Fire Research Report

Spatial Prediction of Wildfire Hazard Across New Zealand

Landcare Research

June 2001

The objective of this project was to develop high-resolution, spatially explicit data layers describing wildfire hazard across New Zealand. These layers include both fuel moisture codes and fire behaviour indices of the Fire Weather Index (FWI) System (Van Wagner & Pickett 1985), which is widely used by Rural Fire Authorities to provide an indication of climatic conditions leading to high fire danger, and derived layers describing fire behaviour. The resulting digital maps will be key inputs to the subsequent prediction of spatial variation of fire hazard by Rural Fire Authorities, performed as part of a Wildfire Threat Analysis Project.

Weather data measured over time across the NRFA weather station network were used to calculate average fire hazard during the worst 20% of days in the fire season. Mathematical surfaces were fitted to these data to enable estimation of standard fire weather indices (FWI) across New Zealand. The resulting grid data layers (rasters) describing FWI indices were combined with data describing fuel loads and slope to derive additional data layers describing rate of fire spread and head fire intensity.

Results indicate considerable spatial variation in fire threat, with highest threats occurring in warm, dry climates. Data manipulation posed challenges, given the size of the datasets involved and the need to convert complex mathematical equations into object-oriented expressions.

Production of spatial data layers describing spatial variation in fire threat will facilitate the incorporation of more detailed information about spatial variation in fuel loads by rural fire authorities.

J. R. Leathwick and C. M. Briggs

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Spatial Prediction of WildFire Hazard Across New Zealand

J.R. Leathwick
C.M. Briggs
Landcare Research
Private Bag 3127, Hamilton
New Zealand

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PREPARED FOR:

National Rural Fire Authority
P.O Box 2133
Wellington

DATE: June 2001

Reviewed by:

Daniel Rutledge
Scientist
Landcare Research

Approved for release by:

Margaret Lawton
Science Manager
Environmental Quality

Disclaimer

Contents

1. Summary

Project and client

- Spatially explicit data layers describing wild fire hazard across New Zealand were developed by Landcare Research, Hamilton, for the National Rural Fire Authority in January and February 2001.

Objective

- To produce spatially explicit data layers predicting fire hazard across New Zealand for use in the NRFA's Wildfire Threat Analysis Project.

Methods

- Weather data measured over time across the NRFA weather station network were used to calculate average fire hazard during the worst 20% of days in the fire season. Mathematical surfaces were fitted to these data to enable estimation of standard fire weather indices (FWI) across New Zealand. The resulting grid data layers (rasters) describing FWI indices were combined with data describing fuel loads and slope to derive additional data layers describing rate of fire spread and head fire intensity.

Results

- Results indicate considerable spatial variation in fire threat, with highest threats occurring in warm, dry climates. Data manipulation posed challenges, given the size of the datasets involved and the need to convert complex mathematical equations into object-oriented expressions.

Conclusions

- Production of spatial data layers describing spatial variation in fire threat will facilitate the incorporation of more detailed information about spatial variation in fuel loads by rural fire authorities.

2. Introduction

The objective of this project was to develop high-resolution, spatially explicit data layers describing wildfire hazard across New Zealand. These layers include both fuel moisture codes and fire behaviour indices of the Fire Weather Index (FWI) System (Van Wagner & Pickett 1985), which is widely used by Rural Fire Authorities to provide an indication of climatic conditions leading to high fire danger, and derived layers describing fire behaviour. The resulting digital maps will be key inputs to the subsequent prediction of spatial variation of fire hazard by Rural Fire Authorities, performed as part of a Wildfire Threat Analysis Project.

3. Background

3.1. Components of the Fire Weather Index System

The following is a brief description of both the standard components of the Fire Weather Index (FWI) system and the derived layers produced by this project.

3.2. Standard FWI Indices

The Fine Fuel Moisture Code (FFMC): a numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel.

The Duff Moisture Code (DMC): a numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in duff layers of moderate depth and medium-sized woody material.

The Drought Code (DC): a numerical rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, and the amount of smouldering expected in deep duff layers and large logs.

The Initial Spread Index (ISI): a numerical rating of the expected rate of fire spread. It combines the effects of wind and the Fine Fuel Moisture Code on rate of spread without the influence of variable quantities of fuel.

The Buildup Index (BUI): a numerical rating of the total amount of fuel available for combustion that combines the Duff Moisture Code and the Drought Code.

The Fire Weather Index (FWI): a numerical rating of fire intensity that combines the Initial Spread Index and the Buildup Index.

The Daily Severity Rating (DSR): a parameter that estimates the severity of the fire weather for each day. This parameter reflects potential fire intensity, control difficulty, and the amount of work required to suppress a fire. It also allows researchers to compare the severity of fire weather from one year to another.

3.3. Derived FWI Layers

Fuel Load: indicates the dry weight of combustible materials per unit area, measured in kilograms per square metre (kg/m3) or tonnes per hectare (t/ha).

Slope Correction Factor: a dimensionless coefficient that indicates the effect of slope on fire rate of spread . Fire is assumed to travel more rapidly up slope due to heat convection and radiation.

Degree of Cure (DoC): indicates the degree of drying and is used in determining rate of fire spread in grass fuel types.

Rate of Spread (ROS): the progress per unit time of the head fire or another specified part of the fire perimeter, generally measured as metres per hour (m/hr).

Head Fire Intensity (HFI): the portion of a fire edge showing the greatest rate of spread and fire intensity (e.g., up slope).

4. Methods & results

4.1. Prediction of FWI Components from Average Climate Data

As originally conceived, this project was designed to produce predictions of long-run average values for the various Fire Weather Index components by coupling the standard FWI model, coded in Fortran (van Wagner & Pickett 1985), with long-run average climate layers developed by Landcare Research staff (Leathwick & Stephens 1998). Values for these indices were then to be combined with data describing slope and land cover to predict fuel load, slope correction factors, rate of spread (ROS) and head fire intensity (HFI).

4.2. Prediction of FWI Components from NRFA Data.

Initial results using this approach were disappointing, reflecting the degree to which conditions of high fire hazard generally occur during particularly extreme climatic conditions e.g., prolonged warm, dry spells, combined with strong winds that are not well described by long-run average climate statistics. After initial evaluation, they were abandoned in favour of the alternative method described below.

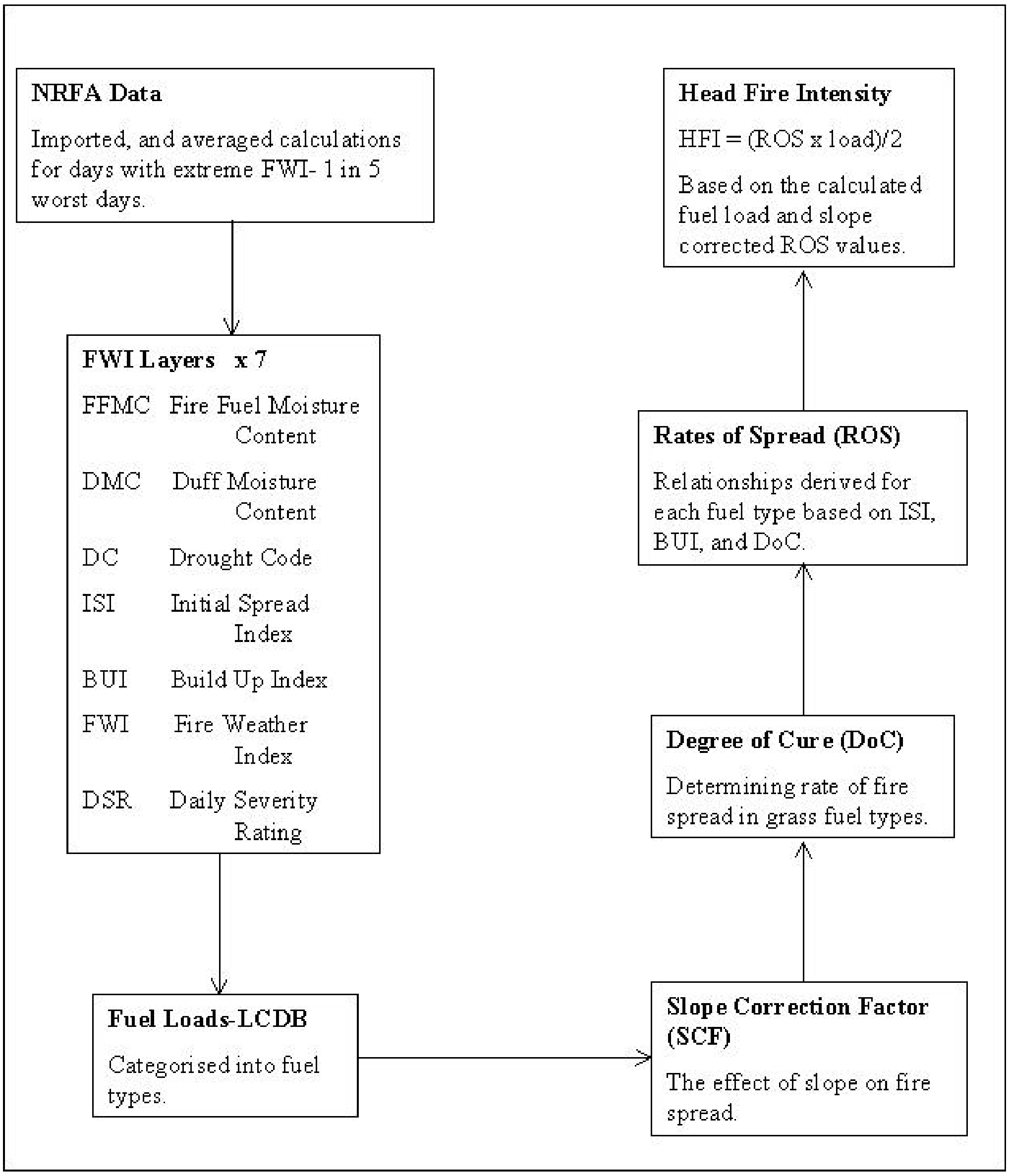

Figure 1. Process used for Developing Fire Hazard Layers for New Zealand.

Given the difficulties described above, we instead utilised existing data describing FWI statistics from the National Rural Fire Authority (NRFA) fire weather-recording network (Fig. 1). Daily weather data for 137 NRFA weather stations were imported into the statistics program, SPLUS, where we calculated various summary statistics. After discussion with NRFA staff, we identified for each station the critical value of the Fire Weather Index which is exceeded on those days constituting the most hazardous 20% of the fire season (October to April), calculated over all data available for each station. Average values were then calculated for each of the fire weather indices for these hazardous days at each station.

These values were then used to fit a thin-plate spline surface (Hutchinson & Gessler 1994) that allows subsequent interpolation of the FWI indices at sites remote from weather stations. Predictor variables used in the fitting of the surface were New Zealand Map Grid easting and northing, elevation, and fire season rainfall as predicted from a similar mathematical surface fitted to long-run average rainfall data from approximately 2200 rainfall stations throughout New Zealand. Data points were weighted by their length of record, so that stations for which long-run data were available were given a higher weighting.

Summary statistics for the surface fitted to these FWI indices are shown in Table 1. Two measures of predictive error are provided for each surface, the square root of the generalised cross validation, and the square root of the mean standard error. Neither is a completely satisfactory measure of the true surface errors, the first over-estimating and the second under estimating the true surface error — the true standard error will be located between these two values (Leathwick & Stephens 1998). Predictive errors for all seven indices are of the order of half a standard deviation, or mostly less than 10% of the range of each index. Perhaps the least satisfactory result is for ISI, where the predictive error approaches 12% of the range.

Table 1. Surface statistics for Fire Weather Index components

FWI	Mean	Std. Deviation	Root GCV	Root MSE	Scale factor
FFMC	86.814	2.017	1.41	0.508	10
DMC	31.628	14.08	9.10	4.05	10
DC	257.70	97.19	60.6	30.2	10
ISI	11.251	7.844	6.06	2.92	10
BUI	46.265	19.74	12.7	5.65	10
FWI	19.738	9.360	6.99	3.47	10
DSR	6.9366	6.115	4.39	2.16	10

Once a satisfactory surface had been derived for these indices, values were interpolated across the whole of New Zealand using a 100 m grid of elevations and estimates of fire-season rainfall, and the resulting files imported into ArcView 3.2 as raster layers using Spatial Analyst. To reduce the size of the resulting files, all layers were multiplied by scale factors to preserve a realistic amount of precision and converted to integer grids This reduced by 90% or more in file size, and allowed for all surfaces to be fitted onto a single CD. However, when using the surfaces in subsequent calculations, values must be divided by the appropriate scale factor or erroneous values will result.

4.3. Calculation of derived layers

The process used to calculate Fuel loads, Slope Correction Factor, Degree of Cure, Rates of Spread, and Head Fire Intensity is shown in Fig. 1. The process was carried out step by step, with each layer inspected for errors before subsequent layers were calculated. Copies of the instructions used in the ArcView Map Calculator tool are provided in Appendix I. In some cases, substantial restatement was required of the formulae provided by the NRFA in conversion to the object-oriented format required by ArcView.

Table 2. Vegetation Cover Classes and Fuel Loads

LCDB Vegetation Types	Fuel Load (t/ha)
Primarily Pastoral	3.5
Primarily Horticultural	0
Tussock/Extensive Grasslands	15.0
Shrublands	20.0
Indigenous Forest	50*(1-EXP(-0.0149*BUI))^ 2.48
Planted Forest	50*(1-EXP(-0.0149*BUI))^ 2.48
Inland Wetlands	10
Coastal Wetlands	5
Coastal Sand	4
Scale Factor	10

4.4. Fuel Loads

Fuel loads were calculated using the LCDB (Land Cover Database), with vegetation cover classes allocated either fixed fuel load values, or, in the case of forests, values that were calculated from previous estimates of the Buildup Index (BUI) (Table 2). The LCDB was first rasterized into a grid at 100 m resolution to enable analysis of individual vegetation cover classes. The variable fuel loads for Indigenous Forest and Planted Forest were calculated using the Map Calculator function of ArcView 3.2a.

4.5. Slope Correction Factor

The equation used to calculate the slope correction factor (SCF) (Table 3) produces a multiplication factor that is combined with estimates of the Rate of Fire Spread (ROS) to account for the upslope effect of increased preheating of fuels through radiation and convection. It is assumed that fires will only run upslope. A lower multiplier is used for scrub.

The slope layer used in calculating the SCF was derived from a 100 m DEM (Digital Elevation Model) for both the North and South Islands.

Table 3. Slope Correction Factor Calculations

SCF = EXP(3.533*(tan(slope)^1.2))

The SCF equation for shrubland fuels only is:

SCF (shrubland) = (EXP(3.533*(tan(slope)^1.2)))/3

Scale factor = 10

4.6. Degree of Cure

The Degree of Cure (DoC) was determined using an equation that defines a constant value of either 70% for damper regions (Drought code < 300), or 80% for drier regions (Drought Code > 300 — Table 4).

Table 4. Degree of Cure Calculations

If DC > 300 then DoC are equal to 80%

If DC =< 300 then DoC are equal to 70%

Scale factor = 1

4.7. Rate of Fire Spread

Rate of Fire Spread (ROS) was separately calculated for each fuel type based on values of ISI, BUI, and in some cases Degree of Curing (DoC) (Table 5). Note that for the horticultural land cover, the rate of spread is set at 0.

Table 5 Rates of Spread (ROS)

4.8. LCDB and Vegetation Types	Rate of Spread (m/h)
Primarily Pastoral	15000*(1-EXP (0.035*ISI)) ^1.7 * (0.02*DoC%-1)
Primarily Horticultural	0
Tussock/Extensive Grasslands	15000*(1-EXP(-0.035*ISI))^ 1.7*(0.02*DoC%-1)
Shrublands	4920*(1-EXP(-0.1*ISI))^ 1.5
Indigenous Forest	((60/100)*1800*(1-EXP(- 0.0697*ISI))^4
Planted Forest	1800*(1-EXP(-0.08*ISI))^ 3*EXP(50*LN(0.8)*(1/BUI-1/62))
Inland Wetlands	4920*(EXP(-0.1*ISI))^ 1.5
Coastal Wetlands	15000* (1-EXP(-0.035*ISI)) ^1.7*(0.02*DoC%-1)
Coastal Sand	15000*(1-EXP(-0.035*ISI))^ 1.7*(0.02*DoC%-1)
Scale Factor	10

4.9. Head Fire Intensity

Head Fire Intensity (HFI) is calculated by combining estimates of the slope corrected rate of spread (ROS), and calculated fuel loads (Table 6). In the absence of detailed information, the specific heat content for individual vegetation types is assumed to have a constant value of 18 000 kJ/kg. HFI is measured in kW/m derived from the rate of spread (m/h) and available fuel load (t/ha).

Table 6.0 Head Fire Intensity

HFI = (ROS x Fuel load)/2
Scale Factor = 1

5. Discussion

Initial problems encountered in this study were unexpected and reflected the challenges inherent in applying climate surfaces developed for one purpose in a new setting. Although the reasons why average-climate oriented surfaces consistently under-estimated fire weather statistics that are highly sensitive to extreme climate events is clear in retrospect, they were not foreseen at the time the project was initiated, and reflect the difficulties that can arise when tools developed in one discipline are applied in another where different assumptions apply. Our subsequent use of NRFA data was also not without problems, reflecting both the more restricted network run by the NRFA (cf. the extensive network of climate stations underlying our climate surfaces), and to a lesser extent, problems with data integrity. In particular, the NRFA network is aimed at measuring high fire hazard where it occurs, and is therefore spatially biased towards drier environments. For this reason, we would expect our predictions of FWI statistics to be more robust in regions of moderate to high fire risk where station intensity is high, but to be less accurate in areas of lower risk, where sampling intensity is lower. Problems with lack of an adequate erroneous data identifier in the NRFA database meant that a relatively conservative approach had to be taken to the elimination of dubious duplicate data entries in the daily records for some stations.

Despite these problems, the surfaces predicted using thin-plate splines appear consistent with both the spatial patterns inherent in the NRFA network data and with the broad climate patterns across New Zealand. The subsequent prediction of the remaining indices was straightforward, although technically challenging, given the difficulties inherent in translating some of the more complex formulae into the object-oriented format required by ArcView.

Inclusion of the resulting object-oriented code in appendices should expedite subsequent use of these surfaces at finer spatial scales by other users. In particular, they could be used to incorporate more detail about the fuel loads present in particular landscapes, e.g., for exotic forests through inclusion of detailed stand data describing stand age and/or silvicultural treatments. Regular updating of such predictions over time could be implemented through use of Avenue scripts in ArcView or similar capabilities in other raster based GIS systems. However, we remind users of these layers that the high spatial resolution (100 m) required by the NRFA necessitated the conversion of all data layers to integer form, after rescaling, to keep data storage requirements to realistic levels. When using the various data layers, values must be divided by the appropriate scale factor, or erroneous values will result.

6. References

Hutchinson, M.F., Gessler, P.E. 1994: Splines – More than just a smooth interpolator. *Geoderma 62:* 45–67.

Leathwick J.R., Stephens, R.T.T. 1998: Climate Surfaces for New Zealand. Landcare Research Contract Report, LC9798/126.

Van Wagner, C.E., Pickett, T.L. 1985: Equations and FORTRAN Program for the Canadian Forest Fire Weather Index System. *Forestry Technical Report 33.* Canada, Canadian Forestry Service.

7. Appendix I – ArcView Formula Converted from Fire Behavioural Models

The following formulae were translated into the object-oriented form required by the ArcView 3.2a Map Calculator when creating the derived FWI grid layers. All grid layers were stored as integers to reduce their size to manageable levels. For some layers this has been achieved by multiplying values by a scale factor before integer conversion to preserve a required numerical precision. When using calculations, values should be divided by these scale factors both in setting up the legends, and when using grids in calculations. For example, dividing the FFMC grid values by its scale factor of 10 gives the true values of FFMC.

7.1. Calculating Forest Fuel Load

((1.asGrid - ((([Bui_nz]/ 10) * -0.0149).Exp).Pow(2.48))) * 50

7.2. Combining Fuel Loads for variable Forest and other fixed Cover Classes

((((([NZlcdb_grd] = 6.AsGrid) or ([NZlcdb_grd] = 7.AsGrid)) * [Fuel_load]) +

((([NZlcdb_grd] = 6.AsGrid) or ([NZlcdb_grd] = 7.AsGrid)).not * [NZlcdb_grd . Fuel_Load]))*10).int

7.3. Degree of Cure (DoC) and Drought Code (DC) Calculations

((([Dc_nz] > 3000.AsGrid) * 80) + (([Dc_nz] <= 3000.AsGrid) * 70)).int

7.4. Slope Correction Factor (SCF) for all vegetation types:

(see below for revised equation)

((((((([Ni_slope]/ 57.29578).Tan).Pow(1.2)) * 3.533).Exp)*10).int

Note conversion of slope from degrees to radians as required for ArcView.

Slope Correction Factor (SCF) for shrubland fuels only:

(see below for revised equation)

(((([Ni_slope]/ 57.29578).Tan).Pow(1.2)/3) * 3.533).Exp

Note, this can be calculated as part of a general slope correction factor, using the formula below.

7.5. Combining Slope Correction Factors (SCF) for Scrub and other Vegetation

((([NZlcdb_grd] = 3) * ([Scf_nz] / 3.AsGrid)) + (([NZlcdb_grd] <> 3) * [Scf_nz])).int

Rate of Spread (ROS) for Prim_Pastoral

(((([NZlcdb_grd] = 1) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * (0.02.asGrid * [Doc_nz] - 1.asGrid) * ([Comb_scf10] / 10.asGrid))

7.6. Rate of Spread (ROS) for Tussock

(((([NZlcdb_grd] = 5) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * (0.02.asGrid * [Doc_nz] - 1.asGrid) * ([Comb_scf10] / 10.asGrid))

Rate of Spread (ROS) for Scrub

(((([NZlcdb_grd] = 3) * ((1.asGrid - ([Isi_nz] * -0.01).exp).Pow(1.5) * 4920)) * ([Comb_scf10] / 10.asGrid))

7.7. Rate of Spread (ROS) for Indigenous Forest

(((([NZlcdb_grd] = 6) * ((1.asGrid - ([Isi_nz] * -0.00697).exp).Pow(4.0) * 1800)) * ([Comb_scf10] / 10.asGrid))

7.8. Rate of Spread (ROS) for Planted Forest

(((([NZlcdb_grd] = 7) * ((1.asGrid - ([Isi_nz] * -0.008).exp).Pow(3.0) * 1800)) * ((((1.AsGrid/[Bui_nz] / 10.AsGrid) - 0.016.asGrid) * (-11.157.asGrid)).exp) * ([Comb_scf10] / 10.asGrid))

7.9. Rate of Spread (ROS) for Inland wetlands

(((([NZlcdb_grd] = 8) * ((1.asGrid - ([Isi_nz] * -0.01).exp).Pow(1.5) * 4920)) * ([Comb_scf10] / 10.asGrid))

Rate of Spread (ROS) for Coastal Wetlands

(((([NZlcdb_grd] = 11) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * (0.02.asGrid * [Doc_nz] - 1.asGrid) * ([Comb_scf10] / 10.asGrid))

7.10. Rate of Spread (ROS) for Coastal Sands

(((([NZlcdb_grd] = 2) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * ([Comb_scf10] / 10.asGrid))).int

7.11. Combined Rate of Spread (ROS) into One Equation

(((([NZlcdb_grd] = 1) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * (0.02.asGrid * [Doc_nz] - 1.asGrid) * ([Comb_scf10] / 10.asGrid)) +

(((([NZlcdb_grd] = 2) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * ([Comb_scf10] / 10.asGrid)).int +

((([NZlcdb_grd] = 3) * ((1.asGrid - ([Isi_nz] * -0.01).exp).Pow(1.5) * 4920)) * ([Comb_scf10] / 10.asGrid)) +

((([NZlcdb_grd] = 5) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * (0.02.asGrid * [Doc_nz] - 1.asGrid) * ([Comb_scf10] / 10.asGrid)) +

((([NZlcdb_grd] = 6) * ((1.asGrid - ([Isi_nz] * -0.00697).exp).Pow(4.0) * 1080)) * ([Comb_scf10] / 10.asGrid)) +

((([NZlcdb_grd] = 7) * ((1.asGrid - ([Isi_nz] * -0.008).exp).Pow(3.0) * 1800)) * ((((1.AsGrid/[Bui_nz] / 10.AsGrid) - 0.016.asGrid) * (-11.157.asGrid)).exp) * ([Comb_scf10] / 10.asGrid)) +

((([NZlcdb_grd] = 8) * ((1.asGrid - ([Isi_nz] * -0.01).exp).Pow(1.5) * 4920)) * ([Comb_scf10] / 10.asGrid)) +

((([NZlcdb_grd] = 11) * ((1.asGrid - ([Isi_nz] * -0.0035).exp).Pow(1.7) * 15000)) * (0.02.asGrid * [Doc_nz] - 1.asGrid) * ([Comb_scf10] / 10.asGrid)))

7.12. Truncate ROS values to < 20 000 or <40 000

(([Ros_calc] >= 20000) * 20000.AsGrid) + (([Ros_calc] < 20000) * [Ros_calc])

(([Ros_calc] >= 40000) * 40000.AsGrid) + (([Ros_calc] < 40000) * [Ros_calc])

This was used to truncate unrealistically high ROS values caused by fuel loads not being reduced on very step slopes.

Head Fire Intensity (HFI)

HFI = ([Ros_nz] * ([Fuelload_nz]/10.asgrid)) / 2