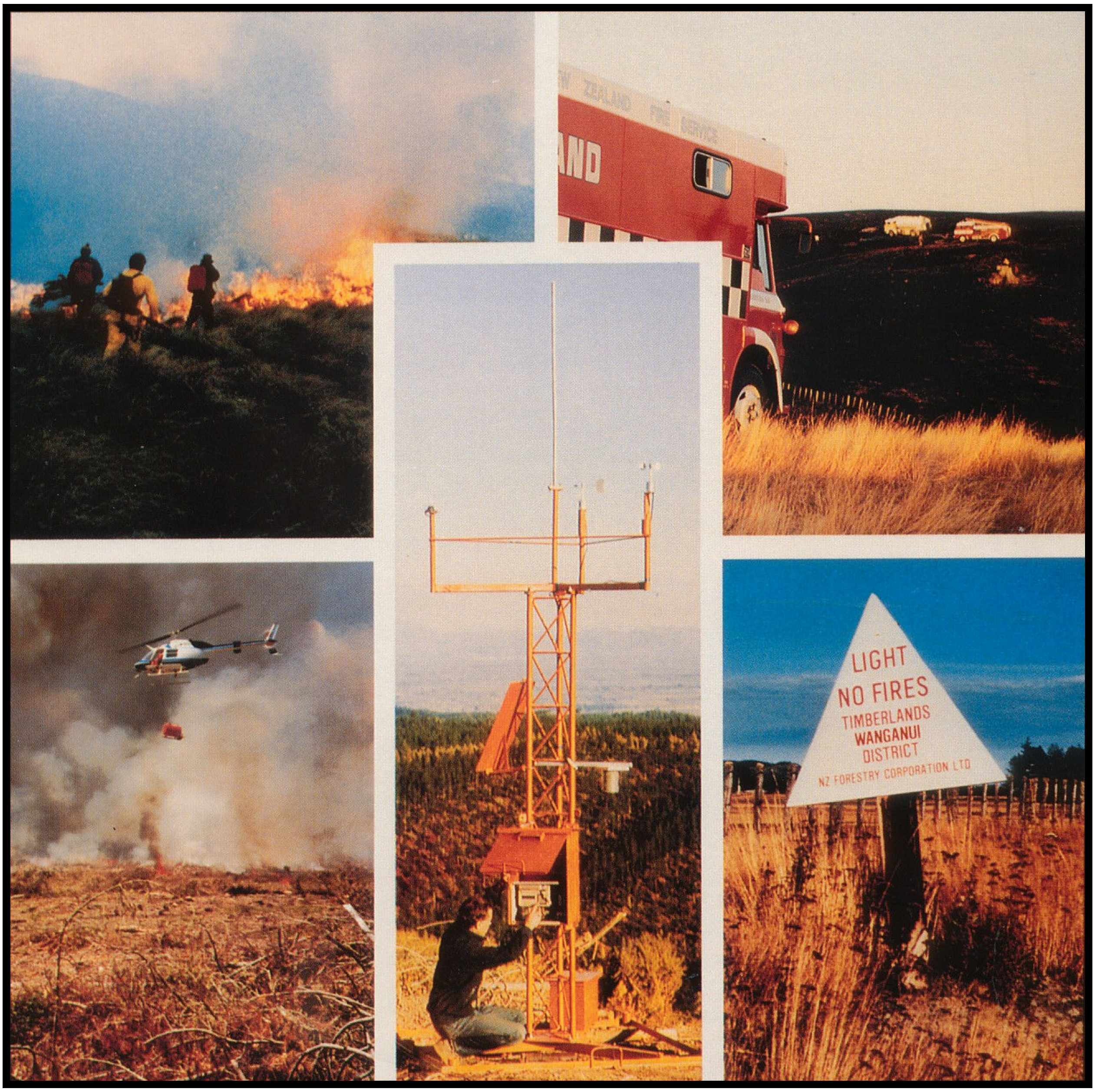
NATIONAL RURAL
FIRE
AUTHORITY
Te mana ahi manaha o te motu

Proposed Revision of Fire Danger Class Criteria for Forest and Rural Areas in New Zealand

Martin E. Alexander

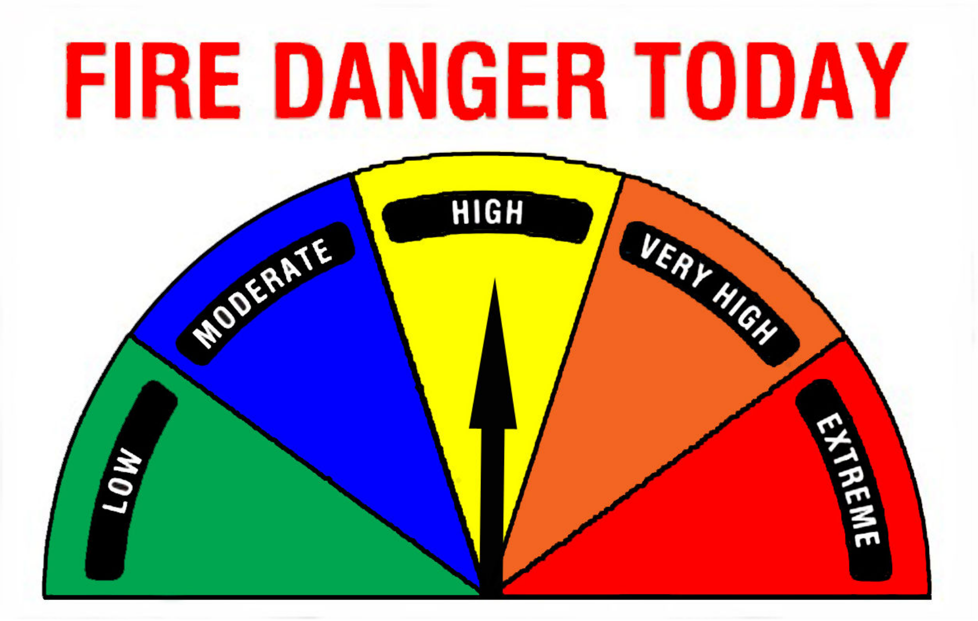


SCION
Next generation biomaterials

PROPOSED REVISION OF FIRE DANGER CLASS CRITERIA FOR FOREST AND RURAL AREAS IN NEW ZEALAND

by

Martin E. Alexander*



---

* Formerly: Visiting Fire Research Scientist (April 1992-April 1993), Plantation Management Group, Forest Technology Division, New Zealand Forest Research Institute, Rotorua. Permanent affiliation: Senior Fire Behaviour Research Officer, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Correct Citation: Alexander, M.E. 2008. Proposed revision of fire danger class criteria for forest and rural areas in New Zealand. 2nd Edition. National Rural Fire Authority, Wellington, in association with Scion, Rural Fire Research Group, Christchurch. 62 p. [Reprint with corrections].

Contents

Page

Figures

Tables

Abstract

A fire danger class scheme based on Byram's concept of fire intensity as a yardstick of suppression difficulty has been devised for two broad fuel types (forests and grasslands) using the Canadian Forest Fire Behavior Prediction System. Five fire danger classes are recognized: LOW, MODERATE, HIGH, VERY HIGH, and EXTREME. Inputs include the Initial Spread Index and Buildup Index components of the Fire Weather Index System and a visual assessment of the Degree of Curing in grasslands. A field application section presents separate tables and graphs for determining Forest and Grassland fire danger classes. A research documentation section describes the derivation of the fire danger class criteria. The classification scheme is designed primarily for fire prevention purposes in connection with the general public (i.e., to inform the lay person of impending fire danger conditions so as to limit the number of potential ignitions -- in other words, the efforts are directed at the "heat" side of the fire triangle).

Acknowledgments

The time required to prepare this NRFA report was made possible in part by the financial contributions from the following organizations which enabled me to undertake a 12-month secondment as a visiting fire research scientist at the then New Zealand Forest Research Institute in Rotorua during 1992-93:

- New Zealand Forest Owners' Association
- Department of Conservation
- Foundation for Research, Science and Technology
- National Rural Fire Authority
- Ministry of Forestry
- New Zealand Forest Research Institute Limited
- Forestry Canada (now the Canadian Forest Service)

Appreciation is extended to H.G. Pearce (NZ Forest Research Institute) for assistance with the work reported on here whilst I was in New Zealand and completion of Figures 3-5, J. Simunkovic (Canadian Forest Service) for word-processing, A.I. Irwin (Canadian Forest Service) for computer programming support, and L.G. Fogarty (formerly, NZ Forest Research Institute) for his scrutiny of Tables 1*a* and 1*b*.

Correct Citation of Original Publication

The original version of this report was incorrectly shown as being published by the National Rural Fire Authority (in conjunction with the New Zealand Forest Research Institute) as part of its *Circular* technical series (as number 94/2). It was in fact produced as a standalone publication and, as such, should more correctly be cited as follows:

Alexander, M.E. 1994. Proposed revision of fire danger class criteria for forest and rural areas in New Zealand. National Rural Fire Authority, Wellington, in association with the New Zealand Forest Research Institute, Rotorua. 73 p.

This second edition is largely a reproduction of the original report with only minor changes to content and formatting.

Introduction

Realizing that the needs and interests of the two major "clients" of this report -- the fire specialist and the generalist -- are different, this report utilizes a format which might be equally useful to both, yet serve this dual purpose better. This report is divided into two separate parts for the convenience of the reader: Field Application, and Research Documentation. Some may be interested only in the application of the results; others may want details on the methods and procedures used to arrive at this end product.

PART I, the Field Application section, is specifically intended for the "person on the ground" who has a particular job to do or problem to solve. This section describes briefly the situation and the problem, and then goes immediately to the solution, emphasizing the how-to-do-it aspect. It is a complete story in itself; the busy field manager need read no further. The idea is to put the research findings into a form that can be more readily utilized by the practitioner. PART II on the other hand, the Research Documentation section, describes the details of the research process. It is for the reader interested in the procedures involved, tabulations, mathematical analyses, philosophical discussion, etc. This section, too, is self-contained.

The purpose has been to separate the practical aspects of research results from the strictly academic ones, yet still make the information available to all readers. If field personnel want to find out how I arrived at my recommendations, the details are given in the Research Documentation section for them to examine. Conversely, if someone is only interested in the practical aspects, they need only turn to the Field Application section.

Part I: Field Application

The value of fire danger rating in forest and rural fire management is a proven fact; fire control planning and decision making without a system of rating fire danger is like operating a boat without a rudder. It is customary in fire danger rating to quote an adjective or descriptive "fire danger class" (e.g., low, moderate, etc.), especially for informing the general public of impending fire danger in terms of fire prevention by using roadside display boards, radio and TV announcements, and newspaper advertisements. This report outlines my final recommendations on the manner in which the daily fire danger class is determined from the outputs of the Fire Weather Index (FWI) System. Little has changed from what I presented during my 2½ hour talk at the National Rural Fire Authority (NRFA) regional annual meetings held in November 1992[1]. However, in this case I've presumed that the reader has at least a working knowledge of the basic principles of the FWI System and of the fundamentals of fire behaviour especially as it relates to wildfire suppression, and therefore no review of these topics is included here. Otherwise this report essentially recaps what was presented.

The major changes in the fire danger class criteria from what has been used in previous years are as follows:

- There are separate schemes for forest and grassland fuel types.
- A "VERY HIGH" category has been added (i.e., instead of four fire danger classes, there would be five).

---

[1] Palmerston North (Nov. 3), Te Awamuta (Nov. 5), Burnham (Nov. 18), Balclutha (Nov. 20) and Nelson (Nov. 24).

- A "MODERATE" fire danger class will be consistently used instead of "Medium" because medium implies a middle position or degree and extreme fire danger is really as open-ended concept (i.e., fire weather severity can always worsen)[2].
- The Initial Spread Index (ISI) and Buildup Index (BUI) components of the FWI System will be used in rating forest fire danger as opposed to just the Fire Weather Index (FWI) component itself.
- In grasslands, the rating of fire danger will be based on the ISI and an assessment of the Degree of Curing that has taken place in the grassland fuel complex, which for the time being must be supplied directly by the user at this stage.

The background information and the technical basis for the proposed revision to the fire danger class criteria are documented in PART II (Annex 4) of this report.

As with any kind of change, I anticipate some "teething" problems or growing pains associated with the proposed revision to the fire danger class criteria during the 1993-94 fire season. I therefore envision this document as representing a sequel to the consultative process between forest and rural fire managers, the NRFA and the New Zealand Forest Research Institute (NZ FRI) which was begun in November 1992. In this regard, all rural fire authorities were invited to submit their comments to the NRFA after having field-tested the criteria during the 1993-94 fire season.

Graphical representation of the Forest and Grassland Fire Danger Classes are presented here as Figures 1 and 2; other versions of the graphs could be produced in which the range in either the ISI and(/or) BUI (in the case of the Forest Fire Danger Class) or the ISI (in the case of the Grassland Fire Danger Class) could be extended further, however, the present version should cover most situations. For example, in forests an ISI of 10 and a BUI of 40 would constitute a HIGH fire danger class day. Similarly, an ISI of 10 and a Degree of Curing of 70% would translate into a HIGH fire danger class for grasslands. **Please note that there is no direct relationship between the BUI on the Forest Fire Danger Class Graph and the Degree of Curing on the Grassland Fire Danger Class Graph. In other words, a BUI of 60 doesn't necessarily mean that the Degree of Curing would be 75%.**

Users may wish to prepare colour coded versions of the two graphs (including enlargements) for display purposes, in which case the following colour scheme should be used:

Fire Danger Class	**Colour Code**
LOW	Green
MODERATE	Blue
HIGH	Yellow
VERY HIGH	Orange
EXTREME	Red

---

[2] I suspect that the reason "Medium" has been used over the years (e.g., on roadside fire danger display boards) instead of "Moderate", even though Valentine (1978) and New Zealand Forest Service (1983) indicated the latter term, is simply a throw back to the New Zealand Fire Danger Meter (Girling-Butcher 1977).

Forest Fire Danger Class Graph

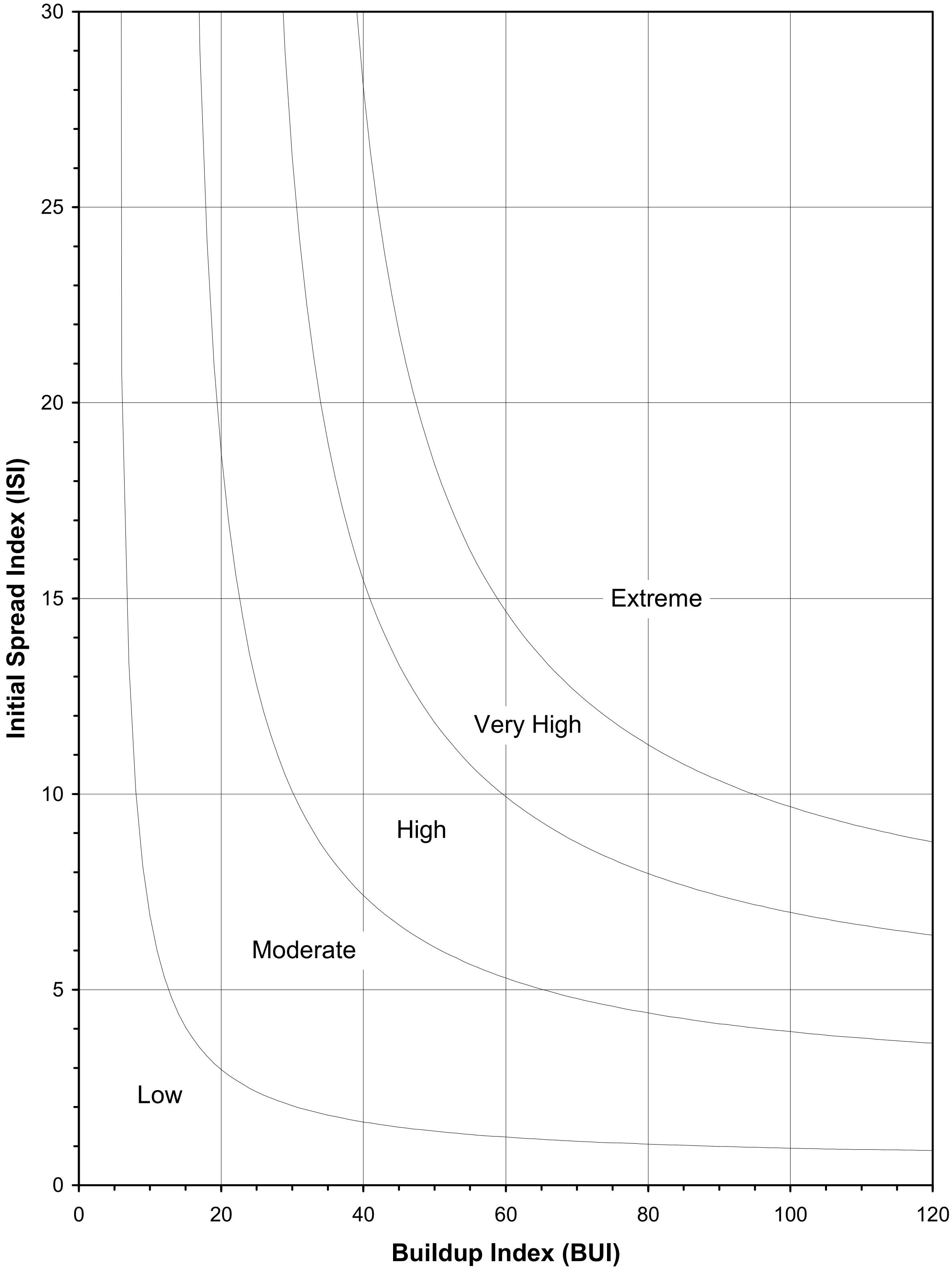


Figure 1. Forest Fire Danger Class Graph.

Grassland Fire Danger Class Graph

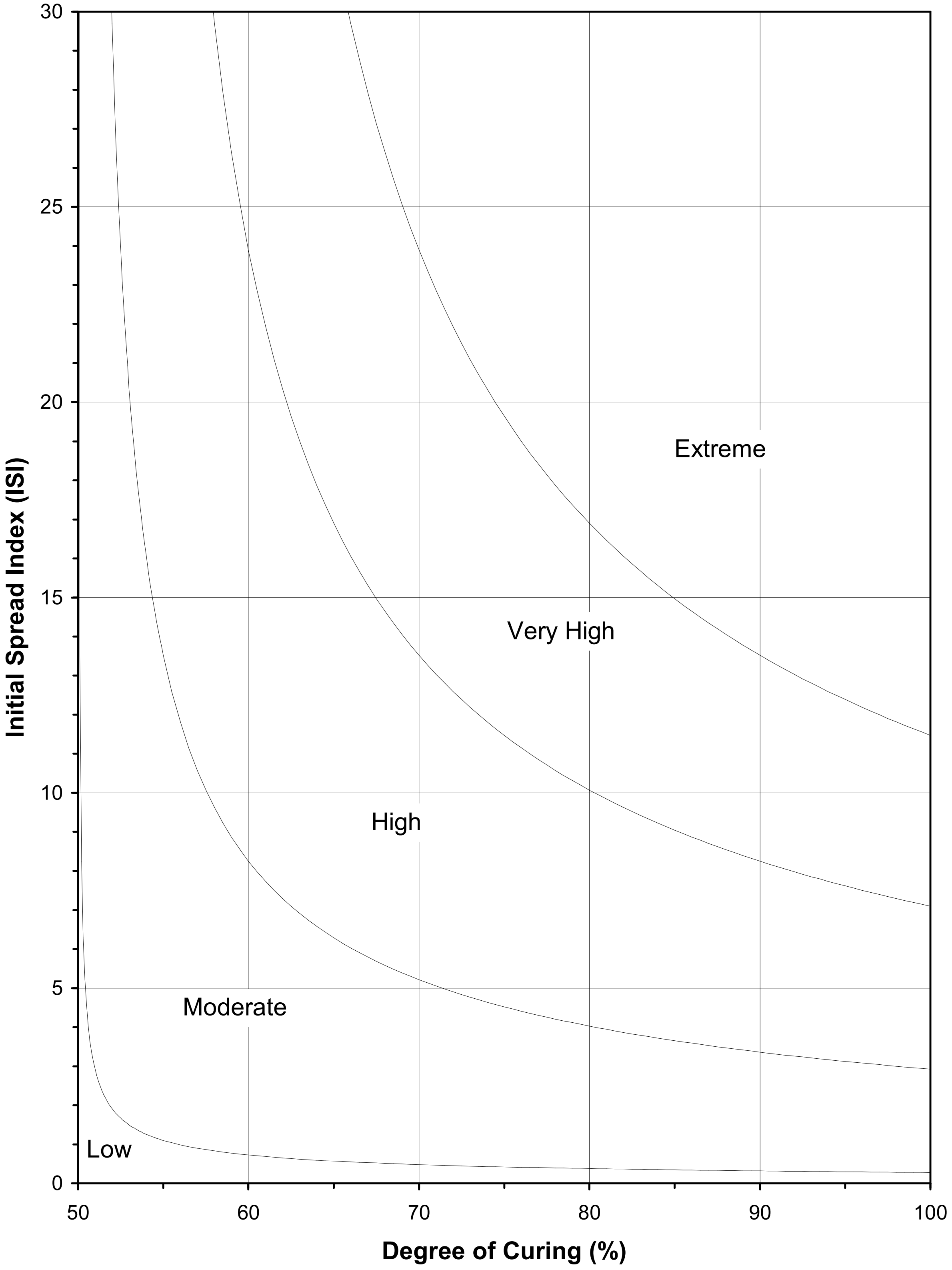


Figure 2. Grassland Fire Danger Class Graph.

If enlargements of Figures 1 and 2 are contemplated, then users may wish to consider supplementing the fire danger class descriptive terms or adjectives with symbols or symbolic fire suppression scenes. Some suggestions are given in Annex 1.

In practice, most users will find the tabular versions of the fire danger class criteria more amenable to daily use. Tables 1 and 2 have been constructed with a view to being compatible with the formats contained in the publication "Fire Weather Index System Tables for New Zealand" (Anon. 1993). The equations used to produce the fire danger class graphs and tables are listed in PART II (Annex 5) of this report. Thus, computer derivation of the fire danger class(es) is also possible. Because of the assumptions used to construct such tables (*cf.* Deeming 1975), there will be the occasional difference in the fire danger class between these tables on one hand and graphs or computer determinations on the other.

The Forest Fire Danger Class Graph (Fig. 1) and Table (Tables l*a* and 1*b*) are deemed to be applicable to both exotic plantations and native forests at this time even though the technical basis for the criteria rests upon research carried out in coniferous fuel types. My feeling is that this will tend to overrate the fire danger conditions in native forests (except when there has been an extended dry spell) when the BUI value is at a relatively low level, which I believe shouldn't nullify the usefulness of what is presented here -- better to be on the safe side!

Many fire managers will surely be asking "well, what do we do about gorse, manuka, kanuka, etc.?" The fact of the matter is that there simply isn't sufficient quantitative fire behaviour information available in New Zealand (or for similar fuel types anywhere else which could be applied to the problem). The Forest and Rural Fire Research Programme at the NZ FRI in Rotorua is attempting to correct this deficiency but it may be 2 or 3 seasons before a Scrubland Fire Danger Class Graph and Table could be developed. Findings from an experimental fire carried in 4-year-old manuka on the Karikari Peninsula in early April 1993, as documented and reported on recently by H.G. Pearce (NZ FRI Forest and Rural Fire Research Scientist) at the 3rd Annual Conference of the Forest and Rural Fires Association of New Zealand in Wellington (4-6 August 1993), suggests that we have, in a scientific sense, much to learn about scrubland fire behaviour.

As described in the New Zealand Forest Service's rural fire fighting manual (Anon. 1982), oldman's gorse has a notorious reputation as a fire hazard ("it'll burn in the rain" I'm told). The available wildfire documentation would suggest that the Forest fire danger class criteria would do a respectful job of rating fire potential[3] in gorse or other scrubland fuel types and yet in other

---

[3] For example, the Worsley Spur Fire of 28.12.88 in Christchurch (see Alexander 1992*a*). Grant's (1992) description of the run made by the Wellington Road Fire of 27.2.89 in Wainuiomata which began at 2:10 p.m. is certainly indicative of extreme type fire danger conditions based on his account (including videotape footage) of the fire behaviour and the difficulty suppressing this fire until weather and fuel conditions ameliorated in favour of effective control action. Fuels in the fire area consisted of "...a mixture of large manuka/kanuka up to 20 cm in diameter, mature 20 year old gorse, broom, bracken fern and regenerating native forest". Grant felt that slope was not a contributing factor in the behaviour of this particular fire. The fire weather observations and FWI System components at 1 p.m. (@ Rimutaka Forest Park HQ, 15 km south of the fire) were as follows: 21.5°C, 40% RH, 10-m open wind 19 km/h, 4 days since ≥ 0.6 mm rain, FFMC 89, DMC 38, DC 415, ISI 10, BUI 62 and FWI 25. According to the Forest Fire Danger Class Graph or Table, this would translate into just barely attaining a VERY HIGH level whereas if the Grassland Fire Danger Class Graph or Table were used, and you assumed a 100% Degree of Curing, although a VERY HIGH category is also attained, the result is considerably closer to the EXTREME fire danger class threshold. In both these instances, the elevated BUI value (~80 in the case of the Worsley Spur Fire) probably partially compensated for the lack of elevated fuels.

Table 1*a*. Forest Fire Danger Class (FFDC) Table.

