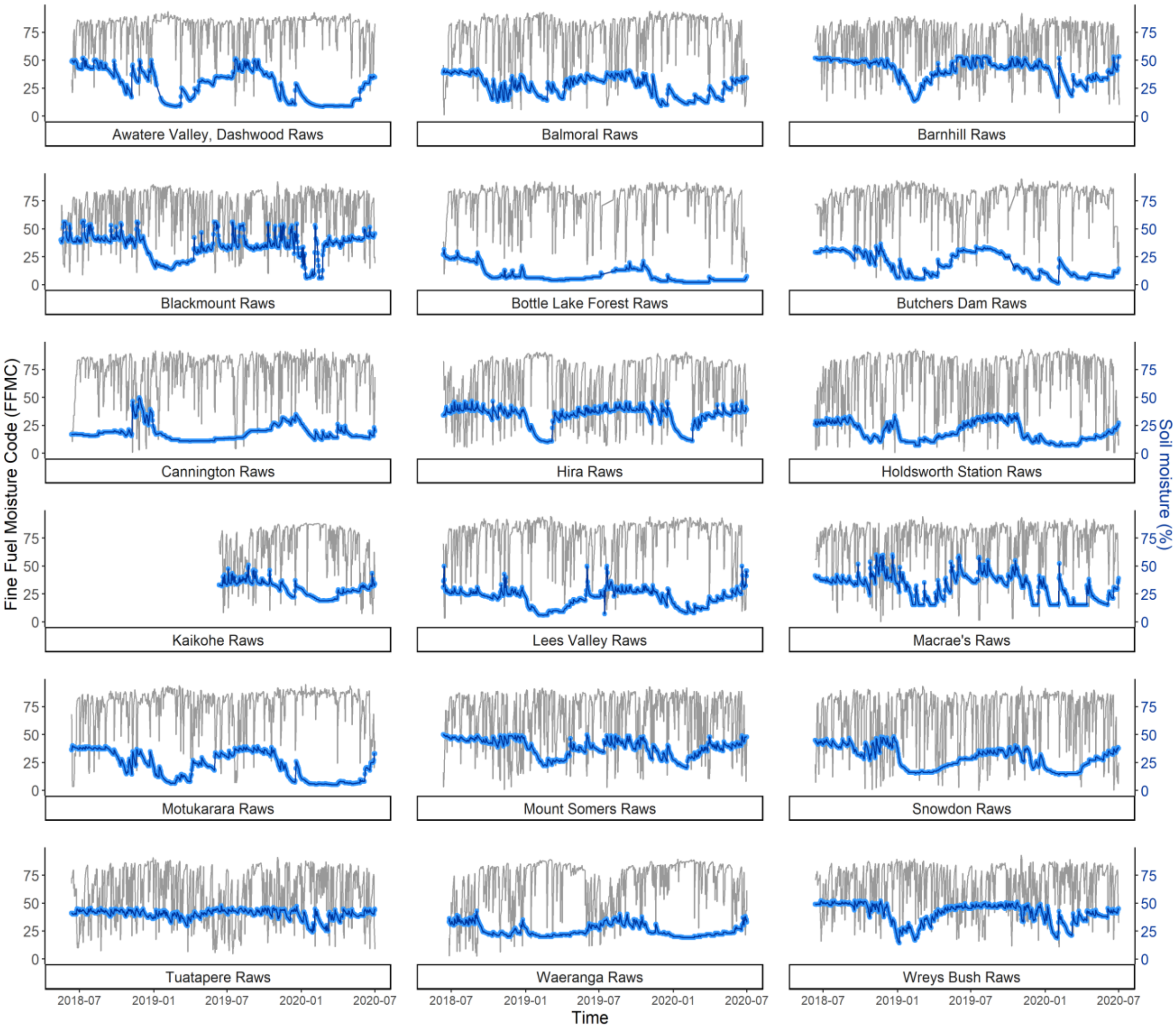


Figure A6: Relationship between mean daily soil moisture contents (blue lines with observations shown as points) and daily Fine Fuel Moisture Code (FFMC, grey lines) from April 2018 to July 2020 for 18 stations spread across New Zealand. Increases in soil moisture generally correspond with low FFMC values, and decreases with high FFMC values.

