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Variation of Live and Dead Fine Fuel Moisture in *Pinus radiata* Plantations of the Australian Capital Territory

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Abstract. A study was made of the variation in moisture content of fine dead fuel (FFM) in relation to 1) differences of fuel type (needles, leaves, twigs, bark), 2) different fuel locations (dead canopy and surface litter), 3) contrasting management of plantations (unthinned-unpruned vs thinned-pruned) and 4) environmental factors (air temperature (T) and relative humidity (H); moisture content of duff (D) and topsoil (S)).

The variation of live (green needle) fine fuel moisture content (LFMC) in relation to needle age, canopy location (shaded vs unshaded) and season was also studied in *Pinus radiata* D. Don plantations over 2 years.

Mean differences of moisture content between the several types of fuel exposed to the same atmospheric conditions were generally significant and ranged from 0.6% (pine twigs vs eucalypt twigs) up to 2.8% oven dry weight (ODW) (eucalypt bark vs recently cast pine needles).

T and H were highly correlated between study sites in pine plantations and an official meteorological station at Canberra airport, 15 km away. In the pine plantations, mid afternoon moisture contents of pine needle litter (litter FFMs) were mostly higher than moisture contents of dead needles in canopies (aerial FFMs); the mean differences between litter FFMs and aerial FFMs were statistically significant. FFMs in the unthinned-unpruned plantation were also generally higher than those in the thinned-pruned plantations.

Regression analyses of relationships between FFM and environmental variables showed that T and H in combination explained a large proportion of the variation in aerial FFM but much less of the variation in litter FFM. However, the inclusion of either D or S in multiple regression models accounted for significant amounts of the variation in litter FFM.

LFMC decreased with needle age and, for full-grown needles, was up to 25% (ODW) higher in shaded compared to unshaded canopy locations. Seasonal patterns of change in LFMC of full-grown needles were not well defined.

Variation in the parameters and the precision of FFM regression relationships between fuel locations and stands with contrasting management demonstrate the site specificity and limitations of empirical FFM models. The results suggest that for prediction of aerial FFM, models based on a combination of T and H are most appropriate; while, models that include a soil moisture variable may predict FFM of litter fuels more accurately. However, the intrinsic variation in FFM revealed in this study indicates that such models, although providing a useful guide, may not predict FFM with the accuracy required for fire behaviour models during high fire danger weather - when fuel moistures are low.

Keywords: *Pinus radiata*; Fine fuel moisture

Introduction

The total area of commercial plantations of *Pinus radiata* in southern Australia has increased to approximately 0.5 million ha (Booth 1984). This represents a highly valuable timber resource and it is very sensitive to fire. The regular seasonal occurrence of extreme fire danger with increased probability of outbreaks of severe bushfire in the region (Gill et al. 1987) periodically puts plantations at risk. For example, amongst the substantial losses caused by the devastating Ash Wednesday bushfires on the 16th of February 1983, were 2300 ha of pine plantations in Victoria (Rawson et al. 1983) and c. 20,000 ha in South Australia (Keeves and Douglas 1983). Financial losses associated with two fires in plantations of the Australian Capital Territory (A.C.T.) during the 1990-91 summer are expected to be in the vicinity of \$(A)3 million (personal communication, A.C.T. Forests).

Young unthinned and unpruned plantations of *P. radiata*, typically with large accumulations of highly flammable dead fine fuels (fuel elements < 6 mm thick), are particularly vulnerable and easily destroyed by fires.

At canopy closure (stand age 10-14 yrs) the load of fine fuel in surface litter may be almost 10 t/ha (Jabbs 1988); and, there may be 5 or more t/ha of dead, and 12 t/ha of living aerial fine fuel (mainly needles) in the tree crowns (Williams 1976). As there is a more or less continuous link between surface fuels and the aerial fuel held on lower branches, surface fires may become crown fires at this stage of development.

Pruning and thinning of young stands breaks the vertical fuel link, but slash increases the load of fuel on the forest floor and is a serious fire hazard to plantations until it is either removed or reduced by weathering and decomposition. Dead aerial fine fuel also persists in the canopy. In some Australian states fire has been used as a management tool to reduce slash and aerial fuels (Woodman and Rawson 1982). However, better definitions of safe and suitable conditions for fuel reduction burning and the prediction of any damage to the crop trees are still required. Although the economic losses arising from fire damage are considerable, and the use of fire as a management tool for hazard reduction may be feasible at certain stages of the life cycle, the literature contains little information on fuel flammability and fire behaviour in *P. radiata* plantations.

Dead fine fuel moisture content (FFM) is an important variable that is either directly or indirectly incorporated into most fire behaviour models or fire danger rating systems; and, for many practical reasons, it usually has to be predicted. Current progress in FFM prediction in Australia appears to be limited as much by the lack of knowledge of the temporal and spatial variability of FFM in the many different fuel types and environments as by the inadequacies of FFM models.

In pine plantations there are three easily recognized components of the fuel arrays in which FFM may vary widely and have a significant influence on forest flammability and fire behaviour. They are (1) litter surface fuels; (2) dead canopy (aerial) fuels, and (3) live, green canopy foliage. The FFM of surface litter is one of the main determinants of the intensity and rate of spread of a fire. The FFM of dead aerial fuel influences the vertical propagation of fire and together with the moisture content of live fine fuels (LFMC) influences 'crowning'. Australian FFM models do not discriminate the variations of FFM between different components of fuel arrays and were not originally designed for pine plantations.

Figure 1 indicates the common assumptions made when data from a standard meteorological station are used as inputs to empirical models predicting FFM at sites in forests or plantations remote from the station. After adjustments for differences in elevation, the minimum assumption is that the weather observations at the meteorological station are the same as the concurrent ambient conditions at corresponding heights above ground at the remote sites. The behaviour of a 'fuel standard', installed and monitored either at the station or 'in situ' at a 'representative' forest site, in some localities, may also be extrapolated to a variety of dead fuels in a wide range of sites. At a forest site where FFM is of interest, it is also assumed that FFM is correlated with atmospheric conditions at 1.5 m height (corresponding to the height of sensors in an instrument shelter), although relative exposure of the fuel to atmospheric conditions may differ from this. The role of subsurface moisture (i.e. moisture in the duff and soil) is either unknown or has not been a consideration in the prediction of FFM of surface fuels.

Current prediction methods were a convenient frame of reference for the conduct and aims of this study which were: (i) to compare simultaneous weather conditions at the meteorological station and in the forest; (ii) to determine the variation of dead FFM between different fuel types, between different locations in fuel arrays, between stands with different management and, in relation to air temperature, air humidity and soil moisture; and, (iii) to investigate seasonal changes in LFMC.