Initial Spread Index (ISI)	Buildup Index (BUI)																	
	0-1	2-3	4-5	6-7	8-9	10-11	12-14	15-17	18-20	21-23	24-26	27-30	31-34	35-38	39-42	43-47	48-52	53-57
	Forest Fire Danger Class (FFDC)																	
0	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
0.5	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
1.5	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	M	M
2	L	L	L	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M
2.5	L	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M
3	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M
4	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M
5	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M
6	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M
7	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M
8	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M
9	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M
10	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M
11	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M
12	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M
13	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M
14	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M
15-16	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M
17-18	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
19-20	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
21-22	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
23-24	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
25-26	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
27-29	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30-32	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
33-35	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
36-38	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
39-42	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
43-46	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
47-51	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
52-57	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
58-64	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
65-72	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
73-81	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
82-91	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
92-102	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
103-114	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
115-128	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
129-144	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
145-163	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
164-185	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

Table 1*b*. Forest Fire Danger Class (FFDC) Table (cont.).

Initial Spread Index (ISI)	Buildup Index (BUI)																	
	58-63	64-69	70-75	76-82	83-89	90-97	98-106	107-116	117-128	129-142	143-159	160-180	181-206	207-238	239-277	278-324	325-381	381
	Forest Fire Danger Class (FFDC)																	
0	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
0.5	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
1	L	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	M
1.5	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
2.5	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
3	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	H	H
4	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H	H	H	H
5	M	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
6	H	H	H	H	H	H	H	H	H	H	V	V	V	V	V	V	V	V
7	H	H	H	H	H	H	V	V	V	V	V	V	V	V	V	V	E	E
8	H	H	H	H	V	V	V	V	V	V	E	E	E	E	E	E	E	E
9	H	H	V	V	V	V	V	V	E	E	E	E	E	E	E	E	E	E
10	V	V	V	V	V	V	E	E	E	E	E	E	E	E	E	E	E	E
11	V	V	V	V	E	E	E	E	E	E	E	E	E	E	E	E	E	E
12	V	V	V	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
13	V	V	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
14	V	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
15-16	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
17-18	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
19-20	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
21-22	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
23-24	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
25-26	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
27-29	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
30-32	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
33-35	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
36-38	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
39-42	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
43-46	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
47-51	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
52-57	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
58-64	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
65-72	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
73-81	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
82-91	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
92-102	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
103-114	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
115-128	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
129-144	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
145-163	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
164-185	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

Table 2. Grassland Fire Danger Class (GFDC) Table.

Initial Spread Index (ISI)	Degree of Curing (%)										
	≤50	55	60	65	70	75	80	85	90	95	100
	Grassland Fire Danger Class (GFDC)										
0	L	L	L	L	L	L	L	L	L	L	L
0.5	L	L	L	L	M	M	M	M	M	M	M
1	L	L	M	M	M	M	M	M	M	M	M
1.5	L	M	M	M	M	M	M	M	M	M	M
2	L	M	M	M	M	M	M	M	M	M	M
2.5	L	M	M	M	M	M	M	M	M	M	M
3	L	M	M	M	M	M	M	M	M	M	H
4	L	M	M	M	M	M	M	H	H	H	H
5	L	M	M	M	M	H	H	H	H	H	H
6	L	M	M	M	H	H	H	H	H	H	H
7	L	M	M	H	H	H	H	H	H	H	H
8	L	M	M	H	H	H	H	H	H	V	V
9	L	M	H	H	H	H	H	H	V	V	V
10	L	M	H	H	H	H	V	V	V	V	V
11	L	M	H	H	H	H	V	V	V	V	V
12	L	M	H	H	H	V	V	V	V	V	E
13	L	M	H	H	H	V	V	V	V	E	E
14	L	H	H	H	V	V	V	V	E	E	E
15-16	L	H	H	H	V	V	V	E	E	E	E
17-18	L	H	H	V	V	E	E	E	E	E	E
19-20	L	H	H	V	V	V	E	E	E	E	E
21-22	L	H	H	V	V	E	E	E	E	E	E
23-24	L	H	H	V	V	E	E	E	E	E	E
25-26	L	H	V	V	E	E	E	E	E	E	E
27-29	L	H	V	V	E	E	E	E	E	E	E
30-32	L	H	V	V	E	E	E	E	E	E	E
33-35	L	H	V	E	E	E	E	E	E	E	E
36-38	L	H	V	E	E	E	E	E	E	E	E
39-42	L	H	V	E	E	E	E	E	E	E	E
43-46	L	H	V	E	E	E	E	E	E	E	E
47-51	L	H	V	E	E	E	E	E	E	E	E
52-57	L	H	V	E	E	E	E	E	E	E	E
58-64	L	V	E	E	E	E	E	E	E	E	E
65-72	L	V	E	E	E	E	E	E	E	E	E
73-81	L	V	E	E	E	E	E	E	E	E	E
82-91	L	V	E	E	E	E	E	E	E	E	E
92-102	L	V	E	E	E	E	E	E	E	E	E
103-114	L	V	E	E	E	E	E	E	E	E	E
115-128	L	V	E	E	E	E	E	E	E	E	E
129-144	L	V	E	E	E	E	E	E	E	E	E
145-163	L	V	E	E	E	E	E	E	E	E	E
164-185	L	V	E	E	E	E	E	E	E	E	E

cases[4] it would appear to grossly underestimate the situation. If sufficient information were to exist locally on past wildfire occurrences (with suitable corresponding fire weather/fire danger data), as attempted for example by Wallace (1989), then one might be able to develop some reasonable rules of thumb, at least on an interim basis. My feeling is that in scrublands, the BUI plays only a minor role in influencing fire spread and intensity since most of the fuel is elevated above the ground surface. Thus, fire behaviour in these fuel complexes is controlled largely by the Fine Fuel Moisture Code (FFMC) (i.e., is the fuel sufficiently dry to support ignition and combustion?) and wind; so, in other words, the ISI. For this reason, fire behaviour in many scrubland fuel types may not exhibit so much a gradual increase in intensity (as compared to forest fuel types) but acts more like there's an on/off switch in terms of no ignition/no fire spread vs. an extreme type rate of fire spread and intensity. Certainly plant age and its relationship to fuel quantity has a great influence on the resulting fire behaviour, especially in oldman's gorse where a significant amount of fine dead material accumulates with time. Perhaps one of the reasons (other than fuel characteristics) that oldman's gorse typically displays such extreme fire behaviour, regardless of the apparent weather conditions, is the fact that it generally, although not always, is found on steep slopes[5]. The only suggestion I can make at this time is to use the Grassland Fire Danger Class Graph or Table and assume the worse case scenario (i.e., 100% Degree of Curing); a high degree of accuracy is not claimed. Since grass often constitutes the "fuse" or "wick" in most scrub fires, consideration might also be given to applying the actual Degree of Curing assessment, at least in the spring and during the early summer period.

In the Grassland Fire Danger Class Graph (Fig. 2) and Table (Table 2), the Degree of Curing represents **the proportion of cured and/or dead material in a grassland fuel complex expressed as a percentage (%) of the total**. Guidelines for assessing the Degree of Curing are given in Annex 2. For example, 100% Degree of Curing means that all of the grass has turned light brown or otherwise has a distinct bleached appearance. On the other hand, a 75% Degree of Curing implies that three-quarters of the fuel complex is comprised of cured or dead grass and the other quarter or 25% is still green. Like many aspects of the fire environment, there will be considerable variation in the degree of grassland curing across the landscape, which will logically frustrate individuals attempting to apply the Grassland fire danger class criteria. Other

---

[4] For example, the Hokitika Fire of 4.11.91 (see Staton 1992*a*, 1992*b*) or the Observatory Hill Fire of 25.1.93 in Nelson (Thompson 1993); unfortunately no weather data is available during the major run of either fire. On October 11, 1992, a scrubland fire near Invercargill displayed characteristics of extreme fire behaviour as evident in photographs taken by the Southland District Council Engineer during the fire which showed 5-10+ metre high flames and a two-lane bitumen road being breached by spotting, radiation and direct flame contact. The fire weather observations and FWI System components at 1 p.m. (@ Wyndham, the closest fire weather station, 35 km to the south-southeast of the fire area) were as follows: 20°C, 55% RH, 10-m open wind 10 km/h, 11 days since rain, FFMC 83, DMC 15, DC 41, ISI 3, BUI 17 and FWI 4. However, as R.F. Morgan (*pers. comm.*) with the Southland Conservancy of the Department of Conservation at Invercargill notes, the weather at "...Wyndham at 1300 hrs does not reflect the conditions at the time of the fire (1720 hrs) as wind strength increased all afternoon with R.H. dropping [as well]..." nor was any "...weather data... taken at the fire...". Although the Meteorological Service of N.Z. weather station at the Invercargill airport is closer to the fire area (21 km versus 35 km), calculations of the FWI System components are not routinely carried out there.

[5] For example, the major run of the Point Howard Fire of 22.2.89 in the Wellington region as described by Borger (1992), which involved several houses being burnt down and one firefighter being hospitalized, occurred in 11 y.o. gorse stands on a 45° slope; the fire weather observations at 1 p.m. (@ Rimutaka Forest Park HQ, 11 km south of the fire) were as follows: 23.5°C, 52% RH, 10-m open wind 40 km/h, 7 days since ≥0.6 mm rain, FFMC 87, DMC 27, DC 382, ISI 22, BUI 46 and FWI 37. However, according to the Forest Fire Danger Class Graph or Table this would still constitute an EXTREME level (a fact substantiated by videotape footage in addition to the post-fire impacts) in spite of the slope steepness. During the major run (late in the afternoon), winds were estimated to be 55 km/h (Borger 1992); this would have in turn have resulted in an ISI of 47 and FWI of 59.

means of determining the Degree of Curing, especially on a spatial basis, are being pursued (e.g., remote sensing by satellite and/or linkage to weather-driven moisture indexes). However, for the time being, the "hands on" approach as described in Annex 2 will be necessary.

A logical question to be asked is "which fire danger class criteria do I use in my patch -- the Forest Fire Danger Class or the Grassland Fire Danger Class?" This will no doubt cause some consternation amongst the forest and rural fire community in New Zealand, at least during the upcoming fire season. As I suggested at the NRFA regional annual meetings in November 1992, I think what has to be done, for fire danger rating purposes (as opposed to a site-specific prediction of fire behavior), is to prepare a map depicting forest **dominated** regions (e.g., Kaingaroa Forest, Golden Downs Forest and adjoining areas), grassland **dominated** regions (e.g., Tongariro National Park, South Canterbury) and scrubland **dominated** regions (e.g., Lower Hutt Hills, Coastal Otago). This should not deter fire managers from calculating both the Forest and Grassland fire danger class in his or her area. For example, throughout much of the Canterbury Plains the Grassland Fire Danger Class would be used for broad fire prevention purposes, but exotic plantation owners would also want to be aware of the Forest fire danger in order judge when their forests may be susceptible to fire damage from internal fire starts in cases where the grasslands aren't necessarily in a highly flammable state (e.g., late spring or early summer) when the Degree of Curing is less than 50%[6]. In the larger exotic forest estates, especially those which have high recreational value (e.g., Hanmer, Balmoral, Ashley, Eyrewell, Bottle Lake), it makes sense of course to use the Forest criteria for the fire danger class display board that's located at the entrance to these areas. As I also indicated at the regional annual meetings last year, I believe there needs to be more thought given to the coordination of the fire weather station network, roadside fire danger display boards and print/electronic media releases of fire danger information to the general public. This obviously needs be done through the regional rural fire coordinating committees in consultation with the NRFA so that the dissemination of information on fire danger conditions at the local, regional and national levels is well coordinated (i.e., consistency, regardless of the source).

The addition of a VERY HIGH fire danger class will necessitate the need for changing or, in some cases, completely replacing the roadside fire danger display or indicator boards which have been in use; until this is done, I'd suggest equating Extreme on the present display boards to the VERY HIGH and EXTREME criteria as described here. As I indicated last year, I believe there can be a distinct advantage, from the standpoint of a national identity for wildfire prevention, to having a common roadside display board which can be recognized throughout the country, rather than continuing with the current menagerie that exists[7]. I personally favour the so-called "half grapefruit" design which was the standard used by the former New Zealand Forest Service (NZFS) among others and is of course still used in many areas. As evident by commercial use of the overall design in other types of roadside display boards and in magazines (e.g., New Zealand Forest Industries), this type of roadside symbolism is a recognized entity in forest and rural areas.

---

[6] In the Mount Gambier region of South Australia, which involves extensive areas of radiata pine plantations and adjoining grasslands or agricultural lands, the McArthur Grassland Fire Danger Meter (Luke and McArthur 1978) is used for determining the daily fire danger with respect to the public at large but the McArthur Forest Fire Danger Meter is used for determining readiness levels for initial attack (J. Pratt, Woods and Forests Department, Adelaide, South Australia, *pers. comm.*).

[7] In my travels throughout New Zealand in October-November 1990 and again during my 1992-93 sojourn, I became acutely aware of the fact that not only was there variation in the style of roadside fire danger display boards but that often "fire risk" or "fire hazard" was used in lieu of the term fire danger.

Other than the obvious need to replace "Medium" with "MODERATE" and add "VERY HIGH", at least two other changes are needed in the former NZFS design:

1. At the top of the sign there should be no reference to "forest", "rural", or "grassland", fire danger. It should simply indicate FIRE DANGER TODAY and certainly not 'Forest Fire Danger Today'.
2. The NZFS title and logo would obviously be removed. If it's felt necessary to include some reference to the organization (e.g., a forest company) or group (e.g., rural fire coordinating committee) then this should come under the main sign as a separate piece of the display board (i.e., length-wise between the two supporting posts).

Most roadside fire danger display boards will dictate that they be seen from both directions of travel (i.e., going and coming). In these cases, it's imperative that in actual fact two display boards be placed back to back with separate pointer arrows rather than having a single board with the "half-grapefruits" on each side of the board and a common pointer arrow. In this way, the progression in the fire danger class will always be consistent (i.e., from left to right the fire danger class would progress from LOW to EXTREME)[8]. This would also allow for the flexibility of displaying the Forest fire danger class on one side (e.g., where you are entering a large- or medium-sized exotic plantation area like the Kinleith Forest or Hanmer Forest) and the Grassland fire danger class on the other (e.g., when you are exiting a large or medium-sized exotic plantation area into a grassland dominated region such as south of Balmoral Forest), especially when there's a difference between the two criteria on a given day.

In some, but not all instances, consideration should also be given to being able to easily remove the display board(s) from its posts during the winter months. In this way, when it becomes functional again in the spring it will have a much greater impact on the local population who repeatedly drive by the location during the rainy winter months.

In the past, forest and rural fire authorities were told how to determine the daily fire danger class, be it on the basis of the New Zealand Forest Fire Danger Meter or the FWI System based classification scheme initially introduced in October 1980. However, they were never really told what a "Low fire danger class" meant or what a "Very High fire danger class" meant, etc. In other words, what sort of fire business or activity should one expect at any given fire danger class? As developed in PART II (Annex 4) of this report, the progression in fire danger class levels (i.e., from LOW through to EXTREME) represents an incremental increase in fire behaviour and, in turn, suppression difficulty. Table 3 has been prepared so that all parties (i.e., the general public, the media and the fire authorities) know exactly what is likely to happen at any given fire danger class level should a fire start take place. Table 3 is applicable to both the Forest and Grassland fire danger class criteria although at any particular time the Forest and Grassland fire danger classes wouldn't necessarily be the same for a given day. Some interpretation on the part of the fire authority is still required for implementing a prohibited fire season and some suggested guidelines to help in this process are given in Annex 3.

---

[8] I have observed several cases in New Zealand where in fact there is only a single display board with a common pointer arrow on each side so that on one side of the board the progression in fire danger from left to right is from EXTREME to LOW.

Table 3. Fire danger class interpretations.

Fire Danger Class	**Description of Probable Fire Potential and Implications for Fire Suppression**[†]	**Nominal Max. Flame Height**
LOW	New fire starts are unlikely to sustain themselves due to moist surface fuel conditions. However, ignitions may take place near large and prolonged or intense heat sources (e.g., camp fires, windrowed slash piles) but the resulting fires generally do not spread much beyond their point of origin and, if they do, control is easily achieved. Mop-up or complete extinguishment of fires that are already burning may still be required provided there is sufficient dry fuel to support smouldering combustion*. Colour code is GREEN.	no visible flame
MODERATE	From the standpoint of moisture content, fuels are considered to be sufficiently receptive to sustain ignition and combustion from both flaming and most non-flaming (e.g., glowing) firebrands. Creeping or gentle surface fire activity is commonplace. Control of such fires is comparatively easy but can become troublesome as fire damages can still result and fires can become costly to suppress if they aren't attended to immediately. Direct manual attack around the entire fire perimeter by firefighters with only hand tools and back-pack pumps is possible. Colour code is BLUE.	up to 1.3 metres
HIGH	Running or vigorous surface fires are most likely to occur. Any fire outbreak constitutes a serious problem. Control becomes gradually more difficult if it's not completed during the early stages of fire growth following ignition. Water under pressure (from ground tankers or fire pumps with hose lays) and bulldozers are required for effective action at the fire's head. Colour code is YELLOW.	1.4 to 2.5 metres
VERY HIGH	Burning conditions have become critical as the likelihood of intense surface fires is a distinct possibility; torching and intermittent crowning in forests can take place. Direct attack on the head of a fire by ground forces is feasible for only the first few minutes after ignition has occurred. Otherwise, any attempt to attack the fire's head should be limited to helicopters with buckets or fixed-wing aircraft, preferably dropping long-term chemical fire retardants. Until the fire weather severity abates, resulting in a subsidence of the fire run, the uncertainty of successful control exists. Colour code is ORANGE.	2.6 to 3.5 metres
EXTREME	The situation should be considered "explosive" or super critical. The characteristics associated with the violent physical behaviour of conflagrations or firestorms is a certainty (e.g., rapid spread rates, crowning in forests, medium- to long-range mass spotting, firewhirls, towering convection columns, great walls of flame). As a result, fires pose an especially grave threat to persons and their property. Breaching of roads and firebreaks occurs with regularity as fires sweep across the landscape. Direct attack is rarely possible given the fire's probable ferocity except immediately after ignition and should only be attempted with the utmost caution. The only effective and safe control action that can be taken until the fire run expires is at the back and along the flanks. Colour code is RED.	3.6+ metres

[†] **THE ABOVE SHOULD NOT BE USED AS A GUIDE TO FIREFIGHTER SAFETY, AS FIRES CAN BE POTENTIALLY DANGEROUS OR LIFE-THREATENING AT ANY LEVEL OF FIRE DANGER!**

* General rule(s) of thumb: certainly when Drought Code (DC) exceeds about 300 and/or Buildup Index (BUI) is greater than around 40, one can generally expect ground or subsurface fires. Please note however, these benchmark values are for moderately well-drained sites, but in actual fact they will vary according to soil type and drainage conditions and should be determined locally on the basis of past wildfire suppression and/or prescribed burning experience.

Please note that it is not necessarily appropriate to use Table 3 by itself for determining initial attack preparedness or dispatching, nor for suppression strategies and tactics on going fires. First of all, the fire danger class is only a reflection of fire intensity which, for present purposes, is represented by the flame heights given in Table 3; in addition to the symbolism for fire danger classes from a fire suppression standpoint as outlined in Annex 1, another possibility is to schematically portray these flame heights in relation to the average height of an adult (say 1.8 m) or in turn use photos (e.g., Lanoville and Mawdsley 1990). The fire danger class by itself doesn't give any indication of how fast a fire is expanding in size. Useful measures of fire size are head fire or forward rate of spread (metres or kilometres per hour) and distance (metres or kilometres), area burned (hectares), length of the fire's perimeter or circumference (metres or kilometres), and rate of perimeter growth (metres/hour) (Alexander 1985). A fire's intensity will dictate the types of resources that will or will not be effective in suppressing the fire but the fire's velocity and growth rate will determine just how many are required to "corral" the fire. The Forest and Grassland Fire Danger Class Graphs can only give you a qualitative assessment of a fire's forward speed and area of expansion (e.g., high spread rates are associated with high ISI levels and conversely, low spread rates commonly occur with low ISI values). Although a fire's intensity is determined in part by its rate of advance, it is simply not possible to quote any of the above measures of fire size by fire danger class. In other words, a fire's rate of spread, for example, will vary within a fire danger class. It is certainly possible to calculate any of the above measures of fire size given the FFMC, wind speed, BUI (for forests) or Degree of Curing (for grasslands), and the elapsed time since ignition (using for example, the Canadian Forest Fire Behavior Prediction (FBP) System or a New Zealand equivalent), but it simply can't be inferred from the fire danger class.

The Forest Fire Danger Class Graph does give a more or less direct indication of mop-up requirements or problems, but wildfire case study documentation is the best way to ascertain "easy" vs. "difficult" situations (e.g., Gaukrodger 1993; Thompson 1993). Fire persistence or duration will certainly increase with increasing BUI levels. However, there's always the possibility of a high DC value (say greater than 300) at a low BUI value (say 20).

The fire danger class criteria as outlined here, like their predecessor, are a reflection of variations in potential fire behaviour as a result of changes in short-and long-term weather influences, although at least now two broad fuel types are recognized. It's assumed that the fuels are continuous and the terrain is flat or undulating; some users may consider this latter assumption totally unrealistic, however, for every steep upslope there's a corresponding a downslope. Furthermore, the fire danger class criteria should not be viewed as a specific prediction of fire behaviour in time and space, but rather as a broad areal representation of fire potential for mid to late afternoon.

If, after the basic fire weather observations are taken, conditions are deemed to be considerably more severe (e.g., winds at the basic observation time were 15 km/h but by 2:30 p.m. they had noticeably increased to 35-50 km/h), then it is perfectly legitimate to revise the fire danger class by taking a new set of fire weather observations and correspondingly updating the FWI System components and fire danger class (Turner and Lawson 1978). To do this, use the previous day's fuel moisture codes as the starting point **NOT** today's values. However, the original calculated values of the FFMC, DMC and DC for the day will be used as the starting point on the following day and not the special updated values.

Since the FWI System is dependent largely on weather observations, it is possible to determine tomorrow's fire danger class up to 24 hours in advance if users have arranged with the Meteorological Service of New Zealand Ltd. (Neal 1987) for special fire weather forecasts of the four required elements (i.e., dry-bulb temperature, relative humidity, 10-m open wind speed, and 24-hour accumulated rainfall at 12 p.m. New Zealand Standard Time or 1 p.m. New Zealand Daylight Time); alternatively, users may wish to estimate tomorrow's likely weather conditions based on a combination of current conditions, the public forecast(s), local knowledge and "persistence forecasting" (i.e., tomorrow is likely to be much like today). It may be especially prudent to begin fire danger class forecasting once certain threshold conditions, such as described in Annex 3, are exceeded; in Australia, for example, "total fire ban" days are based on forecasted fire danger conditions as opposed to the actual calculated index values derived from the standard observations (Cheney 1991*a*). In order to make a fire danger class forecast for tomorrow, simply use the forecasted weather elements as if they were the actual observations and today's fuel moisture codes as calculated at the standard observation time for starting values.

Since the fire danger class criteria is determined largely from the FWI System which is wholly a function of weather, the importance of a suitable number of representative, properly established and maintained fire weather stations throughout the region of interest becomes apparent. A discussion of this issue is beyond the scope of this document.

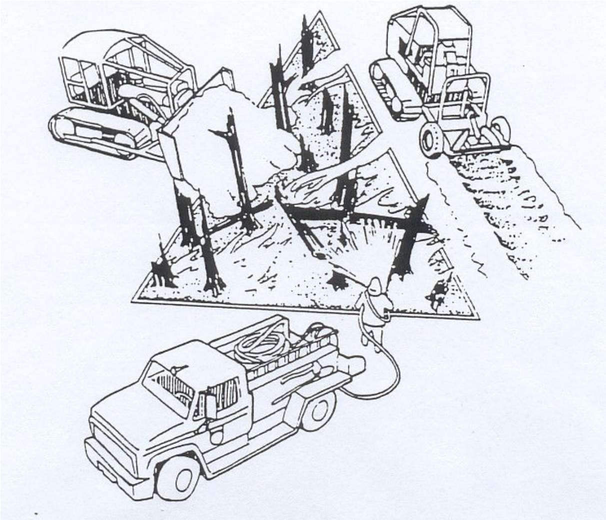
In closing, it's worth emphasizing that in applying the fire danger class criteria there can be no substitute for a good understanding of the FWI System. I believe that part of the reason for the dissatisfaction with the previous fire danger class criteria could be traced at least in part to a lack of understanding about the basic operating principles and philosophy behind the FWI System (e.g., "how come I can't put this fire out and the fire danger class indicates LOW?" or "the fire danger class is LOW and I've got fires spreading in grass -- how can this be?").

Annex 1: Suggested Symbolism for Fire Danger Classes

LOW

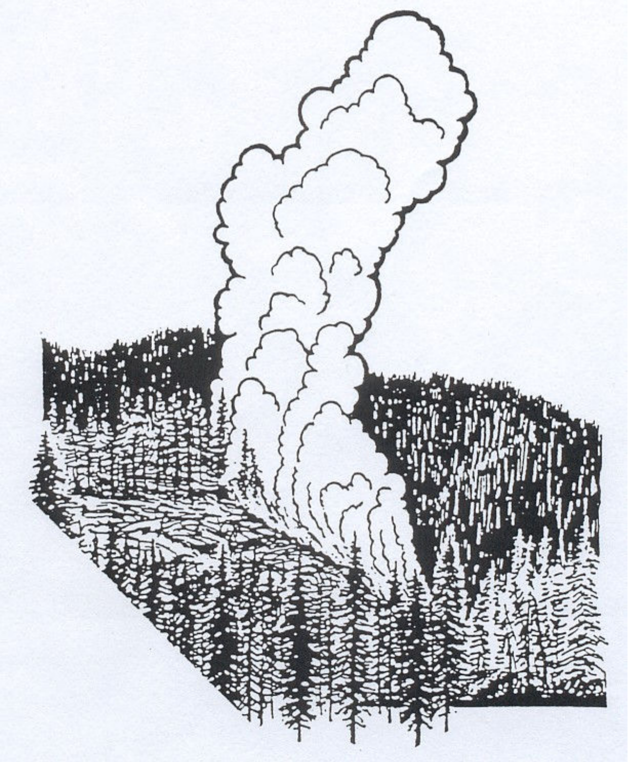
MODERATE

HIGH



VERY HIGH

EXTREME



Annex 2: Degree of Curing Assessment in Grasslands[9]

The most satisfactory means of estimating the Degree of Curing is by direct observation for an area which represents the “typical situation” in which most wildfires are expected to occur; ideally, the location should be within a few kilometers of a fire weather station. Obviously this will require considerable judgement on the part of local fire managers. A permanent transect 100 metres in length should be established for the Degree of Curing assessment rather than relying on a roadside check or cruise. Ideally, the transect should be marked with a steel post at each end as this permanent installation will allow comparisons to be made not only during the current fire season, but also from one fire season to another.

The sampling should be done by the same person. Observations are not required to be made on a daily basis but should be done at least every week or 10 days. Ten evenly spaced out samples (@ 10 m, @ 20 m, etc.) should be evaluated along the transect line. Pacing is sufficiently accurate for locating the sampling points. Care and judgement must be exercised in making the visual estimates of Degree of Curing. The best method is to locate a 1.0 metre by 1.0 metre sized frame (made out of small diameter wooden dowelling, light-weight aluminum or similar material) immediately in front of the toe where the sampler has paced the required distance. Mentally estimate, by **volume** not cover, the cured (i.e., dormant) or dead material in each quadrat to the nearest 5 percent. Often the grass must be pried apart to determine the amount of dead material underneath the current season’s growth, but still undecomposed. Following this, determine an average for the entire transect. For example, assume the following estimates of Degree of Curing for a 100 m transect:

75% @ 10m
80% @ 20m
85% @ 30m
90% @ 40m
85% @ 50m
90% @ 60m
90% @ 70m
95% @ 80m
80% @ 90m
90% @ 100m

The average = 86% or simply 85% for the purpose of the Grassland Fire Danger Graph or Table.

Estimates of cured or dead material less than 50 percent should be considered very carefully. These situations occur only when no litter (excluding decomposed material) or standing dead stems remain from the previous season’s growth. Initially, when the observer is “calibrating” his visual assessment, and then periodically, as a check, all the material within the frame should be clipped, the dead and live material separated and the volume of each determined by ocular means or by drying in a forced-air drying oven and weighed on a electronic balance if such equipment is readily available.

If a camera is available, I suggest that a photo (use 35 mm slide film) be taken at the time of each visit to the site from the starting post looking down the transect and perhaps of a “representative

---

[9] Adapted from Deeming *et al*. (1972), p. 22) and Wright & Beall (1938, p. 4).

quadrat” or two. A permanent record of the degree of curing assessments along with this photographic record should be keep giving the name of the assessor, date of the assessment, the estimated percentages and the mean value.

Annex 3: Some Suggested Guidelines for Declaring Prohibited Fire Seasons

Can the fire danger class criteria as outlined in this circular be applied to the task of deciding when to declare a prohibited fire season (Anon. 1991*b*)? I think it can and here I outline a concept for doing so. The main purpose of the following is to enlighten the reader rather than for he or she to blindly accept the "numbers".

In searching for a point in the fire season at which to invoke a "prohibited" status, one must consider not only the current fire danger conditions (e.g., the Drought Code (DC) component of the FWI System) but the current wildfire situation (especially the number of resources already committed to mop-up and patrol of existing fires which wouldn't be available for initial attack on any new fire starts), the long-term weather outlook, and the calendar date or how much longer the fire season will likely last based on history (e.g., is it January 1st or March 31st?).

Setting these considerations aside for the moment, let's assume that we wish to establish a "trigger point" based on the cumulative level of fuel dryness reached at some point in the fire season. In the case of forest areas, the most appropriate parameter by which to gauge this is the Buildup Index (BUI) component of the FWI System. The Degree of Curing is a reflection of the seasonal state of fuel moisture in grasslands.

Next, let us consider what kind of typical daily weather conditions we would likely experience after this "trigger point" is reached. We'll further assume that little or no rain will fall until the early winter rains commence. I believe that under an extended dry spell 1 p.m. New Zealand Daylight Time (NZDT) air temperatures would in all likelihood be at least 20-25°C and relative humidities would correspondingly be 40-50% or less (this corresponds to dew-point temperatures in the neighborhood of 6-14°C, or say 10°C for simplicity sake); on the basis of hourly summaries available for 15 Meteorological Service of N.Z. Ltd. airport weather stations (Table 4), a 20-25°C temperature appears quite reasonable for the latter half of the fire season when a prohibited fire season is most likely to be invoked.

Interestingly enough, Fenton (1951) pointed out that one of the factors contributing to the disastrous 1945-46 fire season, in addition to the below normal precipitation (Hocking 1946), was the prevalence of days with relative humidities less that 45%, especially when compared to other fire seasons as recorded at the Kaingaroa Forest Headquarters:

Fire Season	**No. of Days RH ≤45%**	**Fire Season**	**No. of Days RH ≤45%**
1942-43	4	1946-47	12
1943-44	15	1947-48	21
1944-45	12	1948-49	22
1945-46	63	1949-50	23

Based on hourly summaries available for the same 15 Meteorological Service of N.Z. Ltd. airport weather stations, the average 1 p.m. NZDT 10-m open wind speed during the fire season is around 22 km/h (Table 5).

In the absence of any rain other than the odd trace amount (say less than 0.6 mm), the Fine Fuel Moisture Code (FFMC) will tend to stabilize at about 89 with 1 p.m. dry-bulb temperatures of 20-25°C, relative humidities of 40-50% and 10-m open wind speeds of 22 km/h repeated day

Table 4. Average 1 p.m. NZDT dry-bulb temperatures during fire season months at airport weather stations around New Zealand.

Station	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	"Fire season"
				1 p.m. NZDT dry-bulb temperature			
Kaitaia	16.7	18.6	20.5	22.3	22.8	21.7	**20.4**
Whenuapai	17.0	18.8	20.7	22.4	22.6	21.5	**20.5**
Auckland	16.2	18.2	20.0	21.7	22.0	21.2	**19.9**
Rotorua	15.1	17.1	19.1	20.9	21.0	19.5	**18.8**
Gisborne	17.4	19.4	21.1	22.6	22.5	21.1	**20.7**
New Plymouth	15.0	16.9	18.8	20.3	20.9	19.9	**18.6**
Ohakea	15.3	17.1	19.1	20.6	21.0	19.7	**18.8**
Paraparaumu	14.7	16.3	18.2	19.5	19.8	19.0	**17.9**
Wellington	14.6	16.2	18.0	19.2	19.3	18.3	**17.6**
Nelson	15.1	16.8	18.8	20.2	20.4	19.3	**18.4**
Hokitika	13.6	15.1	16.9	17.8	18.4	17.6	**16.6**
Kaikoura	13.0	14.6	16.4	17.6	17.7	16.7	**16.0**
Christchurch	15.2	17.1	18.8	19.8	19.6	17.9	**18.1**
Dunedin	14.0	15.5	17.3	18.1	18.2	16.9	**16.7**
Invercargill	12.6	13.8	15.5	16.3	16.5	15.3	**15.0**
Mean	**14.1**	**16.8**	**18.6**	**20.0**	**20.2**	**19.0**	**18.3**

Table 5. Average 1 p.m. NZDT 10-m open wind speeds during fire season months at airport weather stations around New Zealand.

Station	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	"Fire season"
				1 p.m. NZDT dry-bulb temperature			
Kaitaia	24.3	24.1	23.3	21.5	22.0	21.9	**22.9**
Whenuapai	22.6	22.6	22.0	20.7	20.6	19.5	**21.3**
Auckland	24.5	23.9	22.8	21.9	20.7	20.4	**22.4**
Rotorua	18.2	17.6	17.0	16.1	15.2	15.0	**16.5**
Gisborne	23.2	24.1	22.0	21.5	20.2	18.2	**21.5**
New Plymouth	25.0	22.8	23.0	20.9	20.0	19.6	**21.9**
Ohakea	26.3	27.4	25.4	26.1	24.3	22.4	**25.3**
Paraparaumu	22.4	22.4	21.1	21.9	19.8	18.9	**21.1**
Wellington	33.0	34.0	32.8	32.4	30.6	29.8	**32.1**
Nelson	20.9	23.5	23.3	22.8	20.4	17.4	**21.4**
Hokitika	18.0	18.2	18.2	17.0	15.6	14.5	**16.9**
Kaikoura	19.3	18.3	18.2	18.2	17.4	16.5	**18.0**
Christchurch	21.3	22.4	23.0	22.2	20.7	19.1	**21.5**
Dunedin	20.7	21.9	20.0	19.6	16.3	16.3	**19.1**
Invercargill	26.7	26.9	23.7	24.8	22.6	20.7	**24.2**
Mean	**23.1**	**23.3**	**22.4**	**21.8**	**20.4**	**19.4**	**21.7**

after day (Van Wagner and Pickett 1985). An FFMC of 89 and 10-m open wind speed of 22 km/h corresponds to an Initial Spread Index (ISI) of 11; **the reader must bear in mind that there will be days were the ISI could be considerably higher and of course also considerably lower**.

We are now in a position to derive a "trigger point" in terms of the BUI. Let's consider that we wish to invoke a prohibited fire season when we are likely to experience day after day of VERY HIGH or EXTREME fire danger; **one must bear in mind that VERY HIGH and/or EXTREME fire danger class days could have just as likely occurred prior to this time**. For an ISI of 11, the threshold BUI value that results in VERY HIGH fire danger is 53 (see Fig. 1). Considering that the BUI will increase by roughly 3 points per day based on the 1 p.m. fire weather observations as described above, then one would set a BUI of 50 as the "trigger point"; note that if the BUI is increasing at 3 points per day, the BUI threshold (i.e., ≈80) for an EXTREME fire danger class (given an ISI of 11) will be attained in just over two weeks time. One could build in a bit of a "cushion" by selecting the mid-point of the HIGH fire danger class as opposed to the lower end of the VERY HIGH class -- the result is that the "trigger point" is a BUI of 40 which is incidentally, as pointed out in Table 3, likely to be about the point where one could expect a significant amount of ground or sub-surface fire activity leading to above average mop-up efforts (i.e., beyond 1 day).

In light of the above discussion, it's instructive to look back on the 1980-81 fire season (the first year the FWI System was used in New Zealand) in the Nelson region, and specifically at the fire danger conditions leading up to the Hira Forest and Redwood Valley Fires on 5 February 1981. The following account is extracted from a letter prepared by Mr P.W. Maplesden (Conservator of Forests, New Zealand Forest Service, Nelson) dated 15 April 1981:

> *The events leading up to the Hira fire left the Conservancy Fire Organization in no doubt as to the danger which had been built up over some period of time before the outbreak.*
>
> *Although rain was recorded five days before at Spring Grove it had little effect on the overall situation. During the 15 days prior to the Hira fire there were three fires, one in indigenous forest at Murchison on 20 January which burned for over a week; another at Packers Creek in Hira forest on 26 January and a third at Aorere on 3 February which indicated that the potential for fire anywhere and at any time really existed. The dangers were exacerbated by the onset of a strong dry southerly wind on 3 February. Conditions were recognized by my declaration of a total fire ban on the lighting of all fires in the Golden Bay and Nelson areas which was made on 5 February…*
>
> *Precautions had been taken on all forests in the Conservancy, work was either stopped or restricted to morning hours and crews brought closer to Headquarters.*

In a letter dated 11 March 1981 from Mr N.J. Costley (Senior Forest Ranger) to Mr P.W. Maplesden, the following points are noteworthy:

> *The local Fire Authorities had considered the fire danger situation independently and were to meet on 22.01.81 when it would have considered declaring a prohibited season.*
>
> *Rain on 20.1.81 reduced the immediate risk of fire and this reduction was evident until 4.2.81 when a south westerly wind which had been blowing since the late afternoon hours of 3.2.81…*

> *On February 5, 1981 the local fire authorities met and endorsed the Conservator's action to declare a prohibited season under Section 21 (1)(a) of the Forest and Rural Fires Act 1977.*

The FWI System components related to the above dates at three of the fire weather stations in the area are as follows (Nelson Airport was not used for calculating FWI System components at the time):

Nelson Airport

Date	FFMC	DMC	DC	ISI	BUI	FWI
January 19	86.8	79	400	5.2	106	21
January 20	24.2	45	382	0.0	70	0
January 21	35.9	17	271	0.0	30	0
January 22	72.3	19	279	2.1	32	5
January 26	94.3	29	311	37.3	48	52
February 3	87.0	39	370	11.1	62	27
February 4	90.1	42	377	22.9	66	44
February 5	90.1	45	385	44.3	70	69

(41.4 mm rain recorded on January 20-21)

Rabbit Island

Date	FFMC	DMC	DC	ISI	BUI	FWI
January 19	85.6	79	418	3.6	107	16
January 20	30.8	42	387	0.0	66	0
January 21	37.7	18	322	0.0	31	0
January 22	69.7	20	330	1.4	34	3
January 26	86.9	26	362	15.2	44	28
February 3	85.7	28	407	7.8	48	18
February 4	85.8	30	414	21.6	51	38
February 5	89.0	33	422	34.2	55	53

(30.1 mm rain recorded on January 20-21)

Spring Grove

Date	FFMC	DMC	DC	ISI	BUI	FWI
January 19	90.6	99	410	7.3	123	28
January 20	24.2	50	372	0.0	74	0
January 21	48.9	27	345	0.2	45	0
January 22	77.8	29	353	2.1	48	6
January 26	95.4	44	387	30.8	69	54
February 3	89.6	40	421	6.4	65	18
February 4	92.5	44	428	56.0	69	79
February 5	92.5	47	436	56.0	74	81

(22.4 mm rain recorded on January 20-21)

The seasonal trends in the daily 24-h rainfall, the three FWI System fuel moisture codes and the BUI for these three stations are displayed in Figures 3-5. Readers may find it useful to look back at other fire seasons in their particular locale in the same manner as has been done here. A graph comparable to Figures 3-5 for the 1945-46 fire season in the Taupo area has also been prepared (Pearce and Alexander 1994).

From the information presented above, the following conclusions appear warranted (admittedly with the benefit of 20:20 hindsight):

- The rainfall which occurred on January 20-21 did indeed relieve the fire danger situation in the vicinity of Nelson Airport and Rabbit Island, at least temporarily.

- However, given the levels of the DMC and DC prior to the rain on January 20-21 and the lack of rainfall there afterwards, the BUI at Nelson Airport and Rabbit Island was back into a critical range (say, above 40) within 4 days (or within a week if 50 is accepted as the "trigger point").

A prohibited fire season could have possibly been declared as earlier as around Christmas time when the BUI reached 40 and continued to climb until January 20-21, or a few days after Christmas when the BUI exceeded 50. A BUI of 80 was attained on January 9.

The preceding discussion has focused on forest areas. The same methodology can also be applied to grasslands, except instead of the BUI, the Degree of Curing is used, which is a direct reflection of the seasonal state of relative moisture content in these fuels. Given an ISI of 11, the Degree of Curing threshold value for a VERY HIGH fire danger class is between 75-80% (Fig. 2). Cheney (1991*b*) makes the following statement about the degree of curing in grasslands:

> *...it should be considered as a constant fire danger variable as it varies widely by location and rather slowly by time. Early in the fire season, ridges become fully cured well before gullies, creek lines and other moist areas. Fires may spread along the ridges in grasses which are fully cured but stop when they run into grasses in creek lines which are only 50% cured or less. In assessing the curing state of a region, it is necessary to take a broad scale view of the landscape and it is only when the landscape is 90-100% cured that grassfires can spread freely across it.*

In light of the above observation, and since the issue of mop-up difficulty is not as great a problem in grasslands as it is with forest areas, I'm inclined to suggest that a Degree of Curing value of 80% be considered as the "trigger point" for declaring a prohibited fire season in grassland dominated areas.

Figure 3. Seasonal trends in the daily 24-hour rainfall, the three FWI System fuel moisture codes and the BUI for the Nelson Airport weather station in the lead up to the 1981 Hira and Redwood Valley fires.

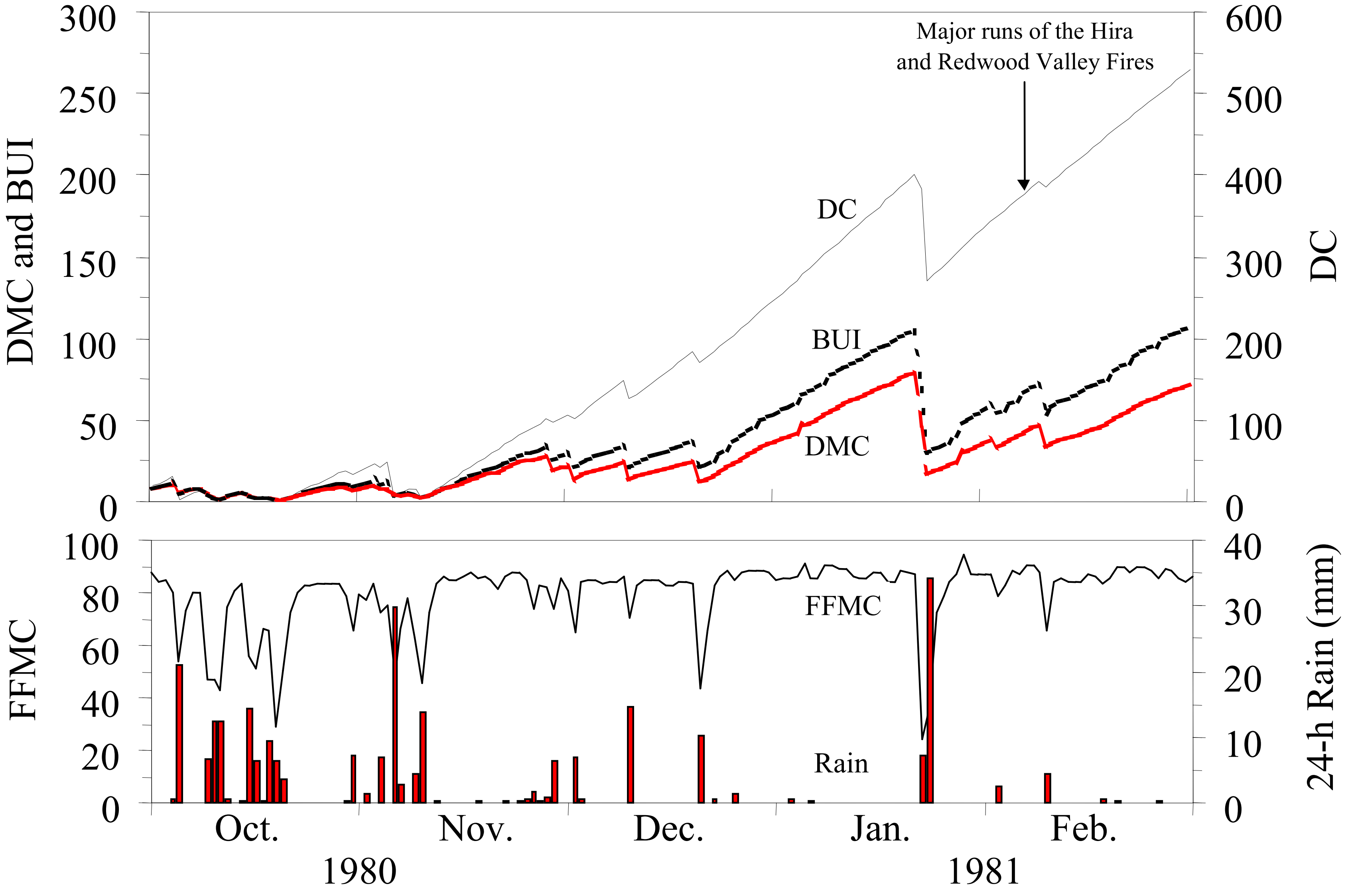


Figure 4. Seasonal trends in the daily 24-hour rainfall, the three FWI System fuel moisture codes and the BUI for the Rabbit Island weather station in the lead up to the 1981 Hira and Redwood Valley fires.

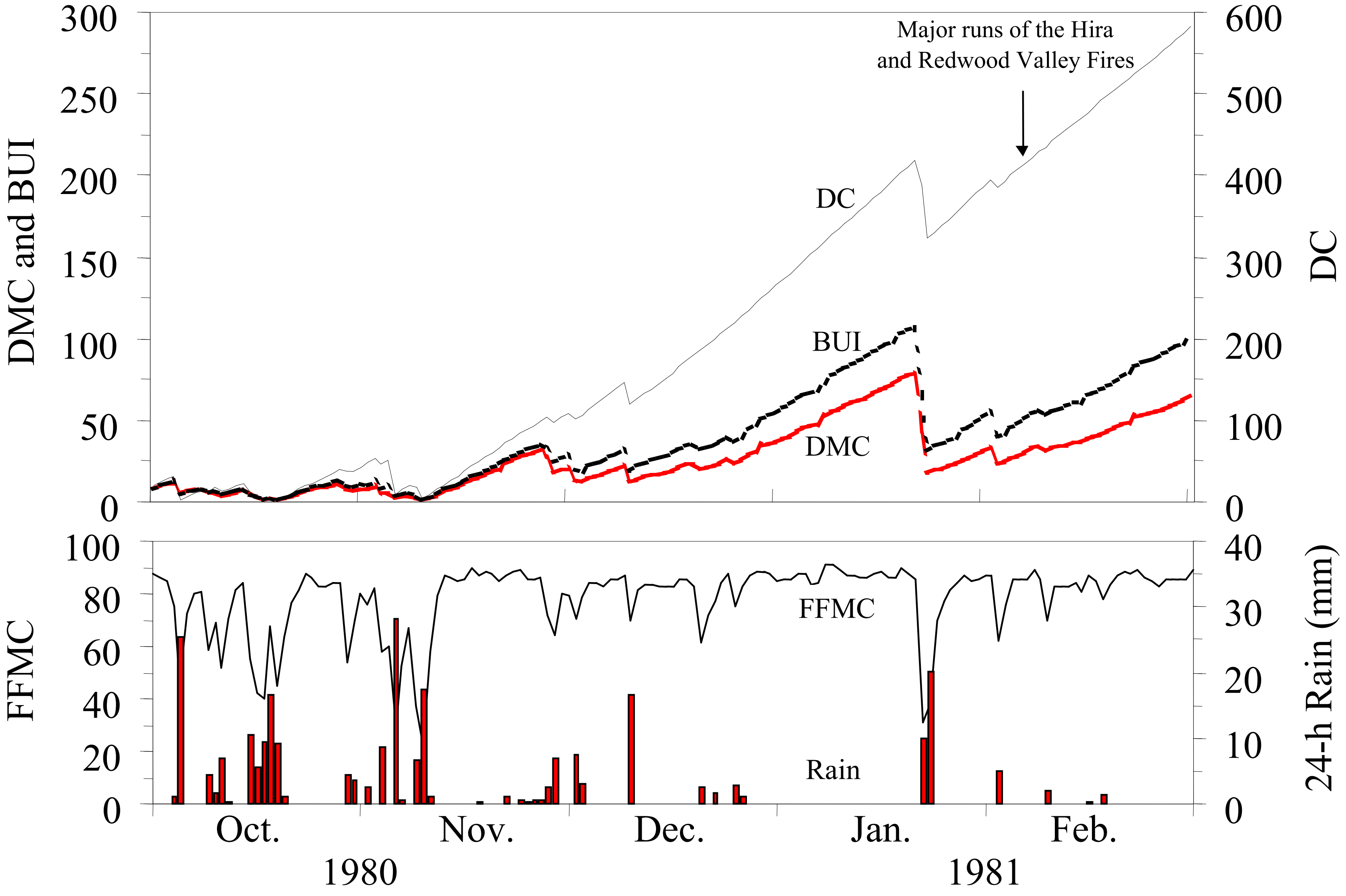
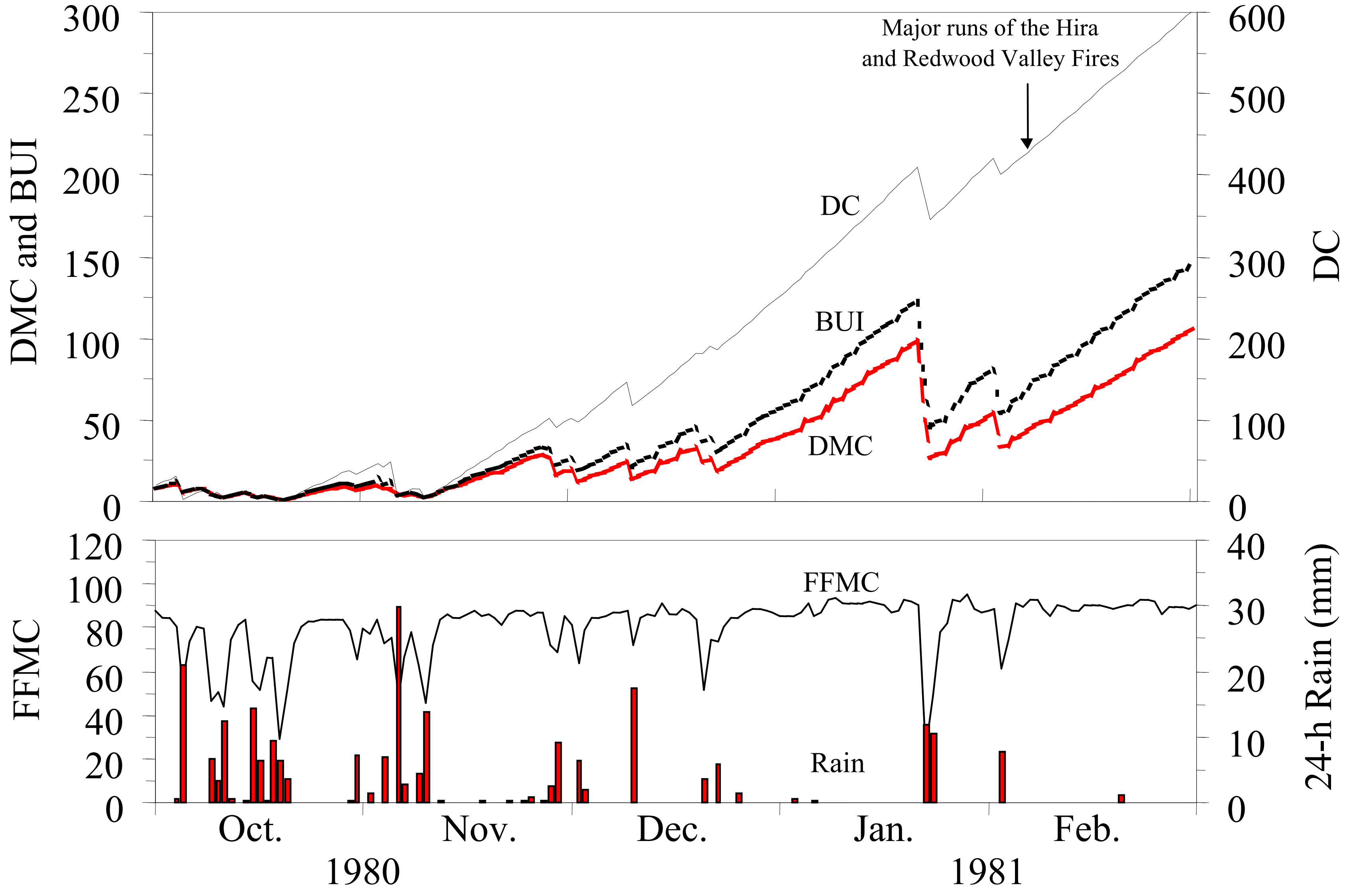


Figure 5. Seasonal trends in the daily 24-hour rainfall, the three FWI System fuel moisture codes and the BUI for the Spring Grove weather station in the lead up to the 1981 Hira and Redwood Valley fires.



Part II: Research Documentation

Annex 4: Background Information and Technical Basis for Fire Danger Classes

Fire danger is “a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control and fire impact(s)” (Merrill and Alexander 1987). Fire danger rating is in turn generally regarded as “the process of systematically evaluating and integrating the individual and combined factors influencing fire danger represented in the form of fire danger indexes” (Merrill and Alexander 1987). A fire danger index is “a quantitative indicator of one or more facets of fire danger, expressed in a relative sense or as an absolute measure” (Merrill and Alexander 1987). All six components of the Fire Weather Index (FWI) System (i.e., the Fine Fuel Moisture or FFMC, the Duff Moisture Code or DMC, the Drought Code or DC, the Initial Spread Index or ISI, the Buildup Index or BUI, and the Fire Weather Index or FWI; see Fig. 6) are fire danger indexes; a concise review of the FWI System can be found in Alexander (1992*b*), (1992*c*) or (1992*e*).

So what is a fire danger class? According to Merrill and Alexander (1987) it is:

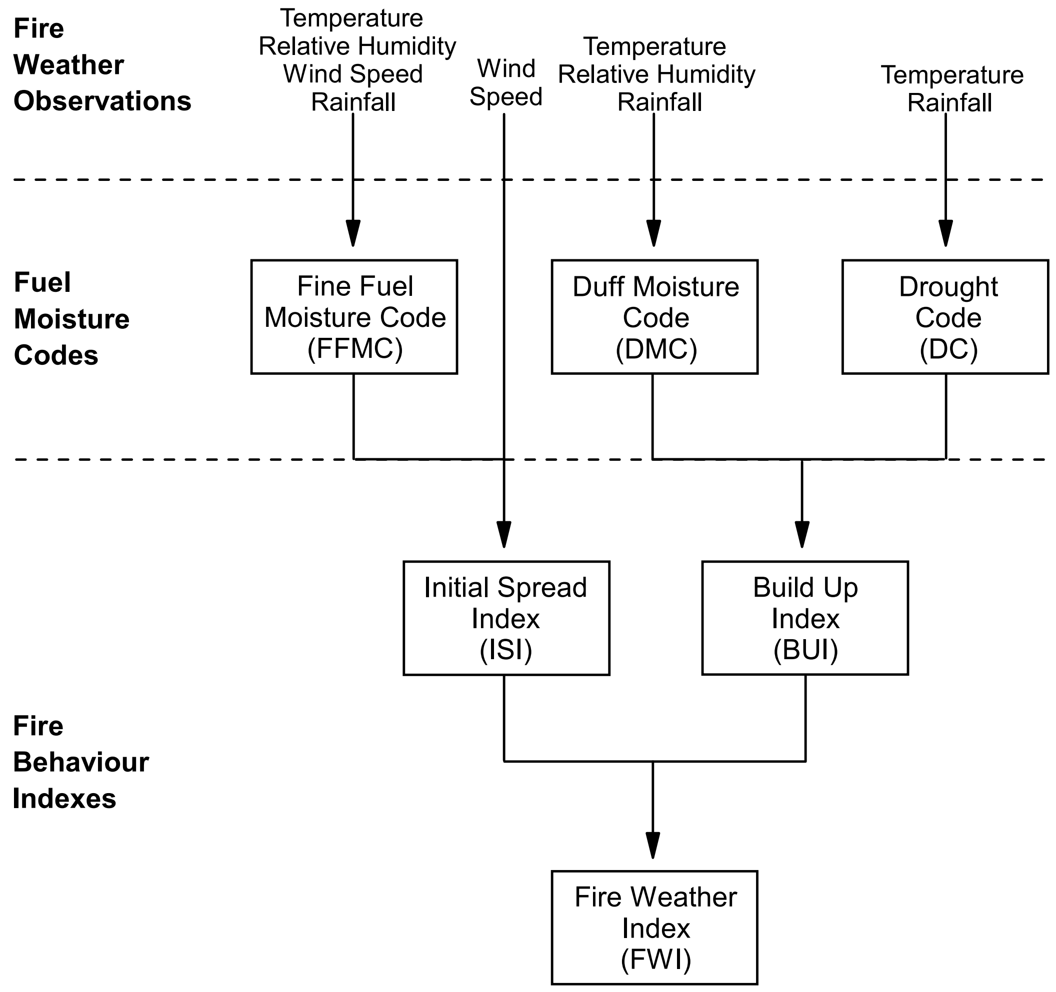
> *A segment of fire danger index scale identified by a descriptive term (e.g., Nil or Very Low, Low, Moderate, High, Very High, or Extreme), numerical value (e.g., I, II, III, IV, or V), and/or a colour code (e.g., green, blue, yellow, orange, or red).*

The FWI System, which was developed by Canadian fire researchers, was adopted by New Zealand Forest Service (NZFS) as the basis for a national system of fire danger rating at the start of the 1980-81 fire season. Fire danger classes were delineated according to the FWI component of the FWI System based on Valentine’s (1978) review and evaluation (from New Zealand Forest Service 1983):

Descriptive Term	**All forests except Balmoral & Naseby**	**Balmoral & Naseby Forests**
Low	0-7	0-11
Moderate	8-16	12-23
High	17-3 1	24-39
Extreme	32+	40+

The practice of using a separate classification for Balmoral and Naseby Forests was apparently dispensed with in 1987 with the demise of the NZFS. Valentine (1978, p. 28) had actually proposed two separate classifications based on areas with mean annual rainfall of more than 750 mm (equivalent to “All forests except Balmoral and Naseby”) and less than 750 mm (equivalent to “Balmoral and Naseby forests”); areas with less than 750 mm of annual rainfall are restricted to the South Island, notably the Canterbury Plains and Central Otago (New Zealand Meteorological Service 1984).

Valentine (1978) in actual fact adopted the fire danger classification scheme used in Fire Danger Regions I and II of British Columbia which had originally been developed in the mid-70s (Anon. 1975*a*) (see also Fig. 3 in Stocks *et al*. 1989; please note that the upper limits of the FWI in the High fire danger class are 30 and 38, respectively, and not 31 and 39 as given in Valentine 1978 and New Zealand Forest Service 1983); this uses both the FWI and BUI components of 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.Times Ne Roman

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 moderate duff layers and medium-size woody material.

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 amount of smouldering in deep duff layers and large logs.

Initial Spread Index (ISI) - a numerical rating of the expected rate of fire spread. It combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel.

Buildup Index (BUI) - a numerical rating of the total amount of fuel available for combustion that combines DMC and DC.

Fire Weather Index - a numerical rating of fire intensity that combines ISI and BUI. It is suitable as a general index of fire danger throughout the forested and rural areas of New Zealand.

Figure 6. Simplified structure diagram for the Fire Weather Index (FWI) System, and definitions for the six principal components (after Anon. 1993).

FWI System (B.C. Ministry of Forests 1983) and is based on an analysis[10] of wildfire report data in relation to fire danger conditions specific to this area of Canada (Turner 1973; Anon. 1975*b*; Lawson 1977). Low, Moderate, High and Extreme fire danger classes[11] were expected to occur, on average, on about 45%, 30%, 20% and 5% of the days, respectively, during the five-month fire season in British Columbia. However, Valentine (1978) stated that "the wisdom of adopting the British Columbian practice of combining FWI and BUI when determining Danger Classes is uncertain... it may be more relevant in the deep duff accumulations in British Columbia than in New Zealand...". Valentine (1978) also noted that "full analysis of past New Zealand fire weather records may indicate these classes need to be adjusted". Unfortunately this was never done. From the information contained in Cooper and Ashley-Jones (1987), which was based on only a four-year review (1981-1985) of the 18 NZFS districts in place at the time, the combined percentage of High and Extreme fire danger class days averaged about 15% for the period November 1 - March 31 with of course some variation (0% at Westland to 30% at Masterton).

Throughout the 1980s and early 90s as experience was gained with the use of the FWI System, various permutations of what Valentine (1978) had originally recommended began to emerge (without any real objective basis or systematic approach to the task) at a local level (Anon. 1992*b*, 1992*c*) and nationally (e.g., Anon. 1986, 1990, 1991*a*), although some organizations made a distinction between fire danger classes for public consumption and the application of the FWI System components for managerial purposes (e.g., lookout scheduling, woods operation shutdown) (Anon. 1992*a*). These guidelines were then promulgated overseas (Dudfield 1988, 1989, 1990). Generally, the trend was to add additional components of the FWI System as criteria for determining the daily fire danger class. I believe this is a reflection of at least one of two things. It may indicate a very poor understanding of the FWI System and/or it points out that the purpose(s) of the fire danger classes has not been well defined because people are attempting to apply the classes to a whole host of fire management activities (e.g., standby readiness, burning permit issuance, controlled burning guidelines, forest operation closures, declaration of prohibited fire seasons). Probably the most common misinterpretation is the fact that most people feel that the fire danger classes should naturally be an indicator of holdover fire problems and mop-up difficulty -- e.g., on-going fires can still be smouldering when the DC is greater than 300 but the fire danger class is only Low (i.e., FWI <7). **The fact of the matter is, it's difficult to portray all the aspects of fire danger in a single number (e.g., the FWI) and only one fire danger class scheme can't be expected to cover the full range of fire management needs**. Following the initial implementation of the FWI System in Canada in 1970, Turner (1971) noted that "…components of the system can... be useful guides, provided they are considered in relation to the other parts of the system… the longer term Drought Code has been used successfully on Vancouver Island as a guide to the possible difficulty of controlling slash burns. However, there's one danger in using one of these isolated components and that is that people try to read too much into it. We've had complaints that the long term Drought Code doesn't tell you anything about how easy it is to light the fire. Well, it wasn't intended to. But sometimes one loses sight of this."

---

[10] The British Columbia approach to fire danger classes encompasses considerations of both fire occurrence and fire behaviour, in other words, "fire load" which is "the number and magnitude… of all fires requiring suppression action during a given period within a specified area" (Merrill and Alexander 1987).

[11] In actual fact, according to the document "Rationale for the B.C. Danger Rating System" (Anon. 1975*b*), "Descriptive names, "extreme", "high", etc. were scrapped in favor of Roman numerals V, IV, etc. to avoid confusion with fire behavior descriptors applying to specific fuels on specific topographic sites." Low, Moderate, High, etc. are only used for the general public (B.D. Lawson, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, *pers. comm.*).

As a first step in revising the fire danger class criteria, a literature review and survey of existing practices in the U.S.A. (Deeming *et al.* 1977; Main *et al.* 1990), Australia (Sneeuwjagt and Peet 1985; Cheney 1991*a*, 1991*b*, 1992), Canada (Anon. 1975*a*, 1975*b*; Van Wagner 1974, 1987), and elsewhere (e.g., Reifsynder 1978; Peet 1980; van Wilgen and Burgan 1984; Cooper 1992) was undertaken in relation to what I perceive New Zealand needs are at this time based on general discussions with numerous individuals coupled with my own personal insights into the New Zealand fire management scene. I suspect that most fire managers have a pretty fair idea of what Low fire danger constitutes and the same for Extreme, although in all likelihood they can't quantify their feelings nor necessarily specify any particular threshold condition(s). The basic problem therefore boils down to, as Deeming (1983) points out, being able "…to divide the continuum of fire-danger into discrete classes…".

Traditionally, the concept of fire danger index frequency of occurrence has been used to demarcate the boundaries or categories of fire danger classes based on a preconceived idea of the percentage of days that should be in each class. This concept was originally introduced in the 1960s in the U.S.A. (e.g., Pirsko 1961*a*, 1961*b*; Barney 1968) and later adopted by Canada (Van Wagner 1974) as near as I can ascertain, and has continued to the present day (Lancaster 1974; Van Wagner 1987; Main *et al.* 1990)[12]. There are obviously many weaknesses with this approach (Deeming 1983), not the least of which is that in certain fuel types, the resulting fire behaviour at Moderate or High fire danger may preclude any suppression action! It is my considered opinion that this approach is no longer relevant nor appropriate for New Zealand in light of advances that have been made in fire behaviour/fire suppression modelling in recent years. In this regard, readers are strongly encouraged to consult Alexander (1992*d*).

Alternatively, historical fire weather/fire danger records could be analyzed in relation to wildfire report data as was done for example in British Columbia (Turner 1973; Anon. 1975*a*, 1975*b*; Lawson 1977). Unfortunately, New Zealand doesn't have a dense enough fire weather station network with a sufficient length of record (say 10 years), nor has it ever had comprehensive fire reporting for the country as a whole to be able to do this.

Fire danger obviously encompasses many facets of fire incidence and fire behaviour as evident by the definition given earlier:

- ignition potential
- spread rate
- control difficulty
- immediate postburn impacts

Rate of fire spread and elapsed time since ignition will determine the potential area burned and length of the fire's perimeter or circumference. The difficulty of control represents "the amount of effort to contain and mop-up a fire based on its behaviour and persistence" (Merrill and Alexander 1987). Fire intensity and spotting potential are the chief determinants of the ability of fire suppression resources to contain a free-burning vegetation fire. A fire's intensity, duration

---

[12] Prior to this time, the determination of fire danger and a corresponding class tended to be somewhat subjectively derived, a fact that was openly criticized by some (e.g., Reifsnyder 1959). This was true of all Canadian, American and Australian fire danger rating systems at the time, including the New Zealand Fire Danger Meter. However, this simply reflected the evolutionary nature of fire danger rating research and development as our scientific knowledge of fire behaviour gradually improved over the years.

and size will dictate the impact (e.g., damages such as loss of tree crops, destruction of native forests, houses having been burnt down).

Given that fire managers want a simple answer to the question: ***How serious is the danger of fires starting, spreading and doing damage today?*** (Brown and Davis 1973), what's the best approach to take? Several years ago, Van Wagner (1970) pointed out that the goal of fire danger rating research

> *...is easily stated: Make an index such that any given value will always represent the same fire behaviour, no matter what weather history leads up to it.*

He also acknowledged that this "...is a very stiff test" and that

> *The trouble is, one quickly outruns the available practical knowledge and theory. A liberal dose of philosophy is therefore required as well.*

The above statements apply equally well to the subject of fire danger classes as they do to fire danger indexes. In my view, the best approach (i.e., the most objective/quantitative methodology) at the present time for delineating fire danger classes is to use Byram's (1959) fireline intensity concept to determine the degree or severity of the containment difficulty **SHOULD AN IGNITION OCCUR**[13]. I've developed this idea in several previous publications (Alexander and De Groot 1988; Alexander and Lanoville 1989; Alexander 1992*d*), as have others (e.g., Wilson 1993). The basic premise is that the ability to control or contain a fire gradually decreases with increasing fire intensity.

The most basic characteristics of a vegetation fire is that it spreads, it consumes fuel and it emits heat energy (principally radiation and convection) and light. Byram's (1959) formula[14] for computing fire intensity incorporates these fundamental ideas:

$$I = H \times w \times r$$

where **I** = fire intensity in kilowatts per metre (kW/m), **H** = net low heat of combustion in kilojoules per kilogram (kJ/kg), **w** = weight of fuel consumed in the active flaming front per unit area in kilograms per square metre (kg/m^2), and **r** = rate of fire spread in metres per second (m/s).

---

[13] The ISI, BUI and FWI are each designed to represent some aspect of fire behaviour after ignition has taken place. The FFMC, DMC and DC, on the other hand, represent fuel moisture and should therefore be related to the ease of ignition. None of the FWI System components says anything about the presence or level of activity of fire-starting agents, in other words, fire risk. Any comparison between actual fire occurrences and the FWI System combines both flammability (i.e., the relative ease with which a substances ignites and sustains combustion) and risk. The FWI System components can measure flammability but cannot account for fire risk. Since a fire start depends most of all on the flammability of the fine surface fuel, the FFMC is the FWI System component most likely to compare well with wildfire occurrence.

[14] Although some of this material is included in the NRFA Crew Boss Course (Anon. 1991*a*), persons who attended one of three NRFA-NZ FRI sponsored Advanced Fire Behaviour Courses in 1992-93 or the NRFA Intermediate Fire Behaviour Course in 1993 will be in a better position to comprehend the principles being outlined here. For a comprehensive review on the subject of fire intensity, see Alexander (1982). Note that some individuals (e.g., Wallace 1993) like to express fire intensity in megawatts per metre (MW/m); 1 MW/m = 1000 kW/m. However, kW/m has been the accepted unit throughout the international wildland fire management community, or at least those countries where the International System of Units (SI) is used (e.g., Canada, Australia).

For practical purposes, **H** can generally be regarded as a constant at 18 000 kJ/kg. For operational purposes, **w** and **r** are more conveniently quoted in tonnes per hectare (t/ha) and metres per hour (m/h), as is the case in Australia, which I certainly concur with. It therefore becomes possible by considering **H** as a more or less constant value, taking into account more convenient units for **w** and **r**, and by the process of simple mathematics, to compute **I** by the following equation:

$$I = \frac{W \times R}{2}$$

where, for the sake of clarity in this presentation, **W** = quantity of fuel consumed (t/ha) and **R** = rate of fire spread (m/h). So, for example, a fire spreading at 600 m/h and consuming 20 t/ha of fuel would have an intensity of 6000 kW/m (i.e., **I** = (20 × 600) ÷ 2). Fire intensity represents the energy output (kW) being generated from a strip of the fire front one metre (m) wide, extending from the leading edge of the fire front back through to the rear flaming zone as illustrated in Figure 7. Fires which are not able to generate intensities of greater than about 10 kW/m tend to be self-extinguishing (Byram 1959).

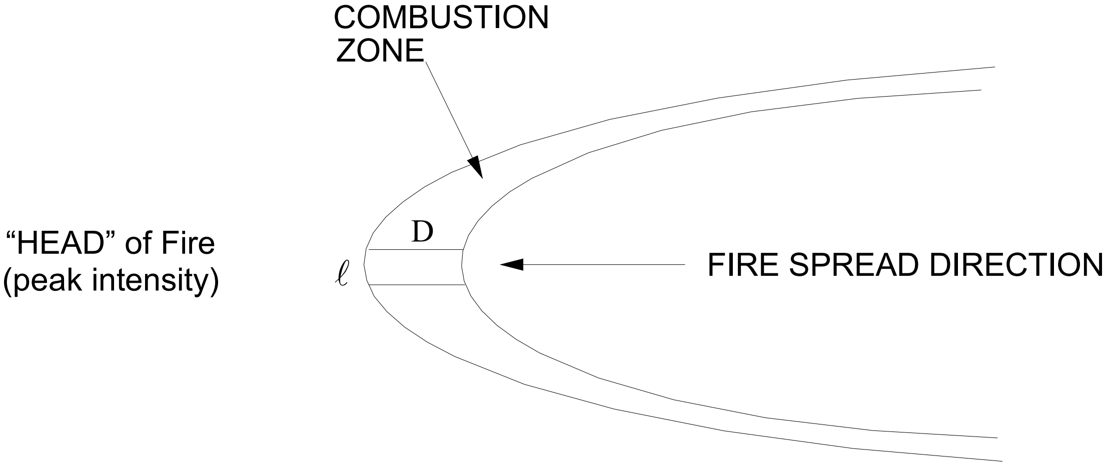


Figure 7. The area of active flame front, ℓ × D, releasing the energy calculated by Byram's (1959) fire intensity formula (after Tangren 1976).

Flame size is a manifestation of fire intensity. For example, Byram (1959) developed the following equation for surface fires which, although it's not applicable to all fuel complexes, is still a useful relationship:

$$L = 0.0775 \times (I)^{0.46}$$

where **L** = flame length in metres (m), and **I** = fire intensity (kW/m). For example, the 6000 kW/m fire noted above would have a flame length of about 4.2 m. Flame length represents the distance between the flame tip and the midpoint of the active combustion zone in a spreading fire (see Alexander 1992*d*, p. 66). In the absence of any wind or slope, **L** can be equated to the maximum vertical extension of the flame front (i.e., flame height). The height of the flame front determines the degree of radiant heat received at a distance from the fire perimeter.

Table 6. Likely tolerable upper limits of fire intensity for various types of suppression resources.

Type of Fire Suppression Force and Equipment Employed	Likely Tolerable Upper Limit of Fire Intensity
Ground crews using shovels, pulaskis, rakes, etc.	~ 500 kW/m
Ground crews working with heavy machinery or power tools	~ 2000 kW/m
Single drops from airtankers and helitankers	~ 4000 kW/m

Fire intensity is one of the major determinants associated with the difficulty of controlling or containing a free-burning vegetation fire. From a fire behaviour standpoint, the other factors include the rate of perimeter increase or growth (which is a function of the rates of spread at the head, flanks and back of the fire), spotting characteristics (which is partly related to fire intensity), development of fire whirls, etc. In 1983, I undertook a comprehensive search of the available information on fire intensity in relation to the effectiveness of various types of suppression resources (Alexander 1984*a*) in connection with a request to develop a fire danger rating methodology for grasslands (Alexander 1984*b*), and to this day have earnestly maintained a file on the subject. The generalities outlined in Table 6 are therefore based on a combination of operational experience, research data and expert opinion, taking into account fireguard construction capability (i.e., typically width and production, and the ability to work near the fire edge) in a direct attack mode in terms of radiation heat loads; no doubt refinements will come about as a result of continued research and operational evaluations. Indirect attack on wildfires by backfiring from the ground or air maybe a possibly up to fire intensities of around 10 000 kW/m, but this doesn't appear to be a firefighting option that's likely to be widely practised in New Zealand, especially in an initial attack situation.

On the basis of the material that's been presented to this point, I'm proposing that the fire danger classes be based on the potential fire intensity in a fuel type as follows:

Fire Danger Class	Fire Intensity (kW/m)
LOW	<10
MODERATE	10-500
HIGH	500-2000
VERY HIGH	2000-4000
EXTREME	>4000

You'll note that this approach does indirectly include consideration of ease of ignition (i.e., fire starts are certainly possible whenever potential intensities exceed 10 kW/m). It also incorporates to some extent rate of fire spread since it is required for the calculation of fire intensity (in actual fact, rate of fire spread has a far greater effect on fire intensity than fuel consumption because of the larger potential variation that's possible). Finally, fire intensity will also determine the negative impacts or damages during and following any fire. For example, fire intensity is one of the factors influencing whether a house will survive the onslaught of a forest or rural fire (Table 7). Furthermore, the height of lethal crown scorching (Van Wagner 1973*a*) or outright death from torching or crowning (Van Wagner 1977, 1989) in conifer forests is also related to fire intensity as evident in the following tabulation:

Table 7. Approximate probabilities of a house surviving a wildland fire*.

Scenario A: Total disregard for any safety precautions.
Scenario B: Fire safety precautions taken only in regards to fuels surrounding house.
Scenario C: Fire safety precautions taken only in regards to the house itself.
Scenario D: All reasonable fire safety precautions to and near the house taken.

Without Persons in Attendance

	Fire Intensity Class (kW/m)		
Scenario	500-1500	1500-10 000	10 000-60 000
A	14.4%	1.2%	0.3%
B	16.0	4.9	1.0
C	26.1	8.7	1.9
D	59.1	28.1	7.4

With Persons in Attendance

	Fire Intensity Class (kW/m)		
Scenario	500-1500	1500-10 000	10 000-60 000
A	29.9%	10.3%	2.3%
B	63.6	32.1	8.9
C	76.5	46.8	15.3
D	93.0	78.2	42.6

* Based on a logistic regression model as developed from an analysis of 455 houses which were either completely destroyed, threatened and/or sustained minor damage by the bushfire which swept through the township of Mount Macedon in Victoria, Australia, on the evening of Ash Wednesday (February 16) in 1983 (Wilson 1986; Wilson 1988*a*); the following attributes were considered in the above scenarios:

House and Surrounding Fuel Conditions	**Scenario**			
	A	B	C	D
Flammable objects nearby (e.g., firewood heap)?	Yes	No	Yes	No
Wooden shingle roof?	Yes	Yes	No	No
Non-wooden or non-tile roof with pitch >10º?	No	No	Yes	Yes
External walls made of brick, stone or cement?	No	No	Yes	Yes
Trees (5+ m high) within 40 m of house?	Yes	No	Yes	No

Fire Intensity (kW/m)	Lethal Crown Scorch Height (m)	Threshold LCBH for Crowning[15] (m)
500	9	1.5
2000	24	3.8
4000	37	6.0

The formulae used to make these computations are as follows (*cf.* Alexander 1982, 1988):

$$h_s = 0.1483 \times (I)^{2/3}$$

$$I_0 = [0.010 \times LCBH \times (25.9 \times FMC + 460)]^{1.5}$$

where h_s = lethal scorch height (m), I = fire intensity (kW/m), I_0 = critical surface fire intensity for crown combustion (kW/m), LCBH = live crown base height (m), and FMC = foliar moisture content (% o.d.w. basis).

Table 3 in PART I of this circular dealing with fire danger class interpretations was developed in part from a host of sources (Nelson 1961, 1964; Williams 1963; Canadian Forestry Service 1970; Brown and Davis 1973; Muraro 1975; Alexander and De Groot 1988, 1989; Alexander and Lanoville 1989). The flame heights contained in Table 3 are based on Byram's (1959) flame length-fire intensity relation-ship described earlier by assuming that flame height and flame length were equal.

Fire intensity as used here applies to the peak value at the head of fire which is generally the most intense portion of a fire's perimeter (see Fig. 7). In actual fact of course, the fire's intensity gradually diminishes from the head down along the flanks to the back or rear of the fire. For example, the approximate distribution of fire intensities for an elliptically shaped fire (Alexander 1985) with a head fire intensity of 5000 kW/m and length-to-breath ratio of 3 to 1 is (after Catchpole *et al*. 1992):

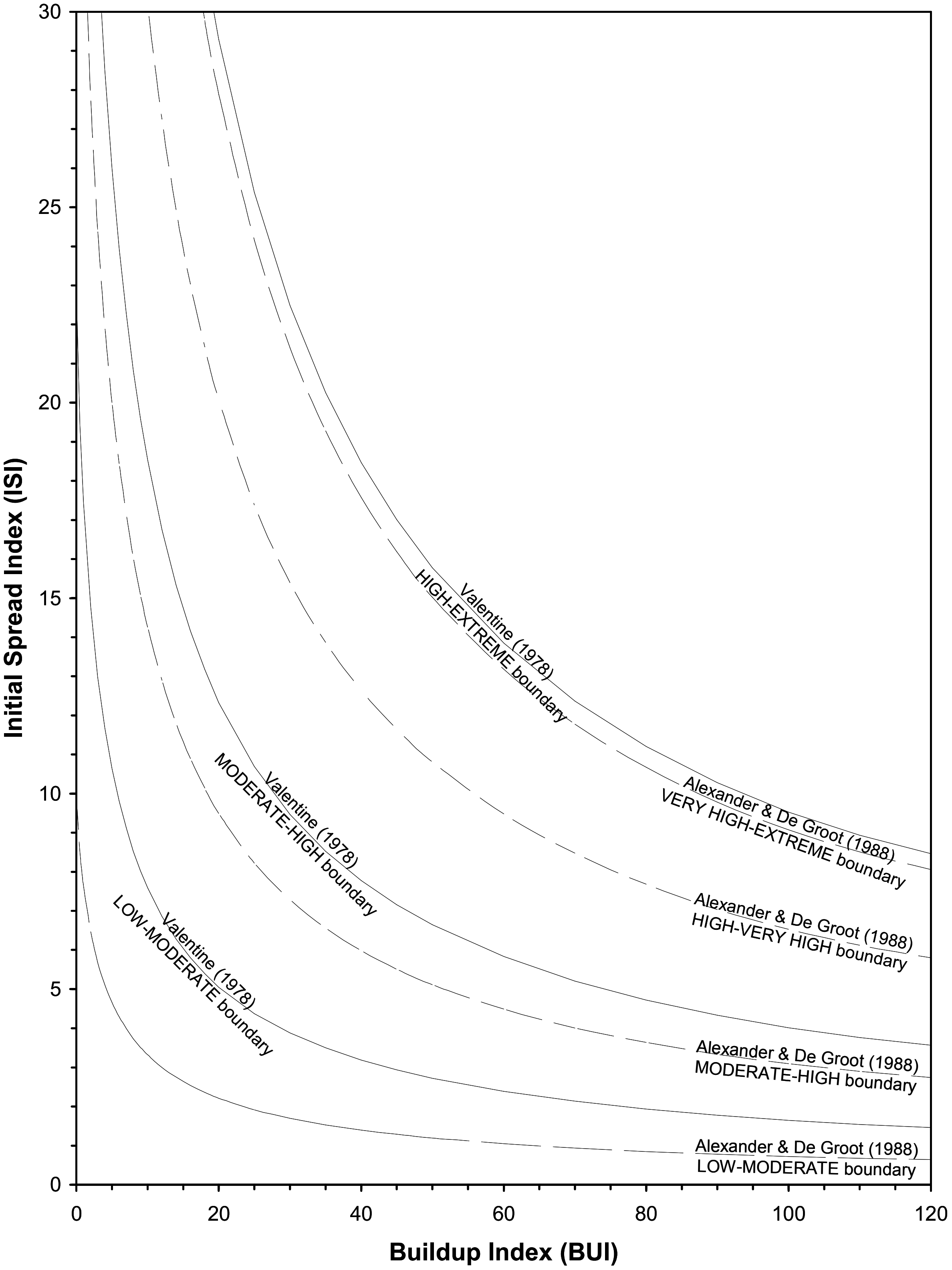
Fire Intensity (kW/m)	Proportion of Total Perimeter Length (%)
<500	25
500-2000	59
2000-4000	12
>4000	4

So, how do we go about defining these fire intensity classes in terms of the FWI System? The fact that New Zealand has no body of wildland fire behaviour research knowledge to draw upon certainly hinders matters, a fact that Cooper and Ashley-Jones (1986) openly lamented about. The simplest solution would be to simply adopt the ISI/BUI criteria depicted in Graph 2 (see also Alexander and De Groot 1989) on the Alexander and De Groot (1988) poster "Fire Behavior in Jack Pine Stands as Related to the Canadian Forest Fire Weather Index (FWI) System". I've reproduced as Figure 8 here, that graph along with a transformation of Valentine's (1978)

---

[15] LCBH = Live Crown Base Height. Based on a foliar moisture content of 145% as determined from samplings undertaken by the New Zealand Forest Research Institute in 1990-93. Sample interpretation: for situations in which the fire environment would result in fire intensities of 2000 kW/m, any stand with a LCBH less than 3.8 will be susceptible to crowning.

Figure 8. Comparison of Alexander and De Groot (1988) vs. Valentine (1978) forest fire danger class criteria.



original criteria using the ISI and BUI rather than simply the FWI component itself, using the equations given in Van Wagner (1987). The most noticeable feature of Figure 8 is the huge range in the High class according to Valentine's (1978) criteria and the need for a Very High Class to, in effect, delineate a transition zone between being able to achieve control with conventional initial attack firefighting forces (i.e., up to and including the High fire danger class) and the probable limit of control (i.e., the Extreme fire danger class threshold and beyond) rather than having such an abrupt delineation (i.e., only High-Extreme as opposed to High-Very High-Extreme). Most fire control organizations generally work on the basis of five fire danger classes (Reifsnyder 1978; Stocks *et al.* 1989; Main *et al.* 1990; Cheney 1991a).

The other matter that appears to require modification in Valentine's (1978) scheme is the obvious need for change in the criteria for the Low-Moderate fire danger class boundary which is presently between an FWI of 7-8. A fine fuel moisture content of 30% is generally regarded as an extinction level for fire spread (*cf.* Brown and Davis 1973). This equates to an FFMC of about 74 (Van Wagner 1987); an FFMC of 74 and a 10-m open wind speed of 22 km/h (see Table 4) is equivalent to an ISI of 2.0. Van Wagner (1972) has shown that unless the DMC exceeds about 20 (reflecting about 6 days since a saturating rain based on a standard drying day), very little of the fuel below the upper fine fuel or litter layer would become involved in the active phase of combustion and therefore contribute heat energy to the spread process. If we were to assume a DC of around 48-50 (which also reflects about 6 days since a saturating rain based on a standard drying day) and a DMC of 20 (the BUI would still equal approximately 20), coupled with an ISI of 2.0, the result would be an FWI of about 3. Furthermore, according to the standard FWI-fire intensity relationship (Van Wagner 1987), a fire intensity of 10 kW/m is equivalent to an FWI of around 3.

Adopting the Alexander and De Groot (1988) criteria would appear to resolve the two major issues noted above. It would also generally lower the criteria for Extreme and High fire danger class days as well as for Low and Moderate. I know that some New Zealand fire managers would welcome this change as well. Perhaps the main problem with outright acceptance of the Alexander and De Groot (1988) criteria, or even staying with Valentine's (1978) scheme, is the anomalous result you get at the higher ISI/lower BUI combinations. For example, a BUI of 5 and ISI of 30, which is a combination that is not very likely to occur simultaneously (and it's difficult to imagine that there would be a sufficient amount of dry fuel available to support a spreading fire which could only occur under an exceedingly strong wind speed, as opposed to a case where the FFMC is in the upper 90s), is equal to an FWI of 18 which translates into a High fire danger class according to both Valentine (1978) and Alexander and De Groot (1988), and thereby questions the integrity of both classification schemes across the entire spectrum of fire danger conditions.

Having at least temporarily rejected the Alexander and De Groot (1988) criteria, I turned to the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) which allows for the quantitative prediction of fire behaviour (including fire intensity) using, among other inputs, the ISI and BUI components of the FWI System; overviews of the FBP System can be found elsewhere (Alexander and Maffey 1992-93; Hirsch 1993). Fire spread rates are based on the FFMC, wind speed, BUI, slope steepness and fuel type (Fig. 9); since the ISI represents only a few days of weather history after rain (via the FFMC), the BUI (which represents the increasing amount of fuel available for combustion as a dry spell lengthens) is therefore presumed to have at least some effect on the rate of fire spread as well (Van Wagner 1973*b*, 1989). Surface fuel consumption is based solely on the BUI. And, of course, fire intensity can then be calculated (Fig. 10). The FBP System fuel type which would appear most applicable

Figure 9. Rate of fire spread in forests as a function of ISI and BUI.

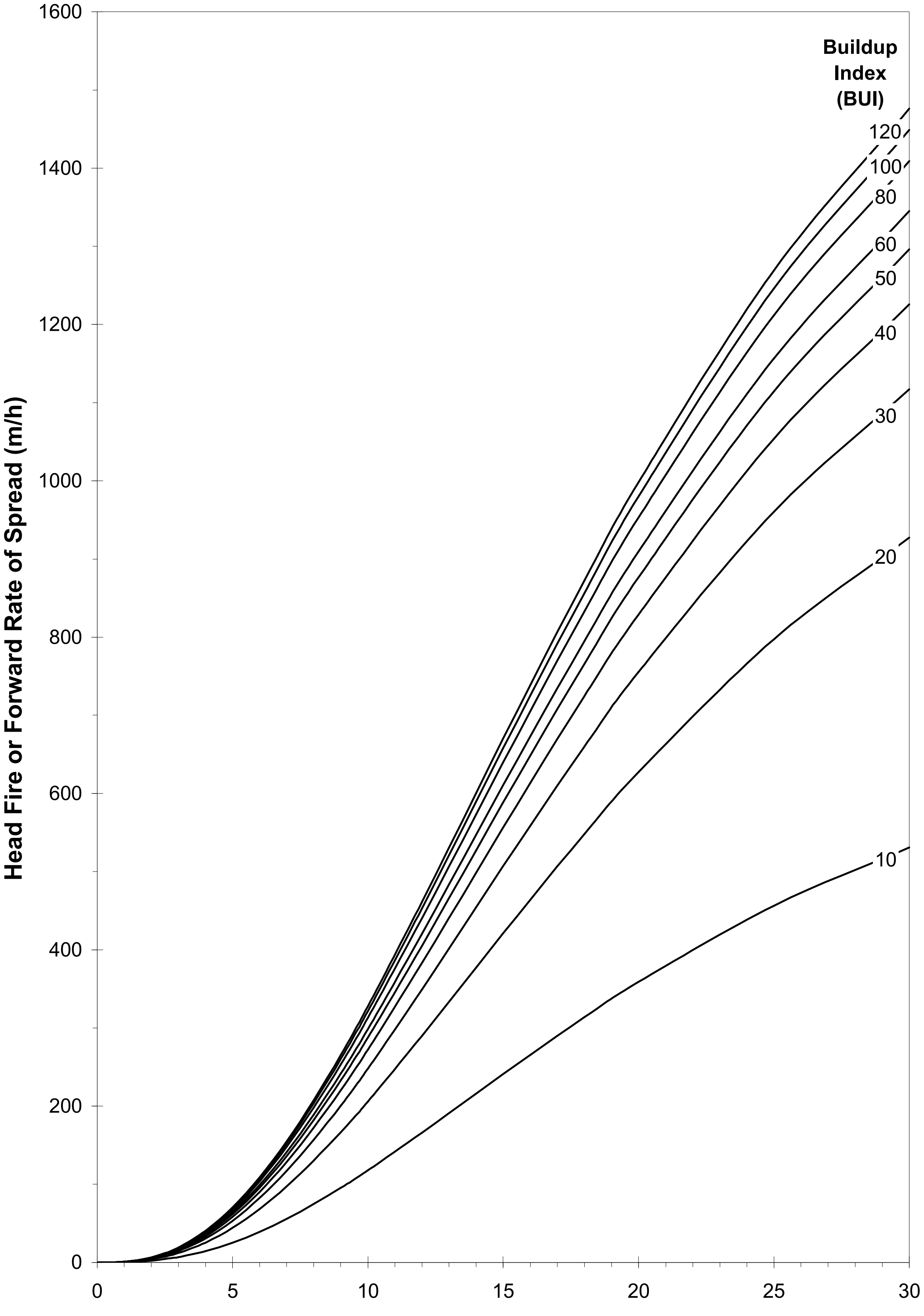
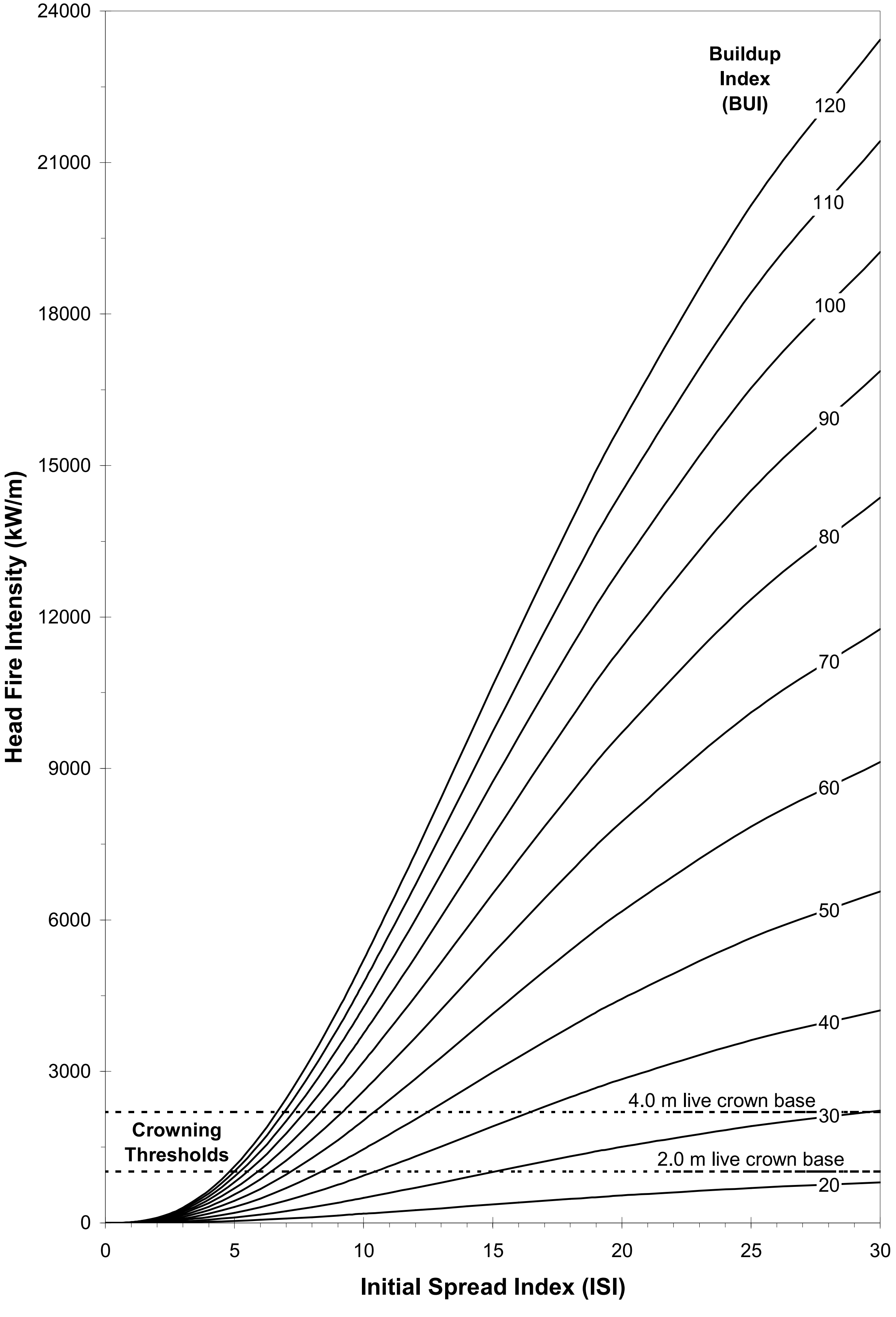


Figure 10. Fire intensity in forests as a function if ISI and BUI.



and of obvious interest to the New Zealand forest and rural fire scene would be the C-6 or Conifer Plantation model, which is based on experimental fire behaviour research carried out in red pine *(Pinus resinosa)* plantations which are, for the most part, structurally and anatomically similar to *Pinus radiata* plantations.

The results of applying the ISI and BUI to the fire intensity classes (i.e., <10, 10-500 500-2000, 2000-4000 and >4000 kW/m) described earlier in terms of FBP System Fuel Type C-6 are presented as Figure 1 in PART I of this report for the case of level terrain (0° slope); the equations used are given in Annex 5. In Figure 11, a comparison is made between Valentine's (1978) criteria and the proposed criteria as was done in Figure 8.

The proposed criteria as outlined in Figure 11 appears to overcome many of the problems associated with the present fire danger classes (Valentine 1978), and incorporates many of the desirable aspects of the Alexander and De Groot (1988) criteria; for comparison sake, the proposed criteria and that of Alexander and De Groot (1988) are shown in Figure 12. There would, however, be very little change for the most part in the boundaries of the High and Extreme fire danger classes, at least in terms of conditions typically encountered (e.g., it's seldom that the ISI would be greater than 8 if the BUI wasn't at least higher than 35, or the ISI wouldn't likely be higher than 15 if the BUI wasn't greater than 60). I, like others (e.g., Cheney *et al.* 1989; Cheney 1991), believe there is a distinct advantage to more or less maintaining the conditions that have been subscribed to over the years for Extreme fire danger amongst the members of the forest and rural fire community in New Zealand. This is certainly more important for the Extreme fire danger class than it is for High.

The transition from a surface fire to a crown fire is obviously of great concern to fire and forest managers since crown fires generally represent a level of fire behaviour that normally precludes any direct fire suppression action. The final area burned is also 4-6 times greater (Alexander 1992*a*). Please note in the proposed criteria that the onset of crowning in forests where the live crown base height is around 6 metres coincides with the Very High-Extreme fire danger class boundary[16]. About 6 metres is commonly accepted as a maximum pruning height (i.e., a final "lift") in pine plantations (A.R. Somerville, New Zealand Forest Research Institute, Forest Technology Division, Rotorua, *pers. comm.*) and hopefully represents the bulk of the exotic forest estate in New Zealand or at least the most typical or average situation. (Anon. 1992*b*); in a practical sense, newly planted or very young plantations (say less than 5 years old) should be considered as if they were in a "grass stage".

On the basis of a formal analysis of various historical forest fires in New Zealand (Pearce and Alexander 1994), coupled with a comparison against other wildfire case studies presented during the three NRFA-NZ FRI sponsored Advanced Fire Behaviour Courses in 1992-93 as well as other wildfires (e.g., Alexander and Pearce 1992, 1993), I feel pretty confident in recommending the Forest Fire Danger Class Graph (Fig. 1) and Tables (Tables 1a and 1b) **PROVIDED** users keep in mind that the purpose is to give an indication of fire potential on a broad areal basis as opposed to site-specific prediction of near-real time fire behaviour characteristics for a certain fuel type/topographic situation (Cohen 1985). In addition to a precise location, the latter would

---

[16] According to the information given earlier, crowning in exotic pine plantations pruned to nominal heights of 2.4 m and 4.0 m (A.R. Somerville, New Zealand Forest Research Institute, Forest Technology Division, Rotorua, *pers. comm.*) would occur at fire intensities of 1018 kW/m (i.e., HIGH fire danger) and 2190 kW/m (VERY HIGH fire danger), respectively. To gauge under what conditions these values would occur in terms of various combinations of the ISI and BUI, consult Figure 10.

Figure 11. Comparison of Proposed vs. Valentine (1978) Forest fire danger class criteria.

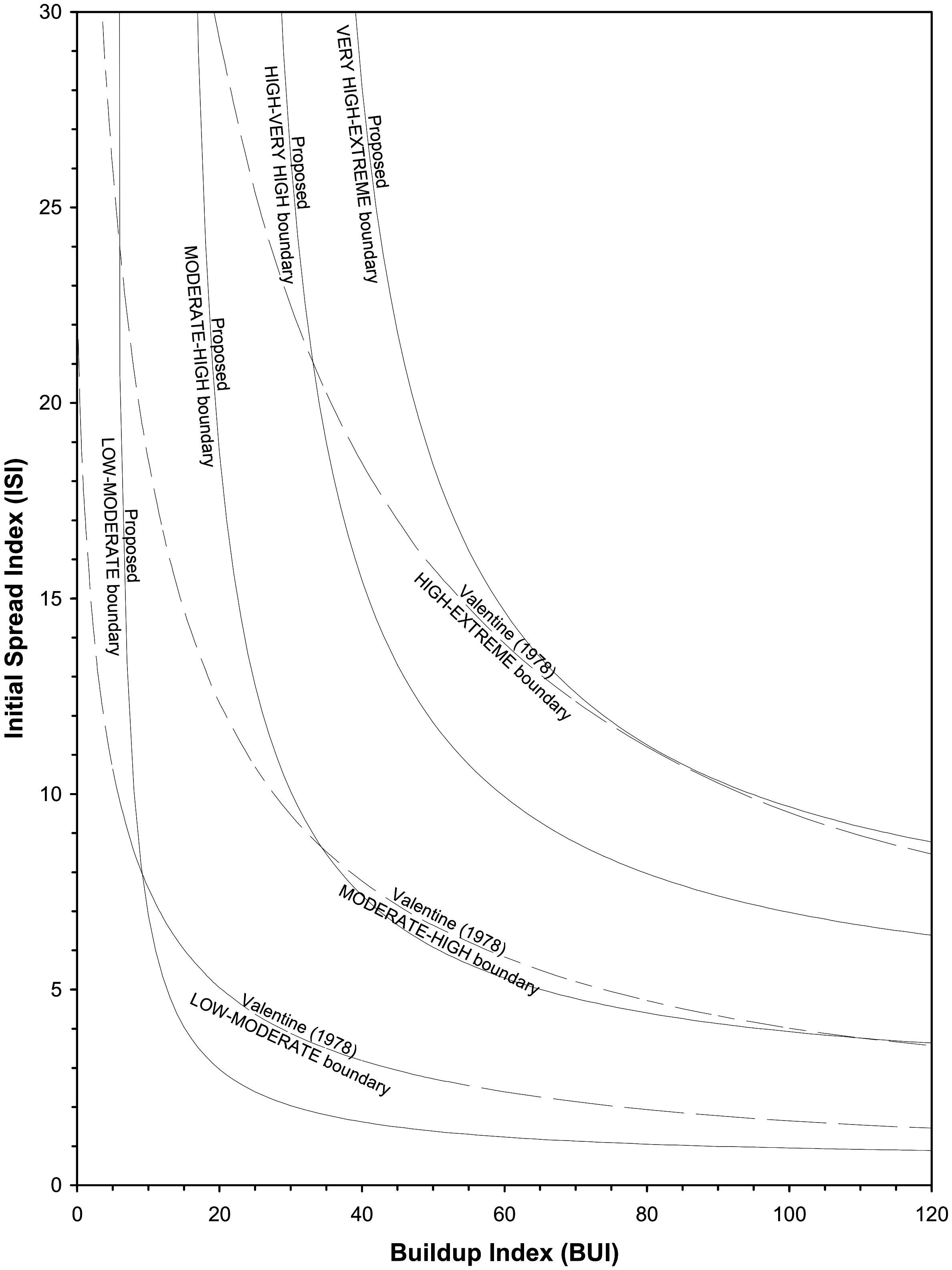
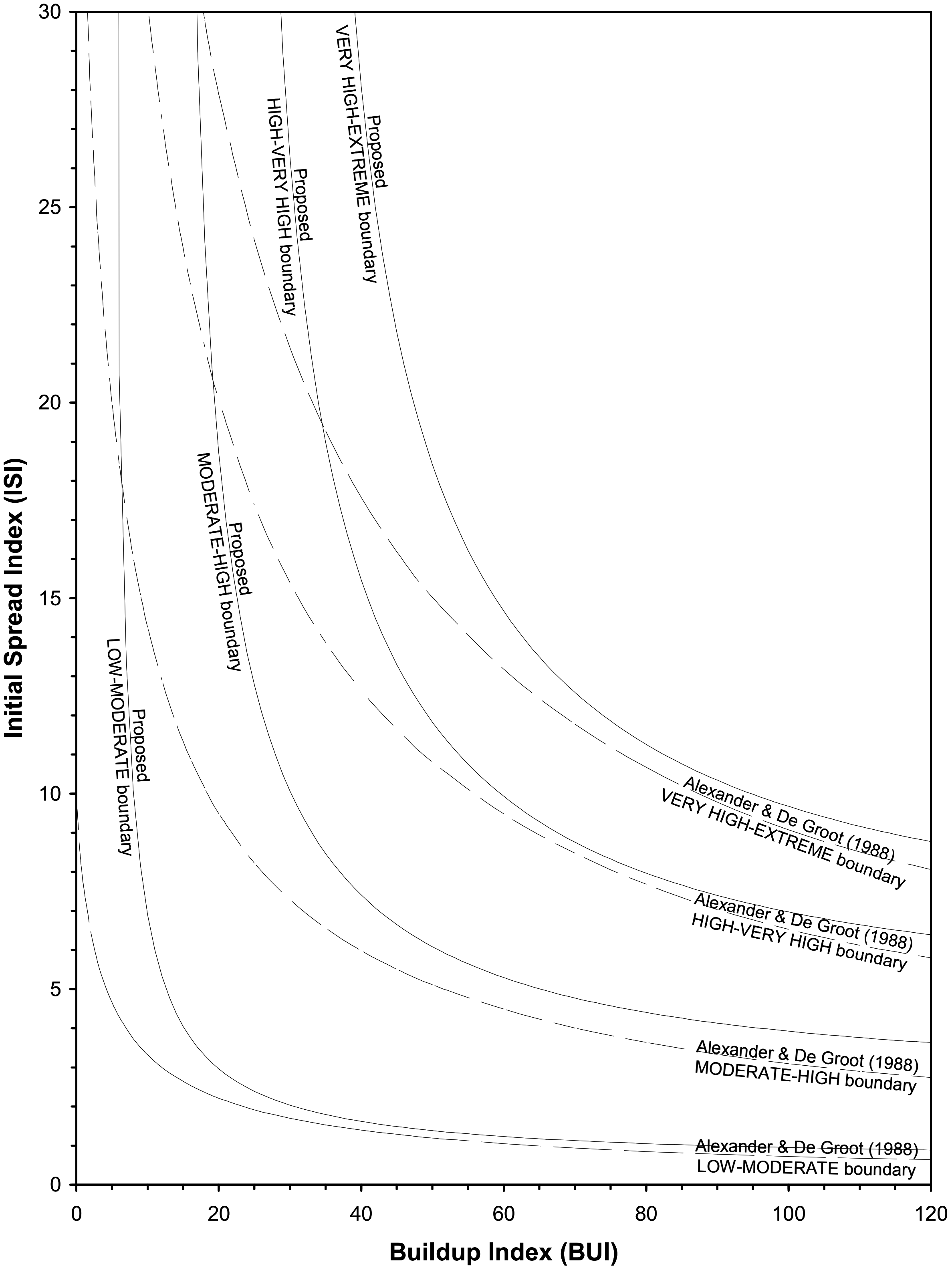


Figure 12. Comparison of Proposed vs. Alexander and De Groot (1988) Forest fire danger class criteria.



require considerably more timely information (e.g., more frequent measurements of wind speed than simply once a day at 1 p.m. as required for the basic FWI System calculations) and other inputs (e.g., fuel/stand characteristics, slope steepness, and the relation of fire to the wind field and slope -- e.g., cross-slope, down-slope, etc.) which are normally not readily available. A precise prediction of fire behavior for a specific location requires a precise fire weather forecast and knowledge of fuel types and topography.

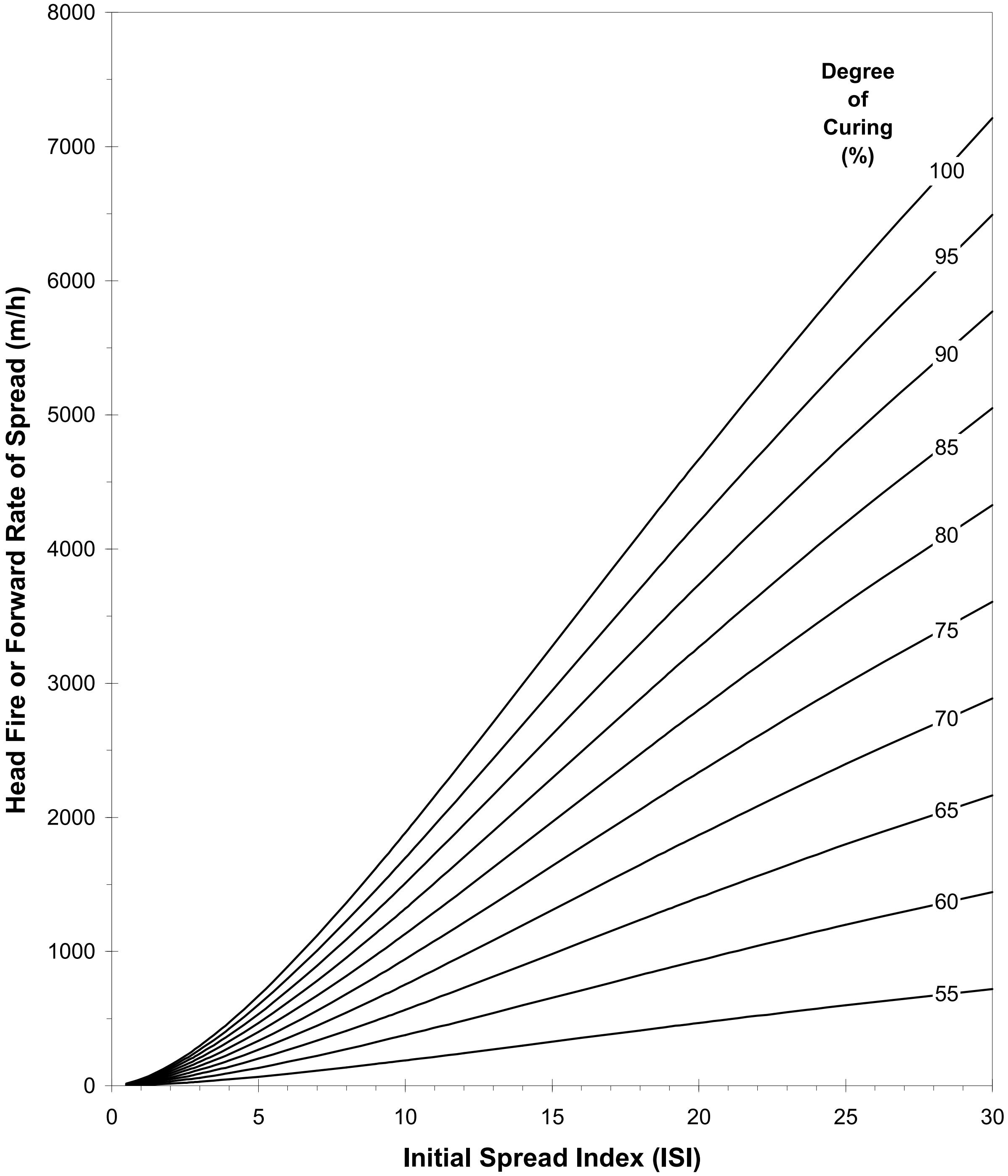
The fire danger class criteria as originally advocated by Valentine (1978) was implemented at a time when the primary fire protection concern of the largest rural fire organization in New Zealand (i.e., the New Zealand Forest Service) was exotic pine plantations. The fact of the matter is that exotic pine plantations occupy less than 5% of the total land mass of New Zealand (Anon. 1992*d*), although admittedly a very valuable resource. Grasslands and pasture lands constitute a far larger proportion of New Zealand's rural landscape as evident for example by the maps contained in various publications (e.g., Hunter and Blaschke 1986; Newsome 1987; Wardle 1991). The need for a separate classification criteria for these fuel types is obviously apparent. In this regard, I have some good news and some bad news. First the good news. Fortunately, the FBP System (Forestry Canada Fire Danger Group 1992) also has a grass fuel type (O-1). The Grass fuel type in the FBP System actually consists of two subtypes -- cut (or matted down) (O-1a) and natural (standing) (O-1b) grass; the latter one is the more flammable of the two, and is probably more representative of the New Zealand situation (O-la is more nearly the case after snow melt in the spring in many parts of Canada where the grasses have been flattened down by the weight of the snowpack. The equations used to generate the Grassland Fire Danger Class Graph (Fig. 2) and Table (Table 2) are contained in Annex 5; some years ago (Alexander 1984a), I developed similar fire danger class criteria for grassland areas for the southern half of the province of Alberta, Canada. Like the Forest fire danger class criteria, I feel quite confident about the Grassland equivalent following comparisons against actual wildfire situations such as the 1986 Awarua Wetlands Fire (Pearce *et al.* 1994), the 1987 Oxford Fire (Pearce and Alexander 1994) and 1991 Tikokino Fire (Rasmussen 1993). An opportunity to evaluate the Grassland fire danger class criteria under mild burning conditions was kindly made available to H.G. Pearce of the New Zealand Forest Research Institute and myself by Warrant Officer R.M. Edwards, Assistant Director-Fire (now retired), Resources Branch, New Zealand Defence Force Headquarters, Wellington; we also owe a debt of gratitude to Waiouru Military Camp Firemaster, J. Sparks and his crew, and to NRFA Regional Rural Fire Officer (Palmerston North), J. Rasmussen, for their assistance in this undertaking[17].

---

[17] The original intent was to burn several 50 × 50 m plots of tussock grasslands within the Waiouru Military Camp lands but unfortunately the inclement weather during the latter half of the 1992/93 fire season prevented this from talking place. However, on 3 March 1993, with the chance of not collecting any fire behaviour data gradually becoming a reality, it was decided to carry out at least a test fire. This took place between 12:00 and 12:17 p.m. NZDT some 30-40 m or so upwind of a two-lane gravel road. The fire weather conditions and FWI System components during the burn were: 16.5°C, 66% RH, 10-rn open wind speed 26 km/h, and 4 days since <0.6 mm rain, FFMC 79, DMC 5, DC 188, ISI 4, BUI 9 and FWI 4. The Degree of Curing for the entire fuel complex was occularly estimated to be no more than 75%; there was a noticeable amount of green material in the herbaceous vegetation between the tussock clumps (no doubt due to the abundant seasonal rainfall).

The ignition pattern used consisted of short (≈5-10 m) line fire strips lit with a hand-held drip torch. The first two attempts failed to spread much beyond their ignition source. The third test did advance downwind, although somewhat slowly (covering a distance of 15 m in 4 minutes for a head fire ROS of 225 m/h -- this compares favourably with the FBP System prediction for Fuel Type 0-lb of 236 m/h), with maximum flame heights only slightly higher than the tussock clumps themselves with minimal flame involvement in between the clumps. Although fuel consumption was not determined, the fire's intensity was certainly less than 500 kW/m. In the videotape documentation of these test fires, as undertaken by P. Sunkell (Phillips & Smith Ltd., Auckland), it's plainly evident that, provided the gap between the clumps wasn't too great (say >1.0-1.5 m), then fire spread was possible.

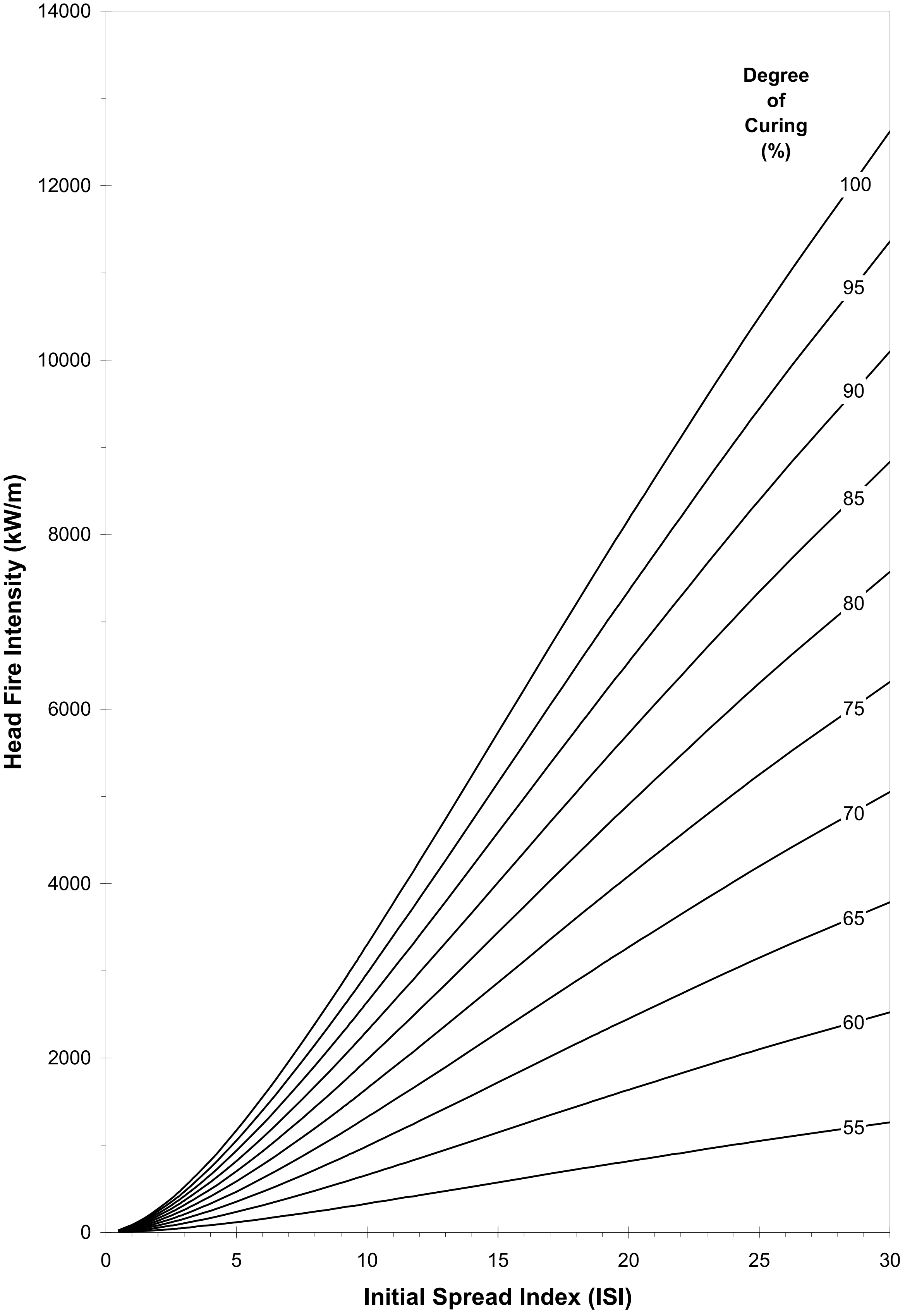
Figure 13. Rate of fire spread in grasslands as a function of ISI and Degree of Curing.



---

(17) The fire danger class display board maintained by the military on the Desert Road just north of Waiouru (and not very far away from the test fire site) was indicating Low on this particular day since the Valentine (1978) fire danger class criteria was being used. Note that according to the fire danger class criteria for grasslands as developed in this report (see Fig. 2 and Table 2), the above conditions would have dictated a MODERATE fire danger class.

Figure 14. Fire intensity in grasslands as a function of ISI and Degree of Curing.



Now for the bad news. Any consideration of potential fire behaviour in grasslands has to involve an assessment of the Degree of Curing that has taken place (McArthur 1966). Thus, in the case of FBP System Fuel Type O-1b (and for that matter, O-1a), Degree of Curing is a required input along with the ISI component of the FWI System. In a sense, the Degree of Curing replaces the BUI which was used in the Forest fire danger class criteria, although I'd acknowledge that there might be a slight BUI effect in tussock grasslands with respect to fuel consumption although research is going to be required to confirm and quantify such speculation. The importance of the Degree of Curing on potential fire behaviour in grasslands as illustrated in Figures 13 and 14 is obviously apparent. Fire intensity in turn determines the effectiveness of fire suppression actions and fuel management practices (e.g., firebreak breaching, Figs. 15 and 16[18]).

Grasses which complete their life cycle within a period of three to six months die when they reach maturity and dry out rapidly when their roots cease to draw moisture from the soil (Fig. 17). This process of progressing from a green state (with exceedingly high moisture contents in the spring following winter rains) to a light brown or bleached state (where moisture contents are controlled by atmospheric conditions) later in the summer is term "curing" and is related to the physiological changes which take place in the plant. The rate of curing varies among species, seasons, and geographical location. Annual grasses are shallow rooted so their curing pattern differs from perennial grasses which are more deeply rooted (Fig. 18). However, once the Degree of Curing in the new grass growth has reached about 60%, completion of the process is generally irreversible. In South Australia, for example, all of the grassland areas are typically fully cured by the first day of the new year (Parrott and Donald 1970; Luke and McArthur 1978). This does not always occur, and Luke and McArthur (1978) note that Australian grassland never becomes fully cured (i.e., at a landscape scale) in about five years out of ten due to sufficient summer rainfall.

There are a number of possible approaches to arriving at a Degree of Curing assessment. Standard values could be assigned (initially on the basis of estimates, and then later as a result of the kind of sampling outlined in Annex 2) to calendar dates during the fire season (for example by month); this, in actual fact, was what was done in the case of the New Zealand Fire Danger Meter. The main problem with this approach, besides the need to develop various regional versions, is the fact that the Degree of Curing trend varies from year-to-year as a result of variations in annual and seasonal rainfall. Ideally, it might be possible to link the Degree of Curing directly to certain weather parameters or weather-based indexes such as Everson *et al.* (1988) and Hosking (1990) have done, although in the present case it would be appropriate if possible to relate these to components of the FWI System (e.g., DMC, DC and/or BUI). Perhaps the major drawback to this approach, besides the necessity for collecting sufficient data to develop a relationship (using, for example, the methodology described in Annex 2), is the need to physically interpolate the "point estimates" of Degree of Curing at individual weather stations over the landscape in a realistic manner. Perhaps the best approach to picking up this spatial variation is with the use of satellite imagery as discussed by several authors (Barber 1987, 1990, 1993; Bell 1987/88; Burgan *et al.* 1991; Burgan and Hartford 1993; Westover and Sadowski

---

[18] The equation used to produce Figure 15 is as follows (after Wilson 1988*b*):

$$P = \frac{e^{(1.36 + 0.00036 \times I - 0.99 \times FW)}}{1 + e^{(1.36 + 0.00036 \times I - 0.99 \times FW)}} \times 100$$

where P = probability of a firebreak being breached by a grass fire where trees are absent within 20 m of the firebreak (%), I = fire intensity (kW/m), and FW = firebreak width (m). The equation used to produce Figure 16 (where trees are present within 20 m of the firebreak) is the same as the above, except the coefficient 0.99 is replaced by 0.38.

Figure 15. Probability of firebreak breaching in the absence of trees within 20 m of the firebreak (adapted from Wilson 1988*b*).

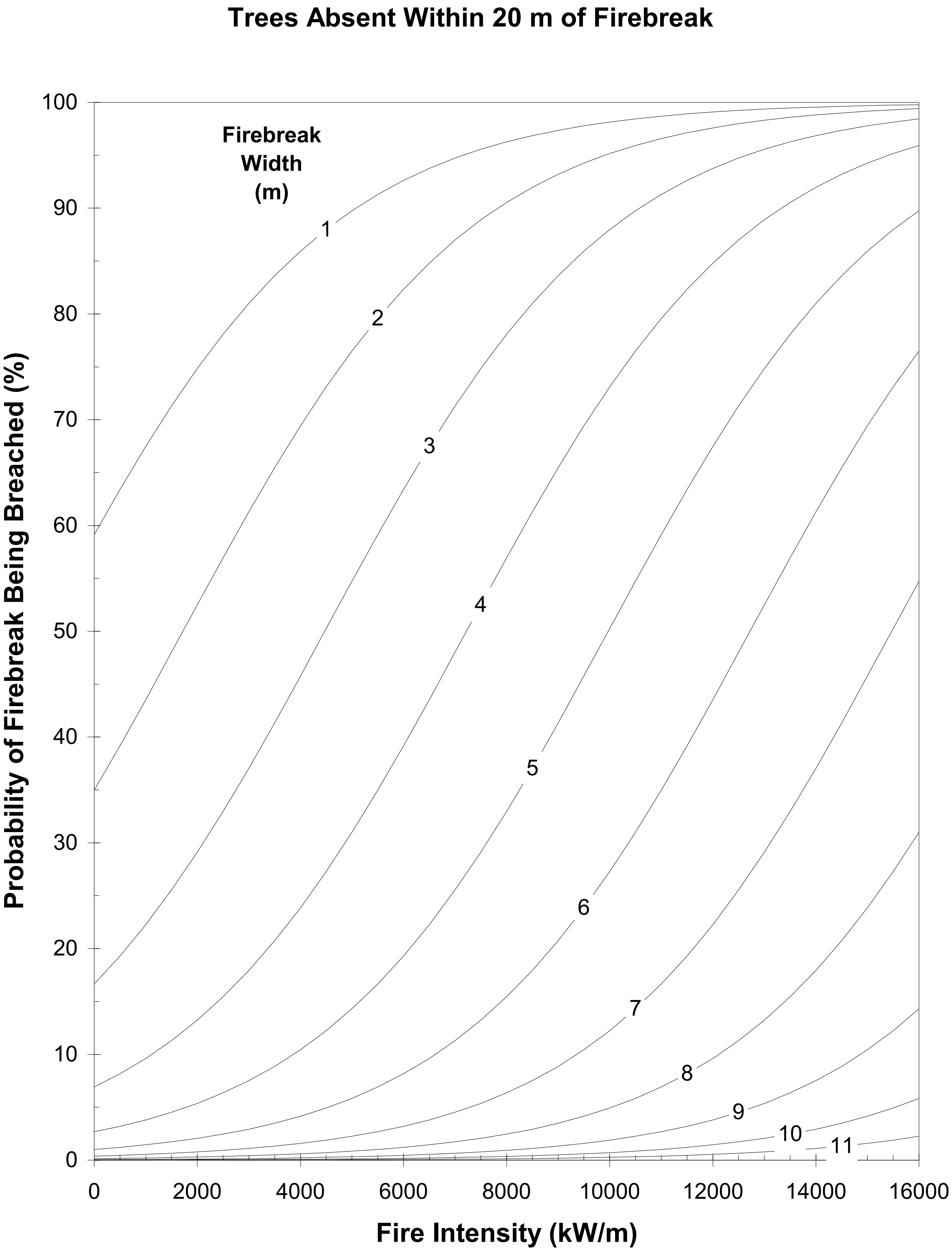
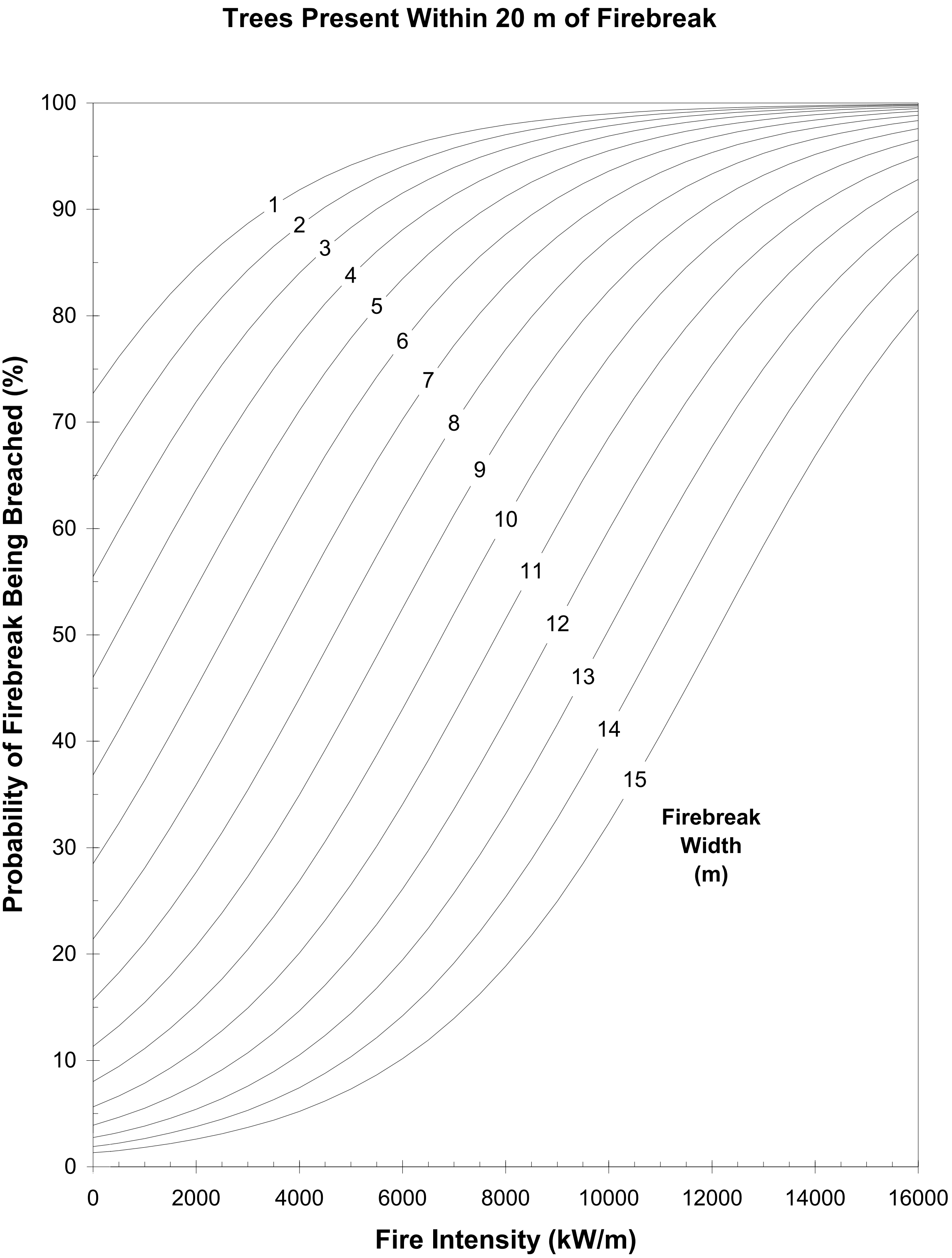


Figure 16. Probability of firebreak breaching in the presence of trees within 20 m of the firebreak (adapted from Wilson 1988*b*).



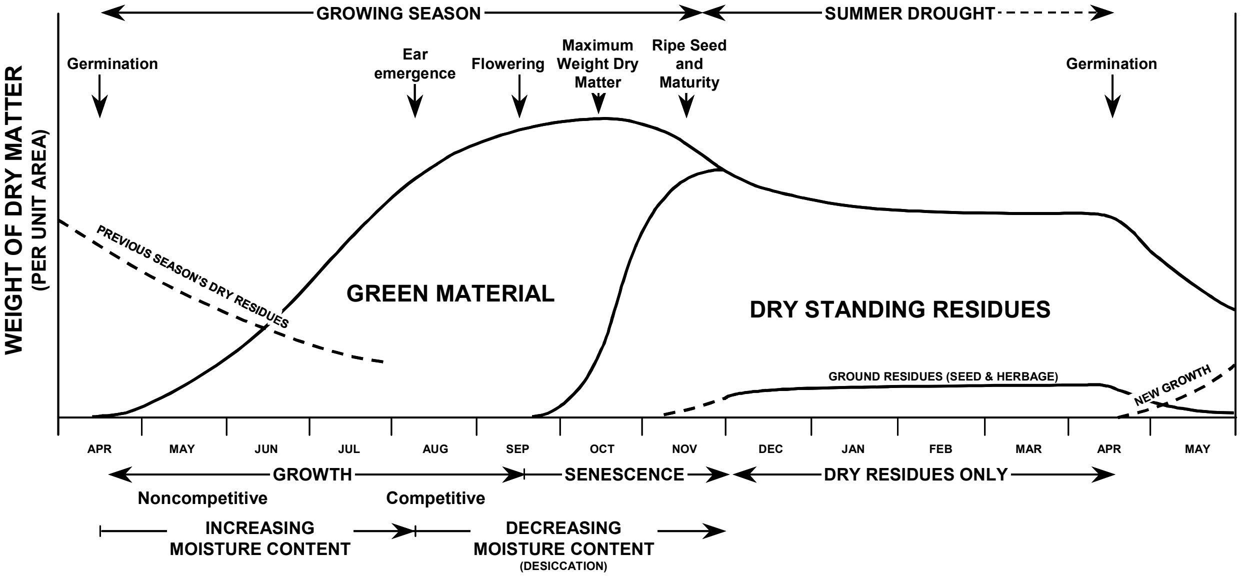


Figure 17. A generalized diagram of the life cycle of a sward of annual grasses near Adelaide, South Australia (from Parrot 1964).

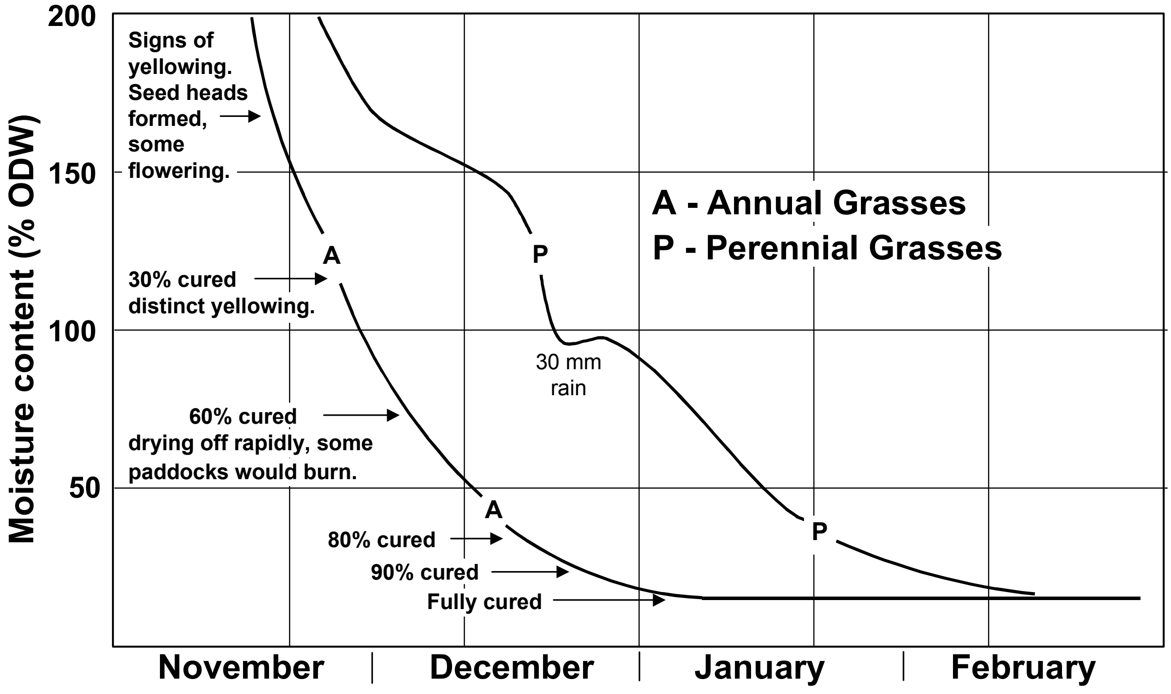


Figure 18. Curing of annual and perennial grasses in the Australian Capital Territory during the 1964/65 fire season (from Luke and McArthur 1978).

1987; Paltridge and Barber 1988); this approach is used operationally in Australia by the Country Fire Authority of Victoria (Garvey *et al.* 1993) supplemented by visual estimates assisted by photo guides (Garvey 1992). Landcare Research Institute consider this to be feasible (Pairman 1993), and the New Zealand Forest Research Institute have initiated the necessary ground truthing data (*cf.* Barber and Pratt 1980) similar to the methodology outlined in Annex 2 in order to calibrate the technology specifically to New Zealand's environment (L.G. Fogarty, New Zealand Forest Research Institute, Forest Technology Division, Rotorua, *pers. comm.*). At least for the interim, the transect approach to determining the degree of curing as outlined in Annex 2 will have to be relied upon. Note that this approach is not all that different from what's required for calibration of the satellite imagery.

It's worth emphasizing that because the FWI System was developed to assess the influences of weather conditions on potential fire behaviour for a standard fuel type (i.e., a mature pine stand) on level ground (Stocks *et al.* 1989), one should fully expect that there can be large differences in fire behaviour characteristics (and in turn in the fire danger class) amongst fuel types at a given index level. For example, consider the following comparison for an ISI 8 and BUI 55:

Fuel Complex	**Fuel Consumed (t/ha)**	**Head Fire ROS (m/h)**	**Head Fire Intensity (kW/m)**	**Fire Danger Class**
Plantation forest	11.8	186	1103	High
Fully-cured grassland	3.5	1366	2390	Very High
Logging slash[20]	63.7	669	21 309	–

The fire danger class criteria originally developed in conjunction with the introduction of the FWI System was obviously antiquated and in need of revision. The present work should be viewed as part of the evolutionary nature of fire danger rating and a periodic review at relatively short intervals (say every 5 years if not sooner) should be undertaken if for no other reason than to confirm that the present criteria is in line with current fire management needs. The most immediate need is to acquire sufficient quantitative data on fire behaviour in scrublands in order to develop a separate fire danger class graph and table for this important fuel type. Although some limited information is available on gorse (Egunjobi 1969; Thomas 1970), it isn't nearly enough to undertake what's been done for forests and grasslands; the means of incorporating the effect of slope steepness on fire spread rate and intensity already exists (McAlpine *et al.* 1991; Forestry Canada Fire Danger Group 1992). Attempts were made by H.G. Pearce and myself during the 1992/93 fire season to locate potential burning sites in old-man gorse and to document the behaviour of experimental fires. A few sites were located, but unfortunately the weather never really cooperated. New Zealand forest and rural fire managers have a long history of banding together to fight a common "enemy" -- wildfire. To develop the kinds of relationships embodied in the FBP System fuel types (which has made it possible to construct the Forest and Grassland fire danger class graphs and tables) for scrublands is going to take the concerted effort of not only the New Zealand Forest Research Institute but forest and rural fire managers throughout New Zealand -- i.e., sites and manpower to conduct experimental fires must be made available and wildfires must be documented as well. There's simply no alternative.

---

[20] The projections for logging slash are based on FBP System Fuel Type S-1 (Jack or Lodgepole Pine Slash) (Forestry Canada Fire Danger Group 1992); see Annex 5 for a list of equations. The variation in head fire rate of spread and intensity for this fuel type in relation to the ISI and BUI components of the FBP System are graphically portrayed in Figures 19 and 20. Very limited testing in New Zealand suggests that the relationships are also applicable to radiata pine logging slash (Alexander *et al.* 1993).

Figure 19. Rate of fire spread in logging slash as a function of ISI and BUI.

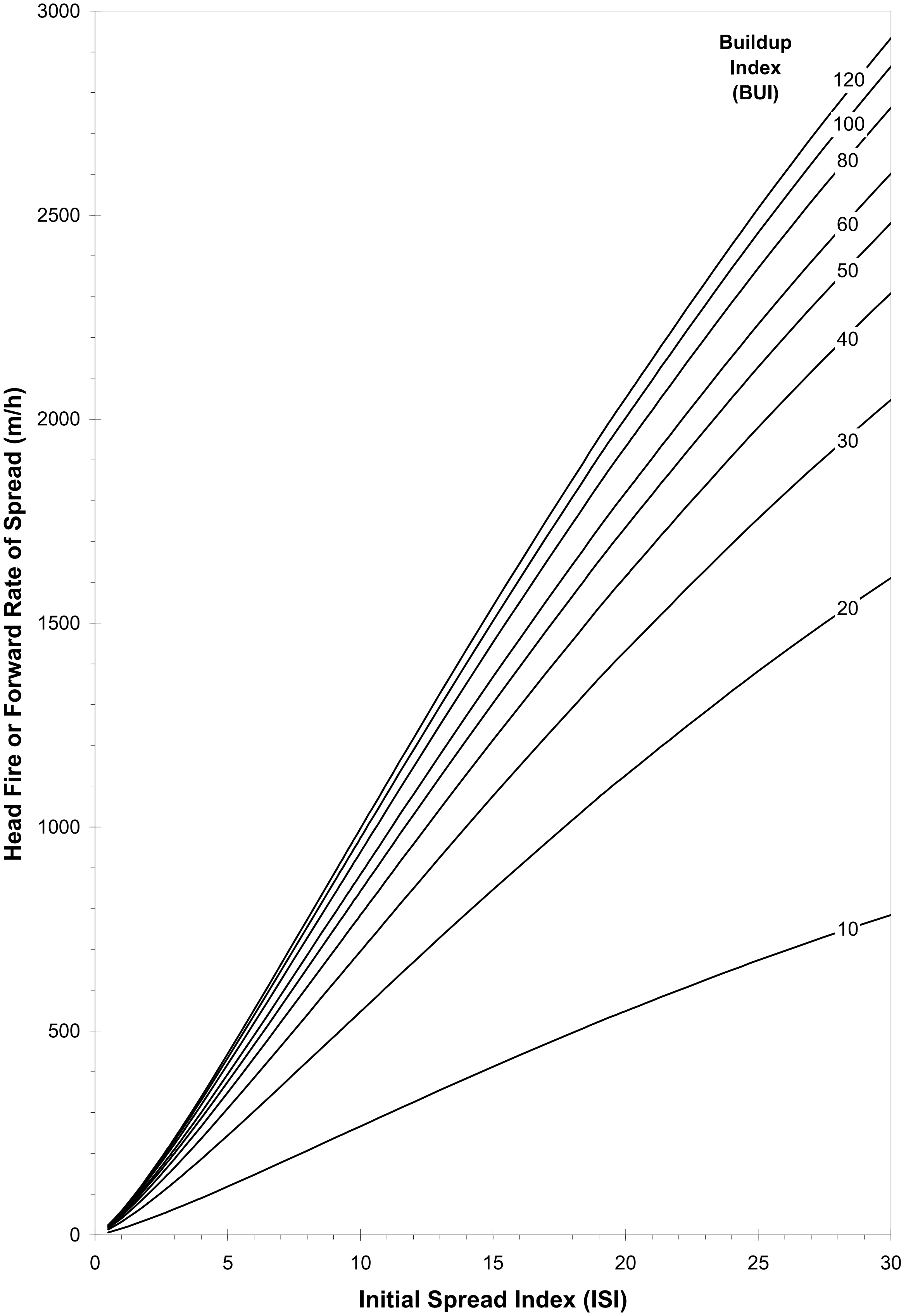
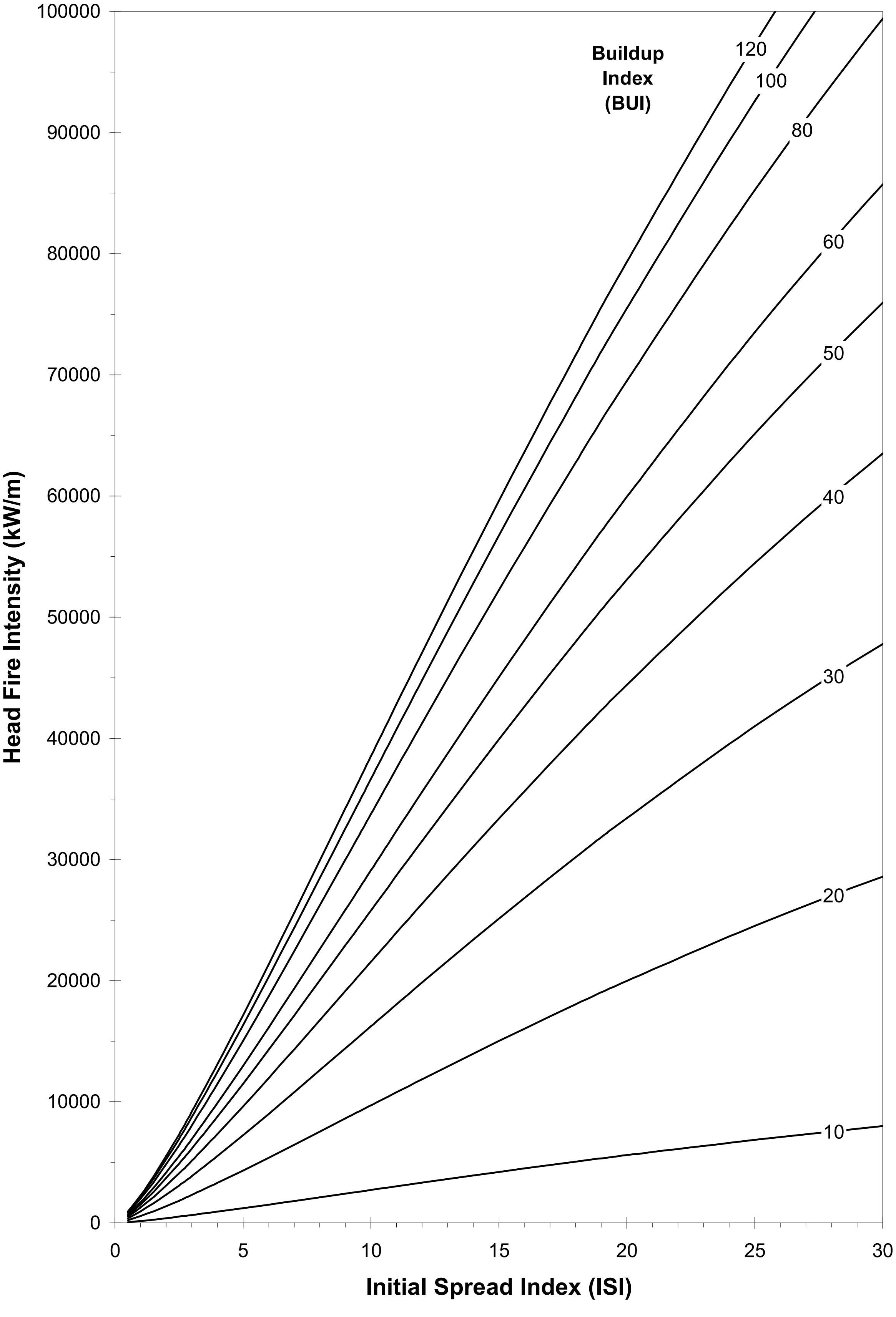


Figure 20. Fire intensity in logging slash as a function of ISI and BUI.



Annex 5: List of Equations for Fire Danger Classes

As eluded to in PART I of this circular, the equations given here are taken or adapted from Forestry Canada Fire Danger Group (1992). Some of the equations have been altered so that fire spread rate would be given in metres per hour (m/h) as opposed to metres per minute and fuel consumed or available fuel load could be expressed in tonnes per hectare (t/ha) rather than in kilograms per square metre as is commonly the practice in Australasian forest and rural fire management community (e.g., Sneeuwjagt and Peet 1985).

The specific equations used to produce the Forest Fire Danger Class Graph (Fig. 1) and Table (Tables la and 1b) are as follows:

$$\mathrm{RSI} = 1800 \times [1 - e^{(-0.08 \times \mathrm{ISI})}]^{3.0}$$

$$\mathrm{BE} = e^{[50 \times ln(\mathrm{q}) \times (1/\mathrm{BUI} - 1/\mathrm{BUI}_0)]}$$

$$\mathrm{ROS} = \mathrm{RSI} \times \mathrm{BE}$$

$$\mathrm{SFC} = 50.0 \times [1 - e^{(-0.0149 \times \mathrm{BUI})}]^{2.48}$$

$$\mathrm{HFI} = \frac{\mathrm{ROS} \times \mathrm{SFC}}{2}$$

where RSI = Initial forward rate of fire spread without BUI effect (m/h)
ISI = Initial Spread Index component of the FWI System
BE = Buildup effect on forward rate of fire spread
q = Proportion of maximum forward rate of fire spread at BUI equal to 50 (q = 0.80 in this case)
BUI = Buildup Index component of the FWI System
BUI_0 = Average Buildup Index for FBP System Fuel Type C-6 (BUI_0 = 62 in this case)
ROS = Head fire or forward rate of spread on level to gently undulating terrain (m/h)
SFC = Surface fuel consumption (t/ha)
HFI = Head fire intensity (kW/m)

The specific equations used to produce the Grassland Fire Danger Class Graph (Fig. 2) and Table (Table 2) area as follows:

$$\mathrm{ROS} = 15\,000 \times [1 - e^{(-0.0350 \times \mathrm{ISI})}]^{1.7} \times \mathrm{CF}$$

$$\mathrm{CF} = 0.02 \times \mathrm{C} - 1.0 \text{ (when C > 50)}$$

$$\mathrm{CF} = 0 \text{ (when C} \geq 50)$$

$$\mathrm{GFL} = 3.5$$

$$\mathrm{HFI} = \frac{\mathrm{ROS} \times \mathrm{GFL}}{2}$$

where ROS = Head fire or forward rate of spread [for FBP System Fuel Type 0-1b] on level to gently undulating terrain (m/h)
ISI = Initial Spread Index component of the FWI System
CF = Grass curing coefficient
C = Degree of grass curing (%)
GFL = Grass fuel load (t/ha)[21]
HFI = Head fire intensity (kW/m)

The Forest Fire Danger Class (FFDC) or Grassland Fire Danger Class (GFDC) is determined by the head fire intensity:

Fire Danger Class	**Head Fire Intensity (kW/m)**	**FFDC or GFDC Table Symbol**
Low	10.5	L
Moderate	10.6 - 500.5	M
High	500.6 - 2000.5	H
Very High	2000.6 - 4000.5	VH
Extreme	4000.6	E

The equations used to produce the head fire rate of spread and intensity graphs (Figs. 18 and 19) for radiata pine logging slash (FBP System Fuel Type S-1) are as follows:

$$RSI = 4500 \times [1 - e^{(-0.0297 \times ISI)}]^{1.3}$$

$$BE = e^{[50 \times ln(q) \times (1/BUI - 1/BUI_0)]}$$

$$ROS = RSI \times BE$$

$$SFC = FFC + WFC$$

$$FFC = 40.0 \times [1 - e^{(-0.025 \times BUI)}]$$

$$WFC = 40.0 \times [1 - e^{(-0.034 \times BUI)}]$$

$$HFI = \frac{ROS \times SFC}{2}$$

---

[21] A grass fuel load of 3.5 t/ha has been assumed, rather than 3.0 t/ha (or 0.3 kg/rn^2) as given in Forestry Canada Fire Danger Group (1992), since this represents the mean fuel load for the experimental fires (Cheney *et al.* 1993) used in the development of FBP System Fuel Type O-1 where the range of fuel loads varied from 1.2-5.7 t/ha. Although this value is low for tussock grasslands (Williams 1977; Meurk 1978), not all of the total fuel complex is considered to be normally consumed by spreading fires (Basher *et al.* 1990). No doubt fire research at NZ FRI will provide better estimates in the future.

where ROS = Initial forward rate of fire spread without BUI effect (m/h)
ISI =Initial Spread Index component of the FWI System
BE = Buildup effect on forward rate of fire spread
q = Proportion of maximum forward rate of fire spread at BUI equal to 50 (q = 0.75 in this case)
BUI = Buildup Index component of the FWI System
BUI_0 = Average Buildup Index for FBP System Fuel type S-1 (BUI_0 =38 in this case)
ROS = Head fire or forward rate of spread on level to gently undulating terrain (m/h)
SFC = Surface fuel consumption (t/ha)
FFC = Forest floor consumption (t/ha)
WFC = Woody fuel consumption (t/ha)
HFI = Head fire intensity (kW/m)

References

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. *Canadian Journal of Botany 60*: 349-357.

Alexander, M.E. 1984*a*. Frontal fire intensity and associated fire behavior characteristics/fire suppression interpretations. Canadian Forest Service, Northern Forest Research Centre, Edmonton, Alberta, Unpublished Report. l3 p.

Alexander, M.E. 1984*b*. A system of fire danger rating for the provincial parks of Alberta's prairie region: an interim manual. *Canadian Forest Service, Northern Forest Research Centre, Edmonton, Alberta, Study NOR-5-05 File Report No. 6*. 45 p. + Appendices.

Alexander, ME. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Pages 287-304 *in* Proceedings, Eighth Conference on Fire and Forest Meteorology, 29 April-2 May 1985, Detroit, Michigan. *Society of American Foresters, Bethesda, Maryland, SAF Publication 85-04*.

Alexander, M.E. 1988. Help with making crown fire hazard assessments. Pages 147-156 *in* "Protecting People and Homes from Wildfire in the Interior West", Proceedings of the Symposium and Workshop, 6-8 October 1987, Missoula, Montana. *USDA Forest Service, Intermountain Research Station, Ogden, Utah, General Technical Report INT-251*.

Alexander M.E. 1992*a*. Fire behaviour in exotic pine plantations of Australasia. *Australian Forest Grower 15(1)*: 20.

Alexander, M.E. 1992*b*. Applying the Fire Weather Index System to the urban-rural interface in New Zealand. Handout prepared for New Zealand Fire Service Commanders' Seminar, 27-30 July 1992, Marton, New Zealand. 13 p.

Alexander, M.E. 1992*c*. Role of fire danger ratings in forest land management. Handout prepared for Advanced Silviculture (FORE 416) Class, School of Forestry, University of Canterbury, 3 August 1992, Christchurch, New Zealand. 15 p.

Alexander, M.E. 1992*d*. Fire behaviour as a factor in forest and rural fire suppression. Pages 64-103 *in* Proceedings, 2nd Annual Conference of the Forest and Rural Fires Association of New Zealand, 5-7 August 1992, Christchurch, New Zealand. Forest and Rural Fires Association of New Zealand, Rotorua, New Zealand. [reproduced as Alexander, M.E. 2000. Fire behaviour as a factor in forest and rural fire suppression. *Forest Research Bulletin No. 197, Forest and Rural Fire Scientific and Technical Series, Report No. 5*. 28 p.].

Alexander, M.E. 1992*e*. Fire danger rating and fire behaviour prediction. Handout prepared for New Zealand Certificate in Forestry (NZCF) Stage Course 5170 - Protection and Environmental Studies, Forestry Training Centre, 17 September 1992, Rotorua, New Zealand. 25 p.

Alexander, M.E. 1992*f*. Standard specifications for Fire Weather Index System computer calculations. Revised version. Prepared for discussion at the 3rd Advisory Committee on Forest and Rural Fire Research, 21 October 1992, New Zealand Fire Service National Headquarters, Wellington, New Zealand. 7 p.

Alexander, M.E.; De Groot, W.J. 1988. Fire behaviour in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Poster (with text). [reproduced in 1992 by the National Rural Fire Authority at 50% of the original size].

Alexander, M.E.; De Groot, W.J. 1989. A decision aid for characterizing fire behavior and determining fire suppression needs. *Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Technology Transfer Note A-008*. 4 p.

Alexander, M.E.; Lanoville, R.A. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. Forestry Canada, Northern Forestry Centre, Edmonton, Alberta, and Government of the Northwest Territories, Department of Renewable Resources, Territorial Forest Fire Centre, Fort Smith, Northwest Territories. Poster (with text).

Alexander M.E.; Maffey, M.E. 1992-93. Predicting fire behavior in Canada's aspen forests. *Fire Management Notes 53-54(1)*: 10-13.

Alexander, M.E.; Pearce, H.G. 1992. Follow-up to the Spokane area firestorm '91 report: What were the Canada's fire danger indices? *Wildfire News & Notes 6(4)*: 6-7.

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

Alexander, M.E.; Pearce, H.G.; Farrow, R.G.; Smart, P.N. 1993. Experimental fires in radiata pine logging slash within the Kinleith Forest during early 1993. Pages 40-41 *in* Proceedings, 3rd Annual Conference of the Forest and Rural Fires Association of New Zealand, 4-6 August 1993, Wellington, New Zealand. Forest and Rural Fires Association of New Zealand, Rotorua, New Zealand.

Anon. 1975*a*. Fire weather indices: decision aids for forest operations in British Columbia. British Columbia Forest Service, Protection Division, Victoria, British Columbia. Non-paged.

Anon. 1975*b*. Rationale for the B.C. Fire Danger Rating System. British Columbia Forest Service, Planning and Resources Section, Protection Division, and Canadian Forestry Service, Pacific Forest Research Centre, Fire Research Group, Victoria, British Columbia. 8 p.

Anon. 1982. "Rural fire fighting - a manual published by New Zealand Forest Service". New Zealand Forest Service, Wellington, New Zealand. 95 p. [reprinted in 1984 and 1985].

Anon. 1986. Videotape: Fire Weather Index (PAL; 15 minutes). New Zealand Forest Service, Wellington, New Zealand.

Anon. 1990. Fire control operations: Instructions and guidelines. Department of Conservation, Wellington, New Zealand. Three-ring binder. Non-paged.

Anon. 1991*a*. Training module 221: fire behaviour. National standard course for Crew Boss, 200 series. National Rural Fire Authority, Wellington, New Zealand. 32 p.

Anon. 1991*b*. Forest and Rural Fires Act 1977 and extracts from the Fire Service Act 1975 relating to the National Rural Fire Authority and rural firefighting fund. National Rural Fire Authority, Wellington, New Zealand. 74 p.

Anon. 1992*a*. Waiariki Rural Fire District Fire Plan, 1992-93. Tasman Forestry Ltd., Caxton Forests Ltd., and Forestry Corporation of NZ Ltd. Non-paged.

Anon. 1992*b*. Tokoroa Rural Fire Committee and NZFP Forests Limited (Kinleith Forest Region) Fire Plan, 1 October 1992 to 30 September 1993. New Zealand Forest Products Forests Ltd. and Tokoroa Rural Fire Committee, Tokoroa, New Zealand. Non-paged.

Anon. 1992*c*. Forestry Corporation Fire Plan, 1992-93. Forestry Corporation of NZ Ltd., Rotorua, New Zealand. Non-paged.

Anon. 1992*d*. "Forestry facts and figures". New Zealand Forest Owners' Association Inc., Wellington, New Zealand. 14 p.

Anon. 1993. "Fire Weather Index System tables for New Zealand". National Rural Fire Authority, Wellington, and New Zealand Forest Research Institute, Rotorua, New Zealand. 48 p.

Barber, J.R. 1987. Remote sensing techniques for monitoring and mapping moisture content of grassland vegetation in Victoria to indicate statewide fuel flammability. *In* Technical Papers, Symposium on Computer Modelling and Remote Sensing in Relation to Bushfires in Australia, 3-4 June 1987, Canberra, Australia. Commonwealth of Australia, Department of Natural Resources, Division of National Mapping, Canberra, ACT. l5 p.

Barber, J.R. 1990. Monitoring the curing of grassland fire fuels in Victoria, Australia with sensors in satellites and aircraft. Country Fire Authority, Oakleigh, Victoria. 58 p.

Barber, J. 1993. Monitoring grassland fire fuels with satellites. *Disaster Management 5(1)*: 11-15.

Barber, J.R.; Pratt, B.T. 1980. The flammability of grasslands. *Country Fire Authority, Oakleigh, Victoria. Operations No. 93*: 1-7.

Barney, R.J. 1968. National Fire Danger Rating System Spread Index and Buildup Index frequencies for interior Alaska. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Institute of Northern Forestry, Juneau, Alaska. 8 p.

Basher, L.R.; Meurk, C.D.; Tate, K.R. 1990. The effects of burning on soil properties and vegetation -- a review of the scientific evidence relating to the sustainability of ecosystems and land use in the eastern South Island hill and high country. *Department of Scientific and Industrial Resources, Land Resources, Lower Hutt, New Zealand, DSIR Land Resources Technical Record 18*. 93 p.

Bell, A. 1987/88. Fire risk ratings by satellite. *Ecos 54* (Summer): 19-20.

Borger, B. 1992. Point Howard Fire. Report prepared for 1st NFRA-NZ FRI sponsored Advanced Fire Behaviour Course, 7-11 September 1992, Rotorua, New Zealand. 5 p. + Appendices.

British Columbia Ministry of Forests. 1983. Fire weather indices, decision aids for forest operations in British Columbia. *British Columbia Ministry of Forests, Protection Branch, Victoria, British Columbia, Forest Protection Handbook 12*. 57 p.

Brown, A.A.; Davis, K.P. 1973. "Forest Fire: Control and Use". Second edition. McGraw-Hill, New York. 686 p.

Burgan, R.E.; Hartford, R.A.; Eidenshink, J.C.; Werth, L.F. 1991. Estimation of vegetation greenness and site moisture using AVHRR data. Pages 17-24 *in* Proceedings of 11th Conference on Fire and Forest Meteorology, 6-19 April 1991, Missoula, Montana. *Society of American Foresters, Bethesda, Maryland, SAF Publication 91-04*.

Burgan, R.E.; Hartford, R.A. 1993. Monitoring vegetation greenness with satellite data. *USDA Forest Service, Intermountain Research Station, Ogden, Utah, General Technical Report INT-297*. 13 p.

Byram, G.M. 1959. Combustion of forest fuels. Pages 61-89 *in* Davis, K.P. (Ed.). "Forest Fire: Control and Use". McGraw-Hill, New York.

Canadian Forestry Service. 1970. Canadian Forest Fire Weather Index. Canadian Department of Fisheries and Forests, Canadian Forestry Service, Ottawa, Ontario. 25 p.

Catchpole, E.A.; Alexander, M.E.; Gill, A.M. 1992. Elliptical fire perimeter and area-intensity distributions. *Canadian Journal of Forest Research 22*: 968-972.

Cheney, N.P. 1991*a*. Development of an Australian Fire Danger Rating System. *Commonwealth Scientific and Industrial Research Organisation, Division of Forestry, Canberra, ACT, Rural Industries Research Development Report, Project No. CSF-35A*. 24 p.

Cheney, N.P. 1991*b*. Models used for fire danger rating in Australia. Pages 19-28 *in* Cheney, N.P.; Gill, A.M. (Eds.). "Conference on Bushfire Modelling and Fire Danger Rating Systems", Proceedings, 11-12 July 1988, Canberra, Australia. Commonwealth Scientific and Industrial Research Organisation, Division of Forestry, Yarralumla, ACT, Australia.

Cheney, P. 1992. A national fire danger rating system for Australia. *International Forest Fire News No. 6*: 19.

Cheney, N.P.; Gould, J.S.; Catchpole, W.R. 1993. The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *International Journal of Wildland Fire 3*: 31-44.

Cheney, N.P.; Gould, J.S.; Hutchings, P.T. 1989. Prediction of fire spread in grasslands. Commonwealth Scientific and Industrial Research Organisation, Division of Forestry and Forest Products, Bushfire Research Unit, Canberra, ACT, Australia. 41 p.

Cohen, J.D. 1985. Should the 1978 National Fire-Danger Rating System be updated?: a technical comparison to fire behavior prediction. Pages 163-168 *in* Proceedings, Eighth Conference on Fire and Forest Meteorology, 29 April-2 May 1985, Detroit, Michigan. *Society of American Foresters, Bethesda, Maryland, SAF Publication 85-04*.

Cooper, A.N. 1992. Analysis of the Nesterov fire danger rating index in use in Vietnam and associated measures. *Food and Agriculture Organisation, United Nations, Rome, Italy, V1E186/028 Field Document No. 6*. l8 p. + Appendices.

Cooper, A.N.; Ashley-Jones, C. 1986. The economics of fire prevention measures in exotic plantations. New Zealand Forest Service, Wellington, New Zealand, Unpublished Report. 14 p. + Appendices.

Cooper, A.N.; Ashley-Jones, C. 1987. Economics of fire prevention in New Zealand plantations. *New Zealand Forestry 31(4)*: 14-18.

Deeming, J.E. 1975. Calculating fire-danger ratings: computer vs tables. *Fire Management Notes 36(1)*: 6-7, 9.

Deeming, J.E. 1983. Reflections on the development, application, and future of the National Fire-Danger Rating System. Pages 139-146 *in* Preprint Volume, Seventh Conference on Fire and Forest Meteorology, 25-28 April 1983, Fort Collins, Colorado. American Meteorological Society, Boston, Massachusetts.

Deeming, J.E.; Lancaster, J.W.; Fosberg, M.A.; Furman, R.W.; Schroeder, M.J. 1972. The National Fire Danger Rating System. *USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, Research Paper RM-84*. 165 p.

Deeming, J.E.; Burgan, R.E.; Cohen, J.D. 1977. The National Fire-Danger Rating System -- 1978. *USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, General Technical Report INT-39*. 63 p.

Dudfield, M. 1988. Fire consultancy report, Fiji Pine Commission. New Zealand Official Development and Assistance Programme, Wellington, New Zealand. 21 p. + Appendices.

Dudfield, M. 1989. Report on fire consultancy, Western Samoa. New Zealand Official Development and Assistance Programme, Wellington, New Zealand. 20 p. + Appendices.

Dudfield, M. 1990. Report on fire consultancy, Bukidnon industrial plantation project, Philippines. New Zealand Official Development and Assistance Programme, Wellington, New Zealand. 8 p. + Appendices.

Egunjobi, J.K. 1969. Dry matter and nitrogen accumulation in secondary successions involving gorse (*Ulex europaeus* L.) and associated shrubs and trees. *New Zealand Journal of Science 12*: 175-193.

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. *South African Forestry Journal 145*: 1-8.

Fenton, G.R. 1951. Regeneration of *Pinus radiata* D. Don following fire. *New Zealand Forest Service, Forest Research Institute, Rotorua, New Zealand, Forest Research Notes l(4)*: 1-8.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. *Forestry Canada, Science and Sustainable Development Directorate, Ottawa, Ontario, Information Report ST-X-3*. 63 p.

Garvey, M. 1992. "Grassland curing guide". Second edition. Country Fire Authority, Victoria. 12 p.

Garvey, M.; Stephenson, K.; Whelan, M. 1993. The use of geographic information systems at the Country Fire Authority. *Fire Management Quarterly No. 3*: 1-8.

Gaukrodger, D.J. 1993. Lake Maratoto fire behaviour report. Report prepared for 1st NRFA-NZ FRI sponsored Advanced Fire Behaviour Course Refresher Seminar, 29-30 March 1993, Rotorua, New Zealand. 4 p.

Girling-Butcher, W. 1977. Forest fire control in New Zealand. Pages 95-99 *in* Chavasse, C.G.R. (Ed.). "New Zealand Institute of Foresters (Inc.) Forestry Handbook". New Zealand Institute of Foresters, Wellington, New Zealand.

Grant, M.C. 1992. Wildfire behaviour documentation - Wellington, NZ: A case study of the Wellington Road Fire, Wainuiomata, 27/28 February 1989. Report prepared for 2nd NRFA-NZ FRI sponsored Advanced Fire Behavior Course, 21-25 September 1992, Christchurch, New Zealand. 21 p.

Hirsch, K.G. 1993. A brief review of the Canadian Forest Fire Behavior Prediction (FBP) System. *HotSheet 2(2&3)*: 3-7.

Hocking, G.H. 1946. Drought in Hawkes Bay. *New Zealand Journal of Forestry 5(3)*: 230-231.

Hosking, R. 1990. Grassland Curing Index -- a district model that allows forecasting of curing. *Mathematical and Computational Modelling 13(12)*: 73-82.

Hunter, G.G.; Blaschke, P.M. 1986. The New Zealand land resource inventory vegetation cover classification. *National Water and Soil Conservation Authority, Wellington, New Zealand, Water and Soil Miscellaneous Publication No. 101*. 92 p.

Lancaster, J.W. 1974. Fire management applications of the National Fire Danger Rating System. Paper prepared for presentation at SAF-AMS Conference on Fire and Forest Meteorology, April 2-4, 1974, Lake Tahoe, California-Nevada. 27 p.

Lanoville, R.A.; Mawdsley, W.M. 1990. Systematic assessment of daily fire preparedness requirements. Pages 253-261 *in* Alexander, M.E.; Bisgrove, G.F. (Tech. Coords.). "The Art and Science of Fire Management", Proceedings of the First Interior West Fire Council Annual Meeting and Workshop, 24-27 October 1988, Kananaskis Village, Alberta. *Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Information Report NOR-X-309.*

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

Luke, R.H.; McArthur, A.G. 1978. "Bushfires in Australia". Australian Government Publishing Service, Canberra, ACT, Australia. 359 p. [revised and reprinted in 1986].

Main, W.A.; Paananen, D.M.; Burgan, R.E. 1990. FIREFAMILY 1988. *USDA Forest Service, North Central Forest Experiment Station, St Paul, Minnesota, General Technical Report NC-138*. 35 p.

McAlpine, R.S.; Lawson, B.D.; Taylor, E. 1991. Fire spread across a slope. Pages 218-225 *in* Proceedings of 11th Conference on Fire and Forest Meteorology, 16-19 April 1991, Missoula, Montana. *Society of American Foresters, Bethesda, Maryland, SAF Publication 91-04.*

McArthur, A.G. 1966. Weather and grassland fire behaviour. *Commonwealth of Australia, Department of National Development, Forest and Timber Bureau, Forest Research Institute, Canberra, ACT, Leaflet No. 100*. 23 p.

Merrill, D.F.; Alexander, M.E. (Eds.). 1987. Glossary of forest fire management terms. Fourth edition. *National Research Council of Canada, Canadian Committee on Forest Fire Management, Ottawa, Ontario, Publication NRCC No. 26516*. 91 p.

Meurk, C.D. 1978. Alpine phytomass and primary productivity in central Otago, New Zealand. *New Zealand Journal of Ecology 1*: 27-50.

Muraro, S.J. 1975. Prescribed Fire Predictor. Canadian Forestry Service, Pacific Forest Research Centre, Victoria, British Columbia. Slide-rule (with text). [reprinted 1980].

Neale, A.A. 1987. "Weather forecasting in New Zealand". New Zealand Meteorological Service, Wellington, New Zealand. 73 p.

Nelson, R.M. 1961. Some applications of danger ratings in forest fire control and management. *USDA Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, Station Paper No. 129*. 26 p.

Nelson, R.M. 1964. The National Fire Danger Rating System: Derivation of Spread Index for eastern and southern states. *USDA Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, Research Paper SE-13*. 44 p.

Newsome, P.F.J. 1987. The vegetative cover of New Zealand. *National Water and Soil Conservation Authority, Wellington, New Zealand, Water and Soil Miscellaneous Publication No. 112*. 153 p.

New Zealand Forest Service. 1983. "Fire Weather Index: The basis for fire danger rating in New Zealand". New Zealand Forest Service, Wellington, New Zealand. 67 p.

New Zealand Meteorological Service. 1984. Rainfall normals for New Zealand, 1951 to 1980. *Ministry of Transport, New Zealand Meteorological Service, Wellington, New Zealand, Miscellaneous Publication 185*. 36 p.

Pairman, D. 1993. Proposal for the National Rural Fire Authority to evaluate satellite derived NDVI for assessing grassland curing. Landcare Research New Zealand Ltd., Wellington, New Zealand. 4 p.

Paltridge, G.W.; Barber, J. 1988. Monitoring grassland dryness and fire potential in Australia with NOAA/AVHRR data. *Remote Sensing and Environment 25*: 381-394.

Parrott, R.T. 1964. The growth, senescence and ignitability of annual pastures. University of Adelaide, White Agricultural Research Institute, Adelaide, South Australia. M.Sc. Thesis.

Parrott, R.T.; Donald, C.M. 1970. Growth and ignitability of annual pastures in a Mediterranean environment. 1. Effect of length of season and of defoliation on the growth, water content and desiccation of annual pastures. *Australian Journal of Experimental Agriculture and Animal Husbandry 10*: 67-74.

Pearce, H.G.; Alexander, M.E. 1994. Fire danger ratings associated with New Zealand's major pine plantation fires. Pages 534-543 *in* Proceedings, 12th Conference on Fire and Forest Meteorology, 25-29 October 1993, Jekyll Island, Georgia. *Society of American Foresters, Bethesda, Maryland, SAF Publication 94-02*.

Pearce, H.G.; Alexander, M.E.; Morgan, R.F. 1995. Wildfire behaviour in a New Zealand wetland: a case study. Pages 168-169 *in* "Fire in wetlands: A Management Perspective", Proceedings, 19th Tall Timbers Fire Ecology Conference, November 3-6, 1993, Tallahassee, Florida. Tall Timbers Research Station, Tallahassee, Florida.

Peet, G.B. 1980. Forest fire management planning, Kenya: fire danger rating for forest areas. *United Nations Development Programme, Food and Agriculture Organisation, United Nations, Rome, Italy, FAO:DP/KEN/741024 Technical Report 1*. 93 p.

Pirsko, A.R. 1961*a*. Selecting fire control planning levels by burning index frequencies. *USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, Miscellaneous Paper No. 55*. 7 p.

Pirsko, A.R. 1961*b*. Why tie fire control planning to burning index? *Fire Control Notes 22(1)*: 16-19.

Rasmussen, J. 1993. Fire behavior study: Tikokino Fire. Pages 25-32 *in* Proceedings, 3rd Annual Conference of the Forest and Rural Fires Association of New Zealand, 4-6 August 1993, Wellington, New Zealand. Forest and Rural Fires Association of New Zealand, Rotorua, New Zealand.

Reifsnyder, W.E. 1959. Book reviews: Forest Fire: Control and Use. *Journal of Forestry 57(9)*: 671-672.

Reifsnyder, W.E. 1978. Systems for evaluating and predicting the effects of weather and climate on wildland fires. *World Meteorological Organisation, Geneva, Switzerland, Special Environment Report No. 11*. 40 p.

Sneeuwjagt, R.J.; Peet, G.B. 1985. "Forest fire behaviour tables for Western Australia". Third edition. Department of Conservation and Land Management of Western Australia, Perth, Western Australia. 59 p.

Staton, J. 1992*a*. Hokitika Fire. Pages 39-40 *in* Proceedings, 2nd Annual Conference of the Forest and Rural Fires Association of New Zealand, 5-7 August 1992, Christchurch, New Zealand. Forest and Rural Fires Association of New Zealand, Rotorua, New Zealand.

Staton, J. 1992*b*. Keogans Road wildfire, Hokitika, West Coast. Report prepared for 2nd NFRA-NZ FRI sponsored Advanced Fire Behaviour Course, 21-25 September 1992, Christchurch, New Zealand. 4 p. + Attachments.

Stocks, B.J.; Lawson, B.D.; Alexander, M.E.; Van Wagner, C.E.; McAlpine, R.S.; Lynham, T.J.; Dubé, D.E. 1989. The Canadian Forest Fire Danger Rating System: an overview. *Forestry Chronicle 65*: 450-457.

Tangren, C.D. 1976. The trouble with fire intensity. *Fire Technology 12*: 261-265.

Thomas, P.H. 1970. The rates of spread of headfires in gorse and heather. *Fire Research Station, Borehamwood, Hertfordshire, England, Fire Research Note No. 796*. 36 p.

Thompson, R.J. 1993. Case study of "Observatory Hill Fire", Nelson of 25 January 1993. Pages 33-39 *in* Proceedings, 3rd Annual Conference of the Forest and Rural Fires Association of New Zealand, 4-6 August 1993, Wellington, New Zealand. Forest and Rural Fires Association of New Zealand, Rotorua, New Zealand.

Turner, J.A. 1971. Canadian Forest Fire Weather Index. Pages 29-31 *in* Proceedings of the 1970 Annual Meeting of the Western Forest Fire Committee, 1 December 1970, Vancouver, British Columbia. Western Forestry Conservation Association, Portland, Oregon.

Turner, J.A. 1973. A fire load index for British Columbia. *Canadian Forestry Service, Pacific Forestry Research Centre, Victoria, British Columbia, Information Report BC-X-80*. 15 p.

Turner, J.A.; Lawson, B.D. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. *Canadian Forestry Service, Pacific Forestry Research Centre, Victoria, British Columbia, Information Report BC-X-177*. 40 p.

Valentine, J.M. 1978. Fire danger rating in New Zealand: review and evaluation. *New Zealand Forest Service, Forest Research Institute, Production Forestry Division, Rotorua, New Zealand, Forest Establishment Report No. 123*. 53 p. (unpublished).

Van Wagner, C.E. 1970. New developments in forest fire danger rating. *Canadian Forest Service, Petawawa Forest Experiment Station, Chalk River, Ontario, Information Report PS-X-19*. 4 p.

Van Wagner, C.E. 1972. Duff consumption by fire in eastern pine stands. *Canadian Journal of Forest Research 2*: 34-39.

Van Wagner, C.E. 1973*a*. Height of crown scorch in forest fires. *Canadian Journal of Forest Research 3*: 373-378.

Van Wagner, C.E. 1973*b*. Rough prediction of fire spread rates by fuel type. *Canadian Forest Service, Petawawa Forest Experiment Station, Chalk River, Ontario, Information Report PS-X-42*. 9 p. [revised 1980].

Van Wagner, C.E. 1974. Structure of the Canadian Forest Fire Weather Index. *Canadian Forest Service, Ottawa, Ontario, Publication No. 1300*. 44 p.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research 7*: 23-34.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest fire Weather Index System. *Canadian Forest Service, Ottawa, Ontario, Forestry Technical Report 35*. 37 p.

Van Wagner, C.E. 1989. Prediction of crown fire behaviour in conifer stands. Pages 207-212 *in* Proceedings, 10th Conference on Fire and Forest Meteorology, 17-21 April 1989, Ottawa, Ontario. Forestry Canada, and Environment Canada, Ottawa, Ontario.

Van Wagner, C.E.; Pickett, T.L. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. *Canadian Forest Service, Ottawa, Ontario, Forestry Technical Report 33*. 18 p.

van Wilgen, B.W.; Burgan,, RE. 1984. Adaptation of the United States Fire Danger Rating System to fynbos conditions. Part II. Historic fire danger in the fynbos biome. *South African Forestry Journal 129*: 66-78.

Wallace, G. 1993. Editorial: Fire research. *The Rural Firefighter 18*: 6-8.

Wallace, K. 1989. Bushfire statistics in Wainuiomata. Unpublished Statistics Assignment term paper supplied by G. Wallace, Wainuiomata Bushfire Force, Wainuiomata, New Zealand. 10 p.

Wardle, P. 1991. “Vegetation of New Zealand”. Cambridge University Press, Cambridge. 672 p.

Westover, D.; Sadowski, F. 1987. Satellites sense rangeland wildfire hazard. *Fire Management Notes 48(1)*: 9-11.

Williams, D.E. 1963. Forest fire danger manual. *Canadian Department of Forestry, Forest Research Branch, Ottawa, Ontario, Publication No. 1027*. 28 p.

Williams, P.A. 1977. Growth, biomass, and net productivity of tall-tussock (*Chionochloa*) grasslands, Canterbury, New Zealand. *New Zealand Journal of Botany 15*: 399-442.

Wilson, A.A.G. 1988*a*. A simple device for calculating the probability of a house surviving a bushfire. *Australian Forestry 51*: 119-123.

Wilson, A.A.G. 1988*b*. Width of firebreak that is necessary to stop grass fires: some field experiments. *Canadian Journal of Forest Research 18*: 682-687.

Wilson, A.A. G. 1993. Elevated fuel guide. *Department of Conservation and Natural Resources, Fire Management Branch, East Melbourne, Victoria, Research Report No. 35*. 22 p.

Wilson, A.A.G.; Ferguson, I.S. 1986. Predicting the probability of house survival during bushfires. *Journal of Environmental Management 23*: 259-270.

Wright, J.G.; Beall, H.W. 1938. Grass-fire hazard tables for eastern Canada. *Canadian Department of Mines and Resources, Lands, Parks and Forestry Branch, Dominion Forestry Service, Ottawa, Ontario, Forest Fire Research Note No. 6*. 16 p.