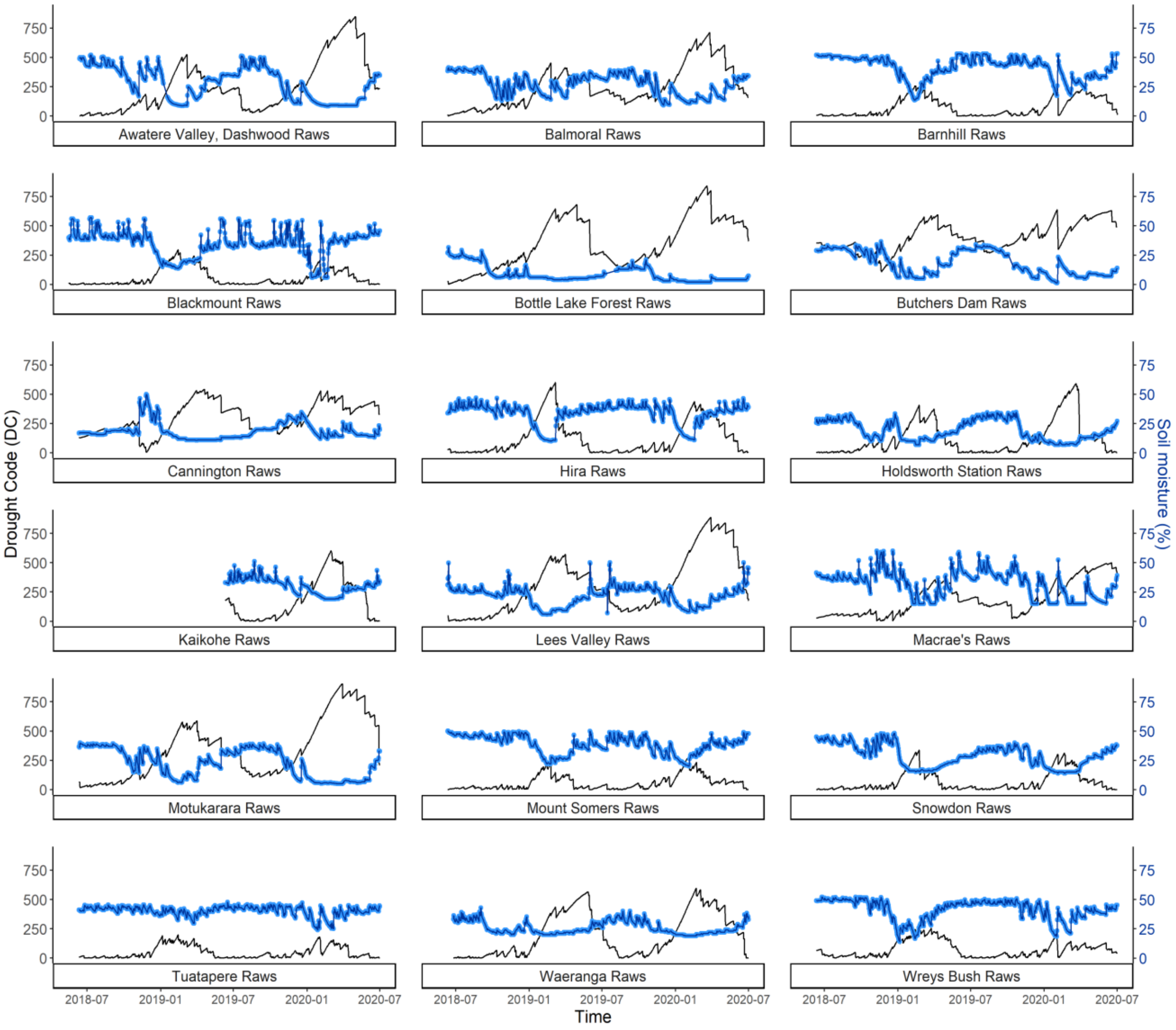


Figure A7: Relationship between mean daily soil moisture contents (blue lines with observations shown as points) and daily Drought Code (DC, black lines) from April 2018 to July 2020 for 18 stations spread across New Zealand. Increases in soil moisture correspond well with low DC values, and decreases with high DC values.

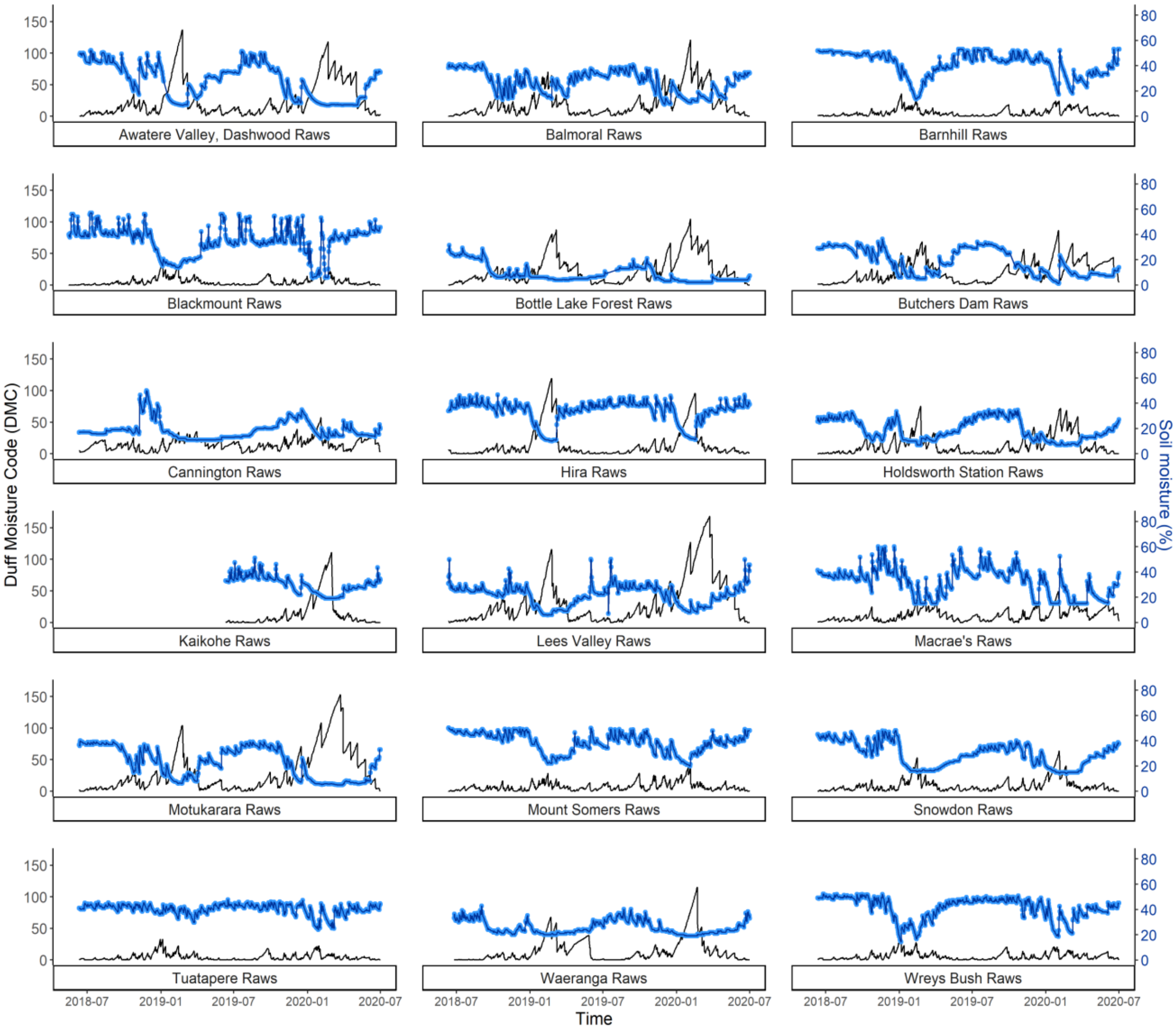


Figure A8: Relationship between mean daily soil moisture contents (blue lines with observations shown as points) and daily Duff Moisture Code (DMC, black lines) from April 2018 to July 2020 for 18 stations spread across New Zealand. Increases in soil moisture correspond well with low DMC values, and decreases with high DMC values.

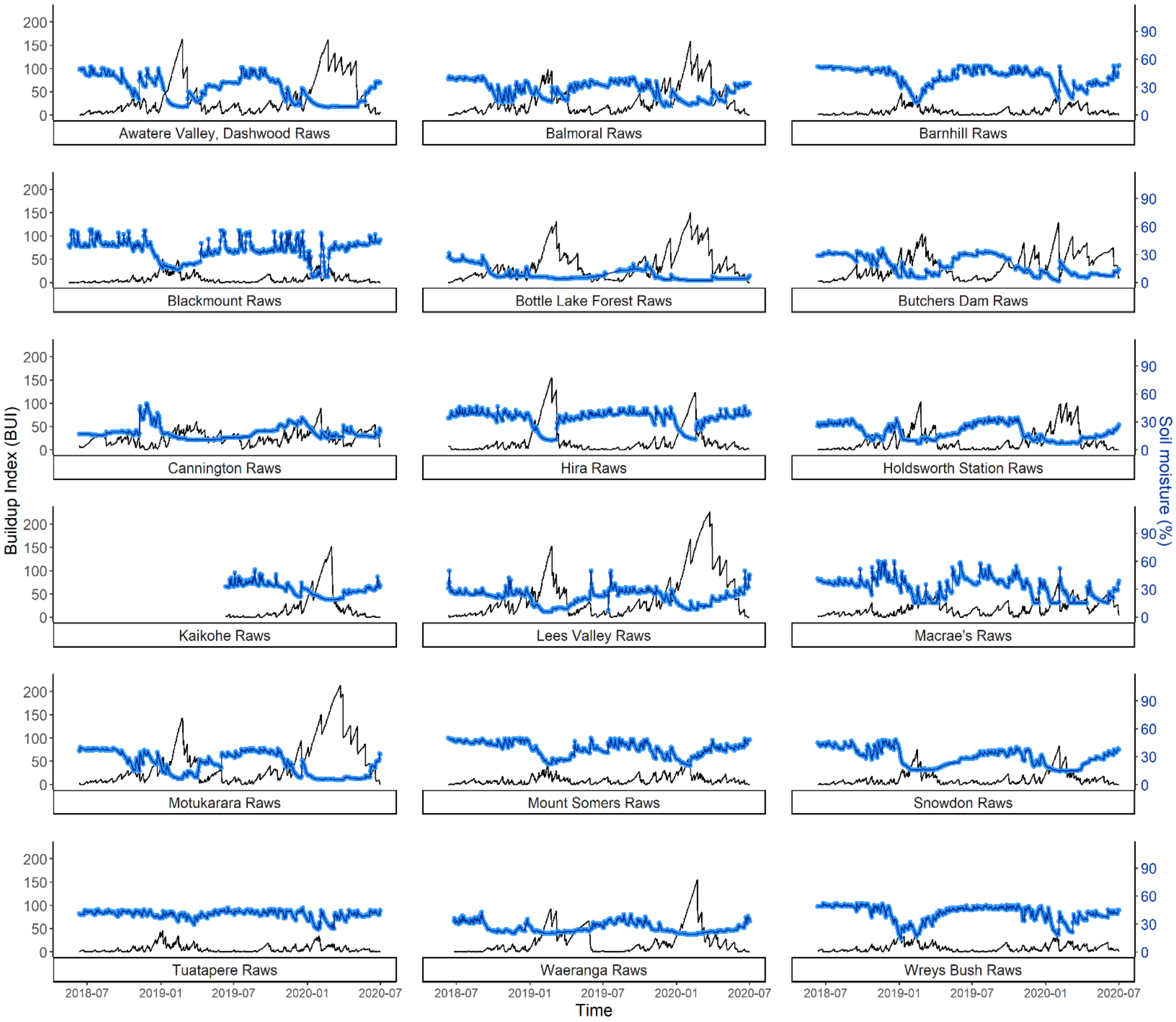


Figure A9: Relationship between mean daily soil moisture contents (blue lines with observations shown as points) and daily Buildup Index (BUI, black lines) from April 2018 to July 2020 for 18 stations spread across New Zealand. Increases in soil moisture generally correspond with low BUI values, and decreases with high BUI values.

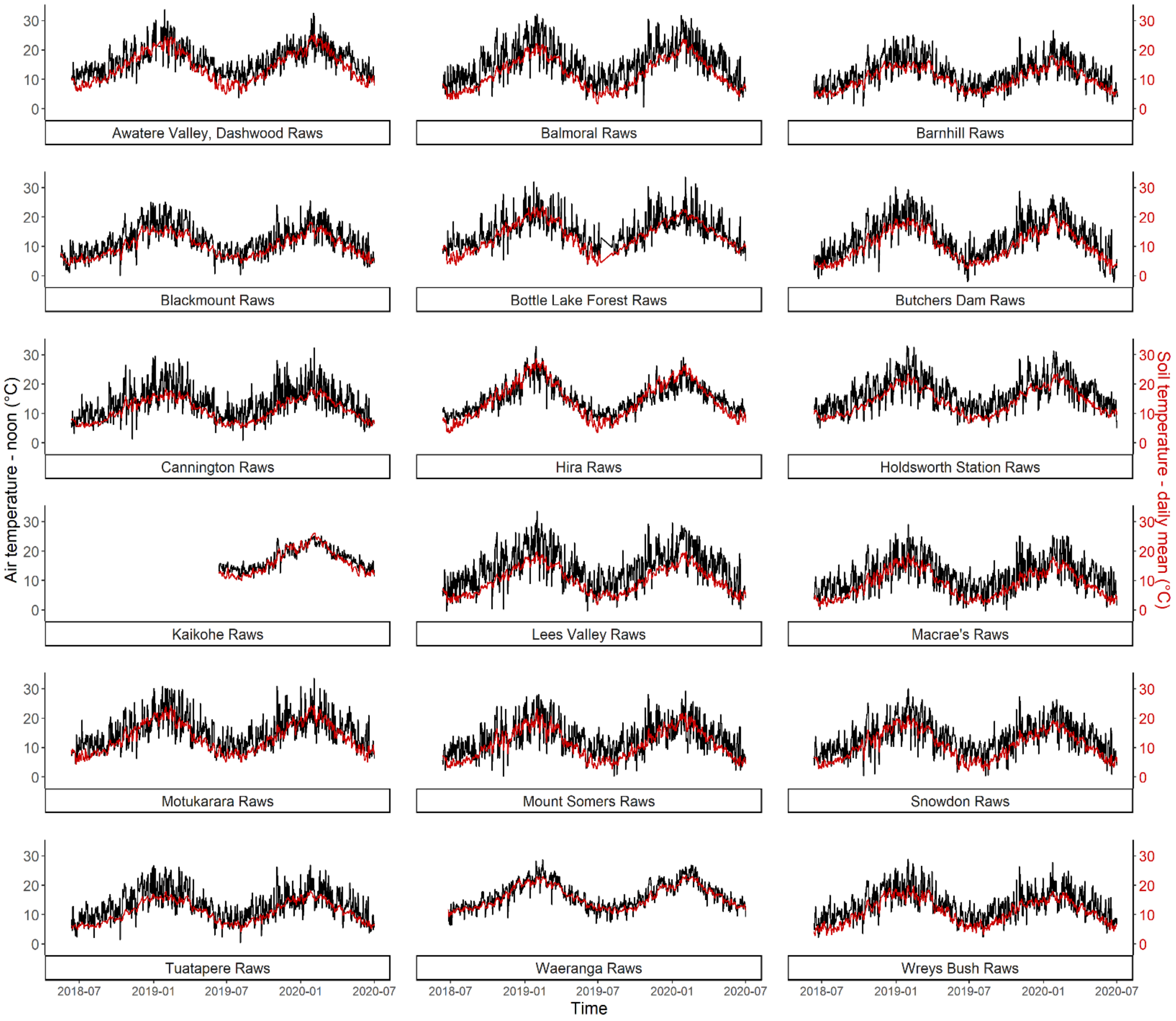


Figure A10: Relationship between mean daily soil temperature (red lines) and daily noon air temperature (black lines) from April 2018 to July 2020 for 18 stations spread across New Zealand. Soil temperature values are strongly correlated with but generally lower than observed air temperatures.

Appendix 2. Station data summary

ISLAND	FENZ.REGION	Station	Start Date	Frequency (Days)					Total Values
				10min	1hour	30min	other	Total Days	
North Island	Northland	Kaeo Raws	11-Jun-2018	934			98	1032	146664
		Kaikohe Raws	11-Jun-2018	1061			14	1075	154537
		Towai Raws	11-Jun-2018	950	3	3	119	1075	148090
		Whangarei Raws	11-Jun-2018	886			175	1061	152053
		Parapara Raws	29-Feb-2020	410			19	429	61489
		Broadwood Raws	12-Apr-2020	314	1		68	383	48401
		Brynderwyn Raws	11-Mar-2021	67			4	71	10030
	Waikato	Hamilton Raws	11-Jun-2018	1045			30	1075	154514
		Paeroa Raws	11-Jun-2018	1038			37	1075	154503
		Piopio Raws	11-Jun-2018	1049			26	1075	154508
		Taharoa Raws	11-Jun-2018	1033			26	1059	151949
		Te Akau Raws	24-Jul-2018	560			470	1030	146706
		Waeranga Raws	25-Jun-2018	1028			33	1061	152419
		Waihi Raws	11-Jun-2018	1009		1	39	1049	149632
		Manaia Raws	17-Jul-2020	252			56	308	44008
	Bay of Plenty	Minden Raws	11-Jun-2018	1060			15	1075	154549
		Tauranga Raws	11-Jun-2018	1012			63	1075	154282
		TECT All Terrain Park Raws	11-Jun-2018	1044			20	1064	152886
		Waihi Beach Raws	11-Jun-2018	1043			30	1073	154043
		Waimana Raws	11-Jun-2018	940			75	1015	142367
		Rotorua Raws	11-Jun-2018	1026			49	1075	154453
		Maungaroa Raws	17-Dec-2020			153	2	155	7343
	Central North Island	Hautu Raws	11-Jun-2018	1012		5	42	1059	149035
		Ruatahuna Raws	11-Jun-2018			1036	39	1075	51065
		Taupo Raws	11-Jun-2018	1006			69	1075	154339
		Tihoi Raws	11-Jun-2018	1054			20	1074	154278

North Island (cont.)	Taranaki	Ngamatapouri Raws	11-Jun-2018			1022	50	1072	50637
		Opunake Raws	11-Jun-2018	1053			20	1073	154045
		Tikorangi Raws	11-Jun-2018	1010		2	57	1069	151322
		Whareroa Raws	11-Jun-2018	1045			30	1075	154539
	Wanganui-Manawatu	Alfredton South Raws	11-Jun-2018	1024			51	1075	154502
		Feilding Raws	11-Jun-2018	836			239	1075	153839
		Hunterville Raws	11-Jun-2018	1041			18	1059	151902
		National Park Raws	11-Jun-2018	1059			16	1075	154553
		Ranana Raws	11-Jun-2018		3	1015	57	1075	50867
		Waimarino Forest Raws	11-Jun-2018	1058			17	1075	154570
		Waione East Raws	11-Jun-2018	1054			21	1075	154563
		Whanganui Raws	11-Jun-2018	1050			25	1075	154515
		Waitarere Raws	5-Aug-2020	278			11	289	41405
	East Coast/Hawkes Bay	Gisborne Raws	11-Jun-2018	1058			17	1075	154532
		Kaitawa Raws	11-Jun-2018	1017			48	1065	151932
		Napier Raws	11-Jun-2018	316			759	1075	152488
		Porangahau Raws	11-Jun-2018	1063			12	1075	154560
		Wairoa Raws	11-Jun-2018	845			230	1075	154193
	Wairarapa	Crofoot Raws	11-Jun-2018	728			260	988	140843
		Featherston Raws	11-Jun-2018	948			122	1070	151398
		Haurangi Raws	16-May-2018	1066			35	1101	157950
		Holdsworth Station Raws	11-Jun-2018	1051			21	1072	153905
		Homebush Raws	11-Jun-2018	997			77	1074	153758
		Ngaumu Forest 2 Raws	11-Jun-2018	1042			26	1068	153070
		Palliser Raws	11-Jun-2018	983			75	1058	151136
		Stony Creek Raws	11-Jun-2018		2	813	33	848	40195
		Te Muna Raws	4-Jun-2019	683			34	717	102987
		Tinui Raws	24-Jan-2019	796			52	848	121729
	Wellington	Long Gully Raws	11-Jun-2018	1049			26	1075	154506
		Remutaka Forest Park Raws	11-Jun-2018	951			110	1061	147872

ISLAND	FENZ.REGION	Station	Start Date	Frequency (Days)					Total Values
				10min	1hour	30min	other	Total Days	
South Island	Nelson	Big Pokororo 2 Raws	11-Jun-2018	875	1	4	192	1072	147891
		Hira Raws	11-Jun-2018	1056			19	1075	154514
		Nelson Raws	11-Jun-2018	1045			21	1066	153179
		St Arnaud Raws	11-Jun-2018	1055			20	1075	154527
		Takaka Aerodrome Raws	11-Jun-2018	1054			21	1075	154542
		Western Boundary Raws	11-Jun-2018	1033			42	1075	154401
		Aniseed Valley Raws	8-Nov-2019	345			215	560	80130
	Marlborough	Awatere Valley, Dashwood Raws	12-Jun-2018	978			87	1065	151014
		Glenveigh Kaikoura Raws	11-Jun-2018	1023		1	43	1067	152221
		Kenepuru Head Raws	11-Jun-2018	284		536	180	1000	75064
		Koromiko Raws	11-Jun-2018	1040			35	1075	154255
		Landsdowne Raws	11-Jun-2018	877	3	1	183	1064	143405
		Lower Wairau Raws	11-Jun-2018	811	165		97	1073	133166
		Mid Awatere Valley Raws	11-Jun-2018			1045	30	1075	51046
		Molesworth Raws	11-Jun-2018			1056	19	1075	51264
		Onamalutu Raws	11-Jun-2018	765			307	1072	152619
		Pudding Hill Raws	11-Jun-2018			1044	31	1075	51059
		Rai Valley Raws	11-Jun-2018	55		946	42	1043	54765
		Tor Darroch Raws	11-Jun-2018			982	93	1075	50713
		Upper Clarence Raws	11-Jun-2018		2	1021	50	1073	50425
		Ward Raws	11-Jun-2018	1033			38	1071	153815
	Canterbury	Ashley Raws	11-Jun-2018	1015			60	1075	154482
		Balmoral Raws	11-Jun-2018	995			80	1075	153045
		Bottle Lake Forest Raws	11-Jun-2018	474			572	1046	148032
		Cass Raws	11-Jun-2018	288	1	742	44	1075	79374
		Cheviot Raws	11-Jun-2018	898			176	1074	147007
		Diamond Harbour Raws	11-Jun-2018	888			187	1075	154298
		Early Valley Raws	15-Oct-2019	569			15	584	83851

South Island (cont.)	Canterbury (cont.)	Godley Head Raws	11-Jun-2018	1012		1	60	1073	152823
		Lees Valley Raws	11-Jun-2018		2	999	67	1068	50355
		Leeston Raws	11-Jun-2018	1034			41	1075	154328
		McLeans Raws	11-Jun-2018	1054			21	1075	154517
		Motukarara Raws	11-Jun-2018	205	1	782	87	1075	71857
		Omihi Raws	11-Jun-2018	1024			51	1075	154459
		Oxford 2 Raws	11-Jun-2018	1030			45	1075	154354
		Panama Road Raws	15-Apr-2018		1	1094	37	1132	53702
		Salt Water Creek Raws	16-Oct-2019	572			11	583	83726
		Snowdon Raws	11-Jun-2018	1036			39	1075	154521
		Southbridge Raws	11-Jun-2018	982			93	1075	153622
		Te Oka Raws	21-Oct-2019		1	569	8	578	27533
	Mid-South Canterbury	Albury Raws	11-Jun-2018	1016			59	1075	154302
		Ashburton Aero Raws	16-May-2018	1017			80	1097	155407
		Ashburton Plains 2 Raws	11-Jun-2018	1033			42	1075	154519
		Cannington Raws	11-Jun-2018	1046			29	1075	154424
		Cattle Creek Raws	11-Jun-2018	885		1	186	1072	148371
		Clayton Raws	11-Jun-2018	960			115	1075	154155
		Geraldine Forest Raws	11-Jun-2018	999		1	75	1075	153323
		Glenaan Station Raws	11-Jun-2018	568			507	1075	151715
		Glentanner Raws	11-Jun-2018	986			58	1044	149863
		Hakatere Raws	11-Jun-2018			1029	46	1075	50957
		Mount Somers Raws	11-Jun-2018	1025			50	1075	154466
		Waihaorunga Raws	11-Jun-2018	1001			72	1073	153205
		Waimate Coastal Raws	11-Dec-2018	814			78	892	129008
		Waimate Forest Raws	11-Jun-2018	1034			31	1065	153033
		Timaru Coastal Raws	11-Jun-2018	1037			37	1074	154059
		Pukaki Aero Raws	11-Jun-2018	827			241	1068	146522
	West Coast	Charleston Raws	11-Jun-2018	536			539	1075	152922
		Haast Junction Raws	11-Jun-2018	782	106	79	108	1075	133488
		Hokitika Raws	11-Jun-2018	1012		1	61	1074	153547
		Karamea Raws	11-Jun-2018	986			89	1075	154418

South Island (cont.)	West Coast (cont.)	Lake Brunner Raws	11-Jun-2018	989			86	1075	154416
		Maruia Raws	11-Jun-2018	1055			20	1075	154518
		Nelson Creek Raws	11-Jun-2018	753			322	1075	153852
	Otago	Butchers Dam Raws	11-Jun-2018	1021		1	40	1062	151861
		Dunedin Raws	11-Jun-2018	1052			22	1074	154224
		Hawea Flat Raws	11-Jun-2018	901			164	1065	150367
		Macrae's Raws	11-Jun-2018	1056			19	1075	154534
		Millers Flat Raws	23-Jul-2018	1008			25	1033	148449
		Otematata Raws	11-Jun-2018	1060			15	1075	154545
		Oamaru North Raws	11-Jun-2018	1030			45	1075	154493
		Queenstown Aero Raws	11-Jun-2018	1043			25	1068	153433
		Toko Mouth Raws	4-Jun-2019	647			70	717	102096
	Southland	Barnhill Raws	11-Jun-2018	1000		1	74	1075	153680
		Blackmount Raws	16-May-2018	1047			54	1101	157290
		Garston Raws	11-Jun-2018	1025		1	46	1072	152316
		Otama Raws	11-Jun-2018	1043			31	1074	154176
		Slopedown Raws	17-Jun-2018		1	869	157	1027	47669
		Tanner Road Raws	11-Jun-2018	1032			34	1066	152975
		Tisbury Raws	11-Jun-2018	1051			24	1075	154538
		Tuatapere Raws	11-Jun-2018	1001			74	1075	153568
		Wilderness Raws	16-May-2018	1071			30	1101	158214
		Wreys Bush Raws	11-Jun-2018	1005			59	1064	152160
Grand Total		**138**		**212560**	**575**	**33114**	**19391**	**265640**	**18181435**