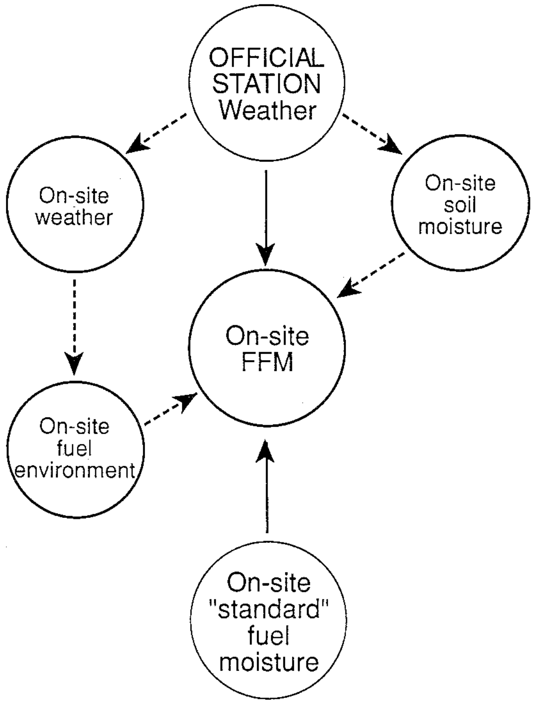

Figure 1. Common pathways of prediction of grassland and forest FFM (inputs to fire behaviour models and fire danger rating systems.)—present prediction pathways; - - - subsumed steps in predictions.

Sample Sites and Methods

FFM data were acquired during the 1988-89 and 1989-90, fire seasons in Canberra, A.C.T. During 1988-89 data collection focussed on early afternoon FFM in fuel arrays of unthinned-unpruned and thinned-pruned pine forest stands. During 1989-90, *ex situ* comparisons were made of diurnal FFM of pine and eucalypt fuel types exposed to atmospheric conditions in an instrument shelter (Stevenson's screen).

In the former period fuel sampling was carried out between 1400 and 1500 hrs Australian Eastern Standard Time (AEST) on days when there had been no substantial precipitation for at least 24 hours. Samples were obtained from an unthinned-unpruned (UTUP) stand (planted in 1975) and two thinned-pruned (TP) stands (planted 1972 and 1967, respectively) of *P. radiata*. The three stands were located in Stromlo Forest, about 15 km to the west of and 30-40 metres higher in elevation than Canberra Airport, A.C.T., the site of the official Canberra meteorological station. They were situated on north-east slopes with gradients of 3 to 6 degrees. The characteristics of the individual stands are given in Table 1. Canopy closure had been reached in the youngest stand. A substantial amount of dead needles was held in tree canopies of all three stands.

Meteorological measurements

Dry bulb and wet bulb temperatures were measured with an Assman hygrometer at a height of 1.5 m above ground in the pine stands. Relative humidity (H) was determined from tables. The measurements made in the forest were compared with those made at Canberra Airport.

Soil moisture measurements

On each occasion that dead fuels were sampled within a stand, the volumetric water content of the 0-40 cm depth interval of topsoil (S_{40}) in each of three undisturbed profiles was measured using the neutron moisture depth gauge technique (I.A.E.A. 1970). The three observations were then averaged. On most occasions three samples of the 0-5 cm depth interval of mineral topsoil (S_5) were also collected from beneath needle bed fuel sampled in the vicinity of the neutron depth gauge profiles. These soil samples were immediately bulked and sealed in a plastic bag. Within one to two hours of collection the bulked soil was weighed in the laboratory. Oven dry weight (ODW) of the samples was obtained after they had been dried in a forced draught oven at 105° for 24 hours and equilibrated in desiccators at room temperature before final weighing.

Water balance of topsoil

A modified form of the WATBAL water balance model (Keig and McAlpine 1974) was used to predict the water storage of topsoil at weekly intervals in the pine stands. Model inputs were total weekly rainfall measured at Stromlo Forest Headquarters and Class A pan evaporation measured at Canberra Airport. The maximum storage of water in topsoil at field capacity (56 mm of available water) was deduced from neutron moisture depth gauge data. The main modification made to the model was the incorporation of two expressions - one to approximate rainfall interception loss in the pine canopies and so estimate net rainfall (Pook et al. 1991); and, the other to proportion evapotranspiration loss to the level of available soil water in storage at the beginning of each weekly interval.

Measurements of dead fine fuel moisture

Needle bed fuel was typically a continuous and compact layer of needles and twigs of relatively shallow depth (c. 5 cm in UTUP stands and 2.5 cm in TP stands). The layer had a profile grading from intact elements (litter) at the surface down through decomposed material (duff) to soil beneath. Slash mounds in TP stands consisted of irregular concentrations of fuel derived from thinnings and prunings up to 15 cm or so in depth. The surface litter of such mounds was more exposed than that of needle beds and the duff included decomposing stem and branch wood.

Table 1. April 1988 fuel loads and characteristics of the *P. radiata* stands in which fuel moisture was studied at Stromlo Forest (after Jabbs, 1988). LCBH, lower crown base height. UTUP, unthinned and unpruned. TP, thinned and pruned.

Year planted	Stand Management	Stand density (stems/ha)	Mean height (m)	Mean basal area (sq. m)	Mean LCBH (m)	Total fine fuel in litter (t/ha)	Needle litter (t/ha)	Needles (% of total fuel)
1975	UTUP	1234	10.1	32	2.7	9.7	9.7	70
1972	TP	909	17.5	52	7.0	10.3	7.3	57
1967	TP	826	18.4	47	9.9	16.4	12.4	60

In the case of needle bed fuel, three samples of needles from surface litter to a depth of 5 to 10 mm were gathered, bulked and sealed in plastic bags. The duff immediately beneath the litter was sampled in like manner. A similar method was used for sampling fine fuel of slash mounds, except that only the upper layer of the deep duff was sampled. In the UTUP 1975 stand, relatively deep accumulations (10-15 cm depth) of fine fuel at the bases of trees were sampled in lieu of slash mounds.

Bulked samples of aerial fine fuel (dead needles from canopy) were gathered from the lowermost (c. 2-3 m high) branches of trees in the 1967 and 1972 TP stands, and from branches at c. 1.5 m height in the UTUP 1975 stand.

The fuel samples were weighed in the laboratory within one to two hours of collection, dried at 95° C in a forced draught oven for 24 hours and equilibrated in desiccators before obtaining ODW. Fuel moisture has been expressed as a percentage of ODW.

Ex situ comparisons of FFM between fuel types

Variation of FFM related to differences of fuel type was investigated in a selection of fine fuels obtained from pine and eucalypt stands. The selection included: old weathered dead needles that had persisted in situ for 6 or more years on the lower branches of *P. radiata* trees in the UTUP stand; younger recently-downed dead needles of surface litter of the UTUP stand; dead pine twigs from slash heaps in the TP 1967 stand; and, separate samples of dead leaves, dead twigs and bark fragments of *Eucalyptus rossii* R.T.Baker et H.G. Smith from surface litter of a local dry sclerophyll forest at Black Mountain, Canberra. All of the fuel particles were less than 6 mm thick. The average thickness of the *P. radiata* needles was about 0.4 mm, but the old needles were slightly thinner and shorter than the younger recently-cast needles. The pine twigs, eucalypt leaves, eucalypt twigs and eucalypt bark fragments averaged 3.6, 0.26, 2.2 and 1.5 mm thickness, respectively.

Five replicate samples of each fuel were loaded separately into terylene mesh bags. Fuels that tended to aggregate or pack down were spread and stapled to the bag walls to maintain separation and, hence, good ventilation. The bagged samples were then suspended in an instrument shelter (a large Stevenson's meteorological screen) outside the laboratory at Black Mountain, Canberra where (except for short intervals required for weighing) they were continuously exposed to ambient atmospheric conditions during January and February, 1990.

Temperature and humidity sensors were exposed at about the same height as the fuel samples in a separate instrument shelter nearby. Samples were weighed and temperature (T) and H were recorded simultaneously at 2 to 3-hourly intervals between 0600 and 2200 hrs AEST for six days. Additional measurements were made on six other days between 0900 and 1500 hrs AEST. For the most part the weather conditions, with wide diurnal fluctuations of T and H, were typical of fine summer days in the A.C.T. and surrounding tablelands of New South Wales. Simultaneously measured T and H ranged from 15°C/89% to 39°C/16%. ODW of each fuel sample was determined at the end of the observation period.

Live needle moisture (LFMC)

Green needles were obtained from shaded and unshaded locations in the 1967 TP stand, usually at about monthly intervals, between August 1988 and May 1990. Shaded needles were taken from the lowermost branches of trees inside the stand while unshaded needles were taken from lower branches of trees at the edge of the stand. In the early afternoon of sampling days, branchlets in each location were cut from 5 or 6 trees and sealed in plastic bags. Thirty minutes or so after collection, the green needles were stripped from the branchlets, bulked according to location and age class, and then weighed in the laboratory. LFMC was expressed as a percentage of ODW.

Statistical analyses

Simple 't' tests were used to assess the significance of the mean differences of FFMs compared within and between pine stands; and, between different fuel types in the *ex situ* study.

Linear and multiple regression analyses were carried out using GENSTAT 5 (Payne et al. 1987) to examine the relationships between FFM of dead fuels and environmental factors (T, H, S_5, S_{40} and duff moisture, D). The effect of stand management (thinning and pruning) on regression relationships obtained for various FFMs (aerial, surface litter of needle beds and slash mounds) was also examined using a test of parallelism for the fitted regression models. Initially, in these tests, a model that allowed for equal slopes but different intercepts was fitted; then a more complex model was fitted that allowed for both different slopes and different intercepts.

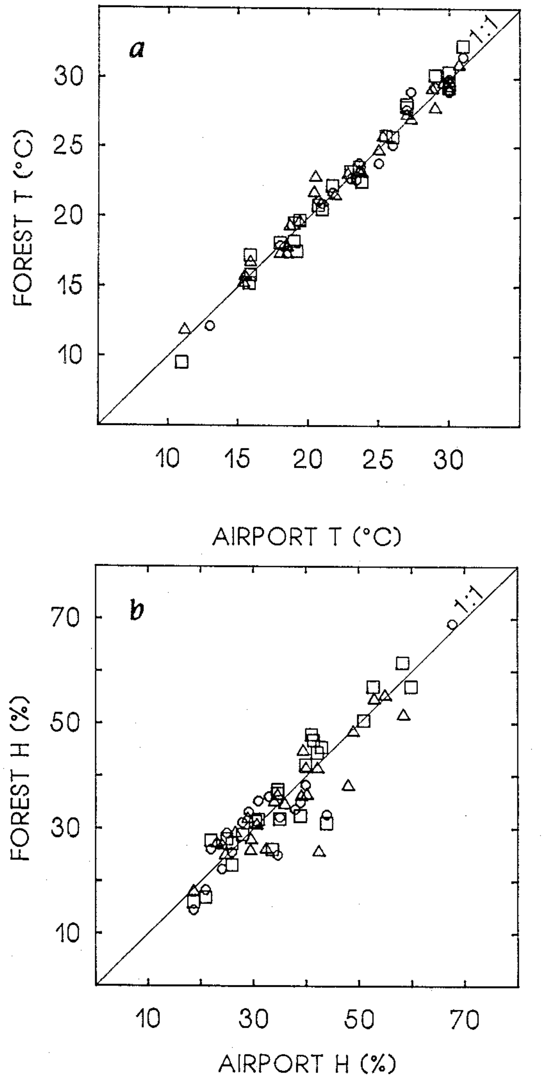

Figure 2. Correlation of air temperature, *a*, and relative humidity, *b*, between Canberra airport and study sites in three pine stands at Mount Stromlo Forest, 15 km to the west.
Datum height of measurements = 1.5 m.
Pine stand (data source), □ 1975; ○ 1972; △ 1967.

Results

Comparison of T and H between weather station and forest

T and H measured in the pine stands and at Canberra airport during the 1988-89 study period are compared in Figure 2. T was highly correlated between sites (r=0.99); the correlation for H was somewhat lower (r=0.83).

Ex situ comparisons of the influence of fuel type on FFM

Comparisons between the simultaneous moisture contents of the pine and eucalypt fuels exposed to atmosphere in the instrument shelter revealed many highly significant differences ranging from as little as 0.58% ODW (between pine and eucalypt twigs) up to 2.81% ODW between "new" pine needles and eucalypt bark (Table 2). Relationships between moisture contents of the different types of fuel were linear and very highly correlated, at least up to c. 15% ODW if not over the entire range of measured FFM (Figure 3, a-f). Old dead pine needles were consistently more moist than new dead pine needles; differences in moisture ranged from 0.3% at low FFM up to 2% ODW at the high FFMs (Figure 3a). Pine twigs were more moist than both types of pine needles (Table 2), except when humidities were high (early in the day) (Figure 3b); but the mean difference in moisture content was significant only for the comparison made between twigs and new needles.

Pine twigs and eucalypt twigs had similar diurnal responses but the former fuel usually remained more moist than the latter. Despite species differences, such as contrasting bark surface characteristics, the relatively small mean difference in moisture content between the two types of twigs (0.58% ODW) was statistically highly significant yet only about half that found between the two ages of *P. radiata* needles (1.1% ODW).

Table 2. Mean differences (A-B) between simultaneous moisture contents of pine and eucalypt fine fuels (% ODW) continuously exposed to the atmosphere in an instrument shelter.
Significance of mean differences; ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$; ns, not significant. n = 48.

	A				
B	Old pine needles	New pine needles	Pine twigs	Eucalypt leaves	Eucalypt twigs
New pine needles	1.10***				
Pine twigs	-0.25^{ns}	-1.35***			
Eucalypt leaves	-0.95***	-2.05***	-0.70***		
Eucalypt twigs	0.33^{ns}	-0.77***	0.58***	1.28***	
Eucalypt bark	-1.70***	-2.81***	-1.46***	-0.76***	-2.04***

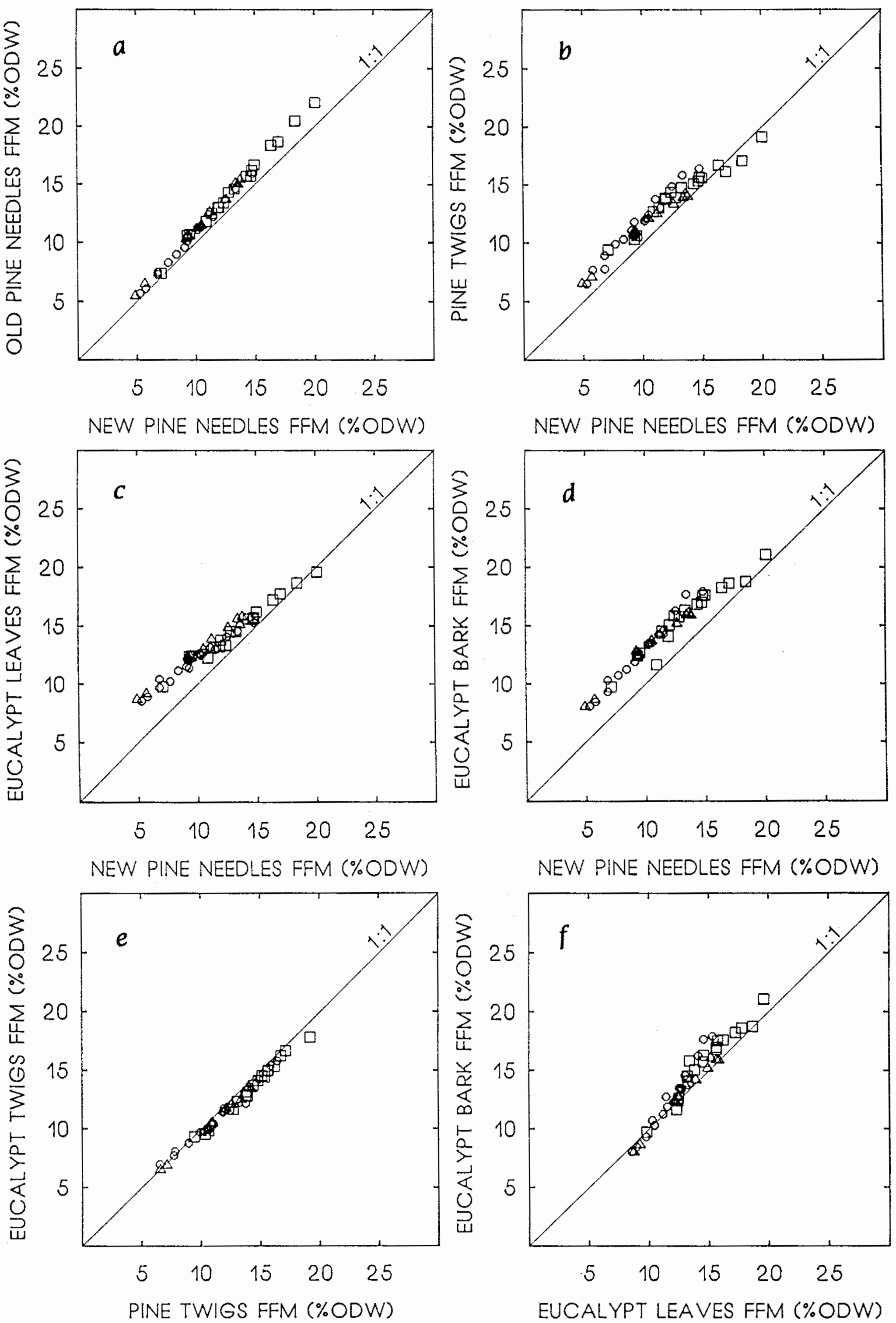

Figure 3. Comparisons of simultaneous moisture contents of dead fine fuels of *P. radiata* and *Eucalyptus rossii* continuously exposed to diurnal changes in atmospheric conditions in a large instrument shelter (Stevenson's screen).
Times of observations, □ 0600-1200; ○ 1200-1800; △ 1800-2400.

Variation of litter and aerial FFM

Although highly correlated, mid-afternoon (1400-1500 hrs) FFM's of needle bed and slash mound litter varied widely and at times differed by up to 5% of ODW (Figure 4a). Even so, the mean differences between these two surface litter FFMs within individual pine stands, within the TP stands combined, or within the UTUP and TP stands combined were not statistically significant.

FFM's of surface litter fuels most frequently were higher than simultaneous aerial FFM's, by up to 6% ODW (e.g. Figure 4b). In the UTUP (1975) stand, mean differences between aerial FFM and either needle bed or slash mound litter FFM were larger than in TP stands, and both were very highly significant (Table 3). In TP stands, the mean difference between needle bed litter FFM and aerial FFM for both pooled data (1967, 1972) and data of the 1967 stand was highly significant, but that of the 1972 stand was not. The mean difference between slash mound litter FFM and aerial FFM was significant only in the 1967 stand.

Variation of FFM related to stand management

Comparisons between the mid afternoon FFMs of the UTUP and TP stands revealed that, on most occasions, fuels of the former stands were more moist than those of the latter, and that the differences in moisture contents increased with increases of FFM (Figure 5). The mean difference between aerial FFMs (all observations) was highly significant (Table 4). However, when the comparison was limited to times when aerial FFM in the TP stand was less than 10% ODW, the much lower mean difference was not statistically significant. For surface fuels, the mean difference between UTUP and TP litter FFMs overall was highly significant; so too was the mean difference when TP litter FFMs were restricted to less than 10% ODW (Table 4).

Data in Figure 5 also show that while the ranges of aerial FFM were similar (6-18% and 6-16% for the UTUP and TP stands respectively), the range of litter FFMs of the UTUP stand (7-26% ODW) greatly exceeded that of the TP stand (6-17% ODW). The latter appreciable difference in FFM range has implications for the precision of relationships between litter FFMs and environmental factors explored later.

Variation of FFM influenced by environmental conditions

Correlations between FFMs of both aerial and litter fuels with environmental factors were mostly significant ($P<0.001$); and, with one exception (slash mound litter FFM v D) the correlation coefficients were greater for the UTUP stand (Table 5).

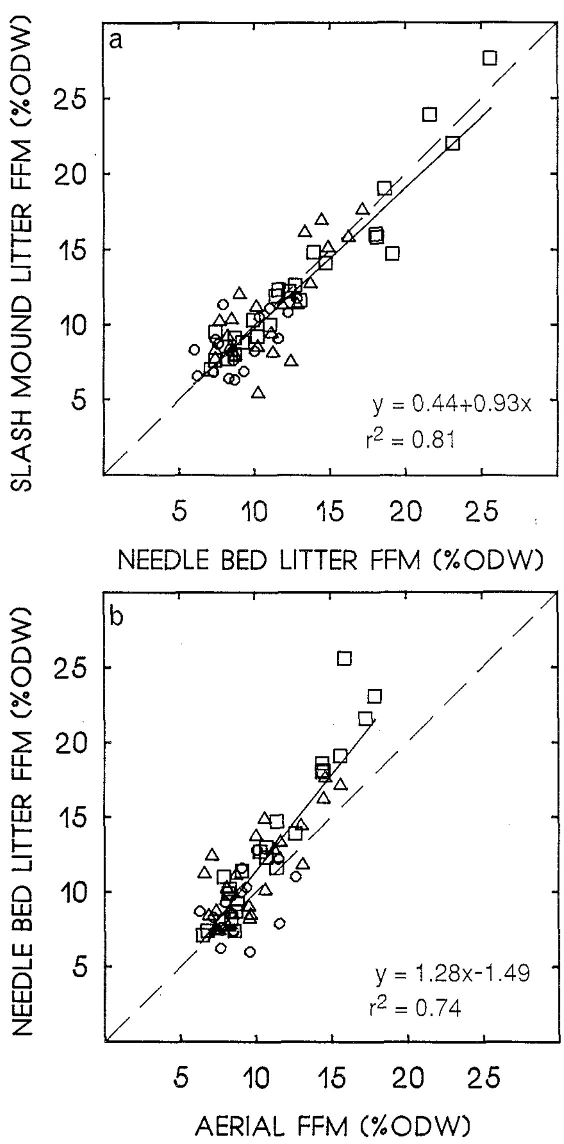

Figure 4. Comparison of dead FFM in UTUP and TP *P. radiata* plantations between 1400 and 1500 hours.
(a) Slash mound litter FFM versus needle bed litter FFM.
(b) Needle bed litter FFM versus aerial FFM.
□ 1975 UTUP; ○ 1972 TP; △ 1967 TP.

Data and trend lines for relationships between needle bed FFM and individual environmental factors (T; H; soil moisture, S_{40}; duff FFM, D) derived from the UTUP and TP stands are compared in Figure 6. Whereas the relationships between litter FFM and T, H and S_{40} are more or less linear, a curvilinear model

Table 3. Mean differences between simultaneous aerial FFM (A) and litter FFM of needle beds (NB) and slash mounds (SM) within pine stands of different age and with different management. UTUP, unthinned and unpruned. TP, thinned and pruned.

Stand Management	FFM Comparison	Stand Origin	Mean Difference	sd	t	df	P
UTUP	NB-A	1975	2.07	± 1.77	5.72	23	<0.001
	SM-A		1.58	± 1.74	4.46	23	<0.001
TP	NB-A	1972	0.19	± 2.07	0.37	16	ns
	"	1967	1.20	± 1.92	3.06	23	<0.01
	"	Pooled	0.78	± 2.02	2.46	40	<0.01
	SM-A	1972	0.38	± 0.97	1.63	16	ns
	"	1967	1.06	± 1.74	2.97	23	0.01
	"	Pooled	0.46	± 1.62	1.81	40	ns

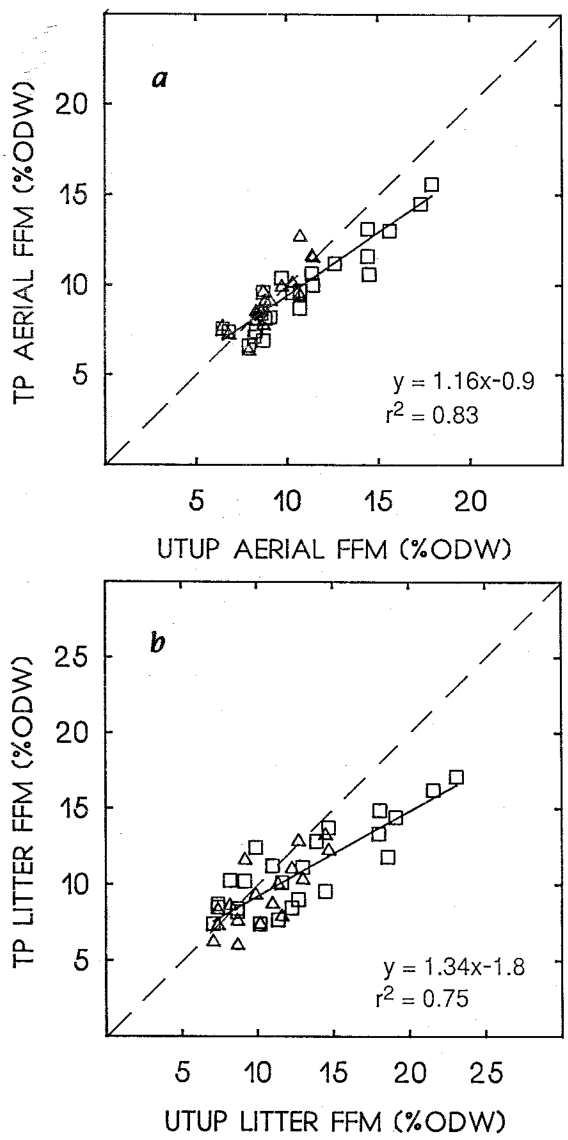

Figure 5. Comparison of mid afternoon (1400-1500 hours) FFM's between UTUP and TP *P. radiata* stands.
(a) aerial FFM; (b) litter FFM of needle beds.
□ 1975 UTUP versus 1967 TP; △ 1975 UTUP versus 1972 TP.

is more appropriate to the relationship between litter and duff FFM.

Considerable variation in the pooled data of the UTUP and TP pine stands arises from the tendency for FFM of UTUP litter to exceed that of TP stands as FFM generally increased in relation to other variables (T, H, S_{40} and D). Similar trends were also found in the relationships between slash mound litter FFMs and environmental variables (not shown). Pooled data for the relationships between aerial FFM and T or H, however, were less variable than pooled data for surface litter FFMs.

Regression analyses performed on data relating aerial FFMs to T, H, and the combination of T and H showed coefficients and constants to vary with stand management and that the relationships for the UTUP stand were the most precise (Table 6). T and H in combination accounted for appreciably more of the variation in aerial FFM than either factor alone in TP stands; and, much more than did T alone in the UTUP stand. However, H alone explained 84% (almost as much as did T and H combined) in the UTUP stand.

The test for parallelism, examining the effects of thinning and pruning on the relationship between aerial FFM and T and H (individually), showed that the regressions derived from UTUP and TP stands had similar slopes but significantly different intercepts (for

Table 4. Mean differences between FFMs of unthinned-unpruned (UTUP) and thinned-pruned (TP) pine plantations in the mid afternoon (1400-1500 hrs).

Fuel location	TP FFM Range (% ODW)	Mean Difference UTUP-TP (% ODW)	sd	t	df	P
Aerial	5-10	0.344	±0.897	1.994	26	ns
	5-20	0.643	±0.123	3.390	41	0.001
Needle bed litter	5-10	1.498	±1.927	3.477	19	<0.001
	5-27	1.791	±2.493	4.657	41	<0.001
Slash mound litter	5-10	1.159	±1.465	3.792	22	<0.01
	5-27	1.262	±2.715	3.013	41	<0.001

Table 5. Correlation between environmental variables and FFM at different locations in unthinned-unpruned (UTUP) and thinned-pruned (TP) *P. radiata* stands at Stromlo Forest. T, air temperature and H, relative humidity at 1.5 m; D, duff moisture (% ODW); S5, moisture (% ODW) in the top 5 cm of soil; S40, available moisture in the top 40 cm of soil (% of volume). Significance of r; ***, P < 0.001; **, P < 0.01; *, P < 0.05.

	Correlation Coefficients, r, for FFM							
	Needle bed Litter		Slashmound Litter		Aerial (Canopy)		n	
Variable	UTUP	TP	UTUP	TP	UTUP	TP	UTUP	TP
T	-0.78***	-0.68***	-0.69***	-0.68***	-0.82***	-0.73***	25	41
H	0.88***	0.57***	0.87***	0.72***	0.92***	0.79***	25	41
D	0.82***	0.79***	0.73***	0.88***	-	-	25	41
S5	0.83***	0.37*	0.83***	0.58**	-	-	16	32
S40	0.91***	0.45**	0.89***	0.41**	-	-	25	41

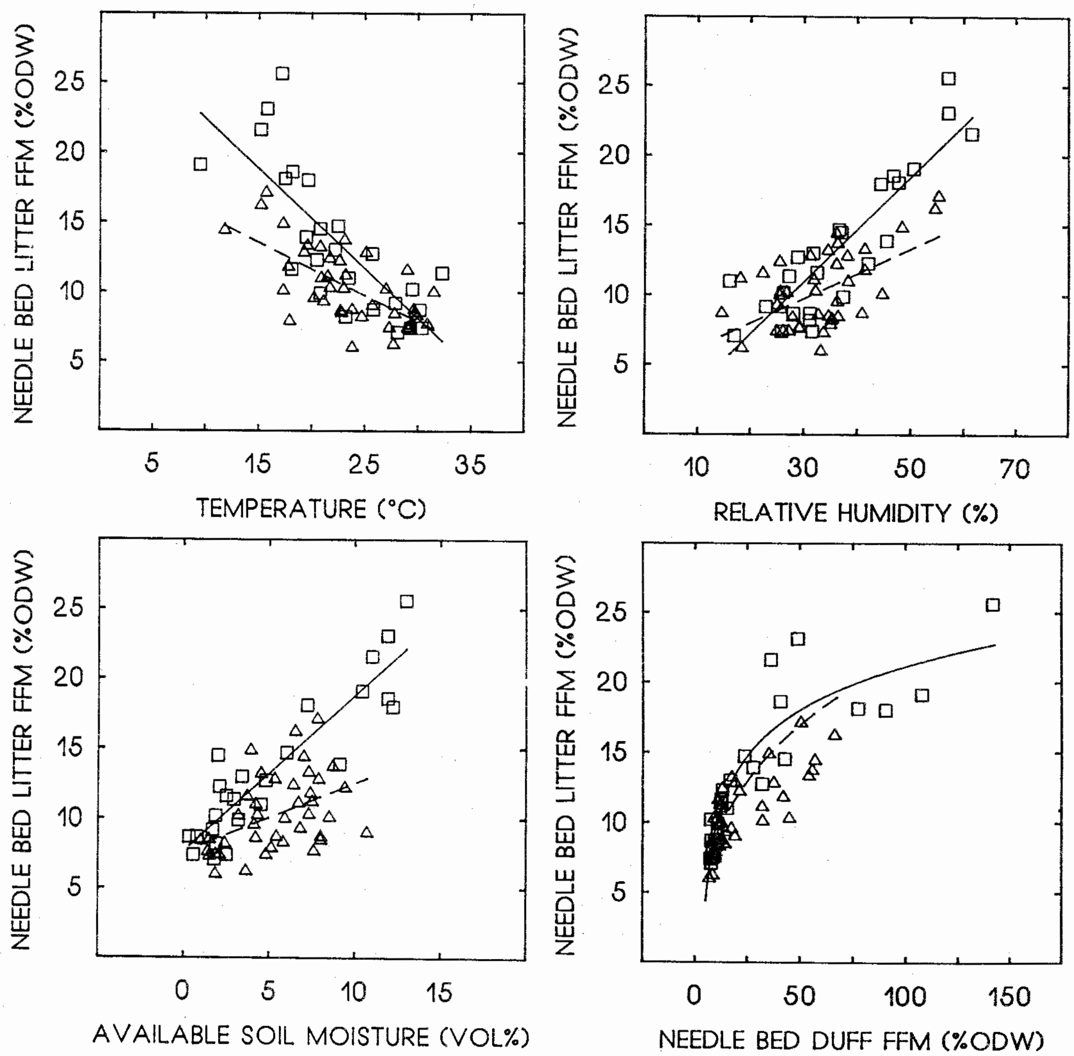

Figure 6. Relationships between needle bed litter FFM and environmental variables in UTUP and TP *P. radiata* stands. Linear regressions of litter FFM on T and H are given in Table 7.
Regressions of litter FFM, m, on available soil water, S40 were:

UTUP $m = 9.51 + 0.12\ S_{40}$; $r^2 = 0.66$.
TP $m = 7.59 + 0.13\ S_{40}$; $r^2 = 0.60$.

Regression of litter FFM, m, on duff FFM, D were:

UTUP $m = 1.4 + 4.32\ l_n\ (D-3)$; $r^2 = 0.82$.
TP $m = -17.6 + 8.28\ l_n\ (D + 15)$; $r^2 = 0.71$.

□ ,—— UTUP; △, - - - T.P.

Table 6. Relationships of aerial FFM to T (°C) and H (%) at 1.5 m height in *P. radiata* plantations. Standard errors of regression coefficients are shown in parentheses. Symbols as for Table 5.

Stand Management	Regressions for FFM	n	R^2
	<u>T</u>		
UTUP	21.9 - 0.48T (1.6) (0.07)	25	0.66
TP	17.14 - 0.32T (1.16) (0.05)	41	0.52
	<u>H</u>		
UTUP	2.16 + 0.24H (0.83) (0.02)	25	0.84
TP	3.17 + 0.19H (0.82) (0.02)	41	0.61
	<u>T and H</u>		
UTUP	7.19 - 0.14T + 0.19H (2.75) (0.07) (0.03)	25	0.86
TP	9.48 - 0.13T + 0.19H (1.68) (0.05) (0.03)	41	0.72
Combined Data (UTUP + TP)	8.38 - 0.17T + 0.17H (1.5) (0.04) (0.02)	66	0.80

T, P< 0.01; for H, P<0.05); and, the regressions of aerial FFM on T and H combined had surfaces with the same slope parameters and significantly different intercepts (P <0.05). Thus, the relationships between aerial FFM and the combination of T and H differed little between the UTUP and TP stands. Although the multiple correlation coefficient was higher for UTUP than for the TP, an examination of the variation in data revealed that 90% of observed FFMs of the former compared to 100% of the latter were within 3% (ODW) of the values expected from regression. When data of the UTUP and TP stands were combined all observations were within 3% ODW of regression; 52% were within 1% ODW of expected values.

The results of analyses of relationships between needle bed litter FFM and stand environmental factors (T, H, S_5, S_{40} and D) were similar to those for aerial FFM insofar as environmental factors accounted for more of the variation in litter FFM of the UTUP stand than they did in the TP stands (Table 7). As there were fewer data for S_5 and correlations with litter FFM of the TP stands were relatively poor (Table 5), that particular soil moisture variable was not included in further analyses.

T and H, individually or in combination explained much less of the variation in litter FFM than they did for aerial FFM. There were also greater differences between the multiple correlation coefficients of regression relationships for the two types of stand management. Examination of the variation about regressions for the relationships between needle bed litter FFM and the combination of T and H revealed that only 80% of observations in the UTUP stand and 90% in TP stands were within 3% (ODW) of expected values.

The inclusion of a subsurface moisture variable, to varying extent, improved the precision of multiple regression relationships for litter FFM. The combination of S_{40} with T and H accounted for a further 10 percent of the variation of litter FFM in the UTUP stand, but only a further 4 percent in the TP stands. Inclusion of D in lieu of S_{40} accounted for a further 8 and 15 percent of the variation in litter FFM in the UTUP and TP stands, respectively. It was also notable that H combined with either S_{40} or D explained as much of the variation in UTUP litter FFM as did the combinations where T was also included; but only H and

Table 7. Relationships between FFM of needle bed litter and environmental variables. Standard errors of regression coefficients are given in parentheses. Symbols for variables as in Table 5 (n: UTUP, 25; TP, 41).

Management	Regression for FFM	R^2
	<u>T</u>	
UTUP	29.55 - 0.72T (2.77) (0.12)	0.59
TP	19.18 - 0.38T (1.57) (0.07)	0.45
	<u>H</u>	
UTUP	0.06 + 0.36H (1.55) (0.04)	0.78
TP	4.47 + 0.18H (1.37) (0.04)	0.31
	<u>T + H</u>	
UTUP	6.87 - 0.19T + 0.30H (5.35) (0.14) (0.06)	0.78
TP	14.32 - 0.29T + 0.09H (2.87) (0.08) (0.04)	0.49
	<u>T + H + S_{40}</u>	
UTUP	5.96 - 0.07T + 0.16H + 0.66S_{40} (4.05) (0.11) (0.06) (0.16)	0.88
TP	11.02 - 0.22T + 0.09H + 0.26S_{40} (3.20) (0.08) (0.04) (0.13)	0.53
	<u>T + H + D</u>	
UTUP	4.42 - 0.06T + 0.23H + 0.06D (4.29) (0.12) (0.05) (0.02)	0.86
TP	10.86 - 0.14T + 0.02H + 0.09D (2.57) (0.07) (0.04) (0.02)	0.64
	<u>H + S_{40}</u>	
UTUP	3.45 + 0.18H + 0.69S_{40} (1.36) (0.05) (0.15)	0.88
TP	2.82 + 0.16H + 0.41S_{40} (1.34) (0.04) (0.13)	0.44
	<u>H + D</u>	
UTUP	2.27 + 0.25H + 0.06D (1.30) (0.04) (0.01)	0.87
TP	6.51 + 0.04H + 0.11D (1.09) (0.04) (0.02)	0.61

D combined had such influence with respect to litter FFM in TP stands. Examination of the variation about regressions revealed that where T, H and D were combined, 92% and 98% of observed litter FFMs in the UTUP and the TP stands, respectively, were within 3% ODW of expected values.

Relationships between slash mound surface litter FFM and environmental factors (individually and in combination) showed trends similar to those between needle bed litter FFM and environmental factors and, hence, are not included here. Parameters of the regression relationships to varying extents, however, differed from those established for needle bed litter FFM.

The test for parallelism between the regressions relating needle bed litter FFM to the various combinations of environmental variables in the UTUP and TP stands, showed that both the slope parameters and the intercepts were significantly ($P < 0.05$) different in most cases . In the two exceptions to this rule (the regressions involving T, H and S_{40} and, H and S_{40}) only the intercepts were significantly different. Similar results (not shown) were obtained from the test for parallelism applied to regressions for litter FFM of slash mounds.

Variation in FFM of live green canopy

Seasonal changes in moisture content of green needles collected from unshaded canopy locations and the water-balance of topsoil in the thinned-pruned stand of *P. radiata* at Stromlo Forest, from spring 1988 through to autumn 1990, are summarized in Figure 7.

At early stages of their growth in spring, young needles had very high moisture contents (ca. 200% ODW) compared to older needles (ca. 125% ODW). A decline in moisture content of needles as they aged is most obvious and rapid in their first year of life. In later years the decline is more gradual and masked by perturbations of varying magnitude (caused by other factors) particularly in shaded needles.

Variations in moisture content of most generations of needles, in both shaded and unshaded canopy, were to some extent synchronous with changes in the predicted water balance of topsoils (Figure 7). However, there was no correlation between LFMC of mature needles and the estimated deficit of water in topsoils.

On all occasions that green foliage was sampled, except one, shaded needles had higher moisture contents than the needles of unshaded canopy across all age cohorts. In old needles the difference ranged up to 25% ODW. On the one occasion that the reverse occurred (late Spring 1988; Figure 17) sampling of foliage was preceded by about 10 days of mostly wet weather.

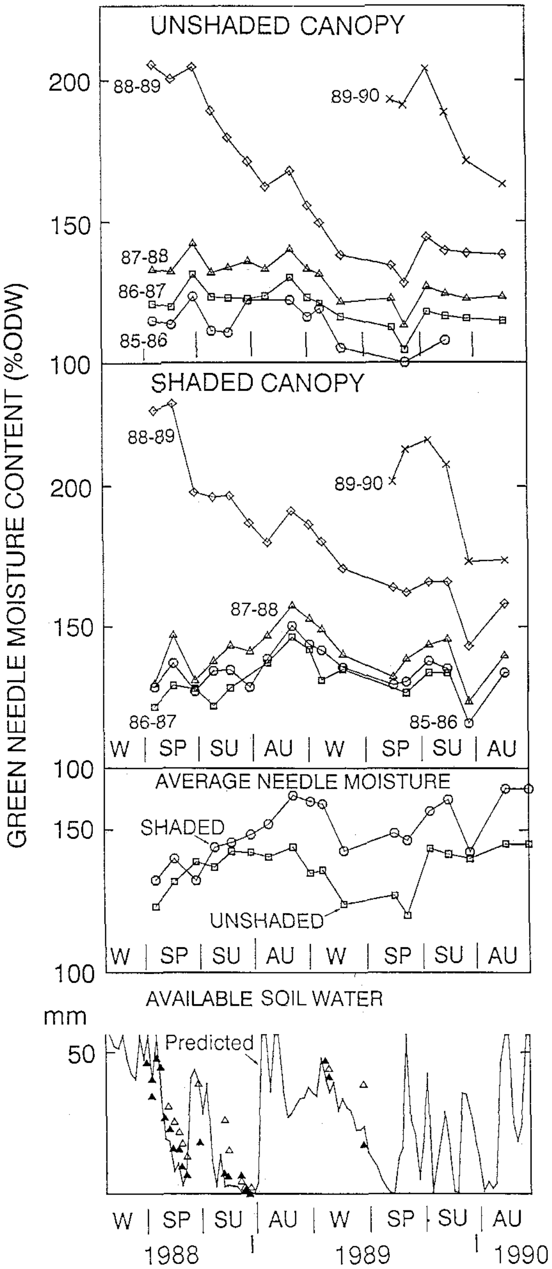

Figure 7. Seasonal changes in the moisture content (LFMC) of different aged cohorts and the average moisture content of green needles from shaded and unshaded locations in *P. radiata* canopies shown in relation to the water balance of topsoils. Needle cohorts and their ages are identified by the growth season of their production e.g. '88-'89.
▲ observed soil moisture UTUP stand; △ observed soil moisture TP stand.

Discussion

This study began with concerns about (i) the differences between environmental conditions at a reference meteorological station and those of remote forest sites and (ii) variability of FFM within the forest that affects the application of model predictions of FFM based on simple data (e.g. T and H) recorded at the reference station. T and H have been shown to be highly self-correlated over considerable distances between stations in the open (Beer and Durré 1991) and this was essentially true for comparisons of T and H between the station in the open at Canberra airport and sites in the Stromlo pine plantations 15 km away. However, whereas T values were very highly correlated and had a relationship close to 1:1, H values were more variable about the 1:1 relationship. Compared to the ambient conditions in an instrument shelter over grass at the airport, the microclimate at the same height in the forest is influenced by a large vertical spread of sources and sinks for water vapour and complex canopy transport processes (Denmead 1984) that may account for the apparently less predictable behaviour of forest H.

The results of the novel but relatively simple *ex situ* comparisons of FFM showed that the differences in moisture content of common pine and eucalypt fine fuels influenced only by atmospheric T and H were relatively small; and that the diurnal ranges of variation of moisture content were quite limited compared to those of fine fuels in eucalypt forest litter influenced by dew and soil moisture (Viney and Hatton 1989).

Differences in the amplitudes of diurnal fluctuations of moisture content of the fuels, to varying extent, influenced the relationships between pine needle FFMs and the FFMs of the other fuel types (Figures 3b-d). Around dawn, when H was high and FFMs were at their peak, moisture contents of old pine needles were slightly higher than those of the other fuels (which all had similar moisture contents); but as H and FFMs declined over the rest of the day, moisture contents of both old and new pine needles were progressively reduced below FFMs of other fuels and remained at lower values through the afternoon and into the evening.

Although factors such as the size (thickness), shape and weathering of fuel particles may influence variation, the moisture contents of contrasting fuel types such as isobilateral eucalypt leaves, thin flat fragments of eucalypt bark and pine twigs showed more or less similar behaviour when each was compared to pine needles (Figure 3). Amongst the significant differences of moisture content between fuels, the smallest was between pine and eucalypt twigs. The relatively large mean difference in moisture content between the old and new needles may, perhaps, be related to differences in weathering and corresponding contrasts in water vapour exchange characteristics of the fuels (cf. Anderson 1990).

One notable outcome of the ex situ comparisons that may be of significance to FFM prediction is that in most cases the relationships between pine and eucalypt fuel moisture were linear and very highly correlated over the FFM range from 5 up to 15 or 20% ODW. This suggests that models designed for prediction of eucalypt FFM (e.g. McArthur 1962; 1967) might be easily calibrated for application to pine fuels (Sneeuwjagt and Peet 1985).

Although it has long been known that thinning and pruning treatments profoundly modify environmental conditions that may influence evaporation from forest understoreys (e.g. Geiger 1959), the scientific literature contains little or no information on the influence of such treatments on variation of moisture content of dead fuels in forests. However, one unpublished report based on limited observations of concurrent changes of T, H, and FFM over 24 hours in thinned and unthinned stands of *P. radiata* in northeastern Victoria (Woodman and Rawson 1982) showed that (apart from wide diurnal fluctuations of litter FFM) there were varying but substantial differences of FFM within and between stands, and that H and dead needle FFM were always higher in the UTUP stands. Generally, the results of the present study, based on mid afternoon measurements in UTUP and TP stands, were consistent with such observations.

Thinning and pruning reduce canopy cover and generally increase the exposure of fuels to drying influences (wind, insolation). Hence, FFMs of surface fuels in particular were mostly lower in the TP stands than in the UTUP stand; and, in each fuel location the upper range of FFMs in the TP stands was limited compared to that in the UTUP stand (Table 4; Figure 5). Because of the limited range of FFMs, the correlations between FFM and environmental factors (T, H, S_{40} and D) were consistently lower for the TP stands than for the UTUP stand (Table 5; Figure 6). A difference in the numbers of observations and the contrasting ranges of FFM also influenced the precision of regression relationships between FFM and environmental factors and must temper interpretation of the influence of management on FFM models. Despite lower values of R^2, the variation of FFM about regression in absolute terms (%ODW) was no greater (or sometimes less) in TP stands than in the UTUP stand.

As dead fuels in lower canopies were shaded and well ventilated, and because environmental conditions were measured at the fuel height, relationships between aerial FFM and the combination of T and H were the best obtained for on-site fuels (Table 6). Indeed, an aerial FFM model based on the combined (UTUP and TP) data is possibly the only one that has general portability between *P. radiata* stands.

Regression relationships between litter FFM and the atmospheric variables (T and H) were generally of lower precision than those for aerial FFM because the atmospheric variables were measured well above the level of the litter fuels and, because other factors also influence the dynamics of surface FFM. Thus, an appreciable improvement in the precision of relationships between litter FFM and environmental factors was obtained where a subsurface moisture variable (duff or soil moisture) was combined with atmospheric variables; but only in the UTUP stand did the precision of such relationships match that of the models for aerial FFM based on T and H. The evidence for a general substantial effect of subsurface moisture on litter FFM corroborates the findings of Hatton et al. (1988) and emphasises the need to incorporate a soil moisture factor into models if more accurate prediction of litter FFM is to be achieved.

Overall, the comparisons made within and between stands with contrasting management demonstrate a sometimes substantial range of variation in mid afternoon FFM in pine fuel arrays that has important implications for the use of empirical models, such as those of McArthur (1962,1967), to predict FFM from simple meteorological data (T and H). The results of the tests for parallelism, that identified a varying and significant influence of management on regression relationships between FFM and environmental factors, underline the site specificity of empirical models and indicate that calibration may be required to allow for differences of FFM related to site, fuel type, and fuel exposure. Considering the intrinsic variation in data of the relationships between litter FFM and the combination of T and H in the present study it is suggested that such models are useful as a guide to FFM but, even if calibrated to specific fuel locations, they are unlikely to be sufficiently precise in the critical lower end of the FFM range.

As fire behaviour models are particularly sensitive to error in low FFM (Trevitt 1991) and because fewer than 50% of observations were within 1% ODW of values expected from regression (regardless of the combination of environmental factors included in litter FFM relationships) it would appear that direct measurement, rather than prediction by empirical models, may be necessary to determine surface FFM with the accuracy appropriate to dry fuels and high fire danger weather conditions.

The green needle moisture data for *P. radiata* obtained from Stromlo Forest were the first depicting seasonal changes of LFMC in exotic pine plantations in Australia. In contrast to such paucity of local information, there is a considerable amount of data available for conifers in North America that shows LFMC to vary in relation to species, season and foliar age. Moisture contents of needles frequently reach lowest values in spring just prior to budbreak and flush of new foliage. Data of the present study (Figure 7) also suggest that shading (which would limit starch production) has a consistent influence on LFMC. The decrease in moisture content of *P. radiata* foliage with increase of needle age is analogous to changes that occur with aging of foliage in North American conifers (e.g. Chrosciewicz 1986). Seasonal patterns of change in LFMC were not well defined for *P. radiata* possibly because of the frequency of limited water supply, particularly in warm seasons. However, there is a discernible trend for moisture content of mature needles to decline to low values in spring and to recover in summer apparently independent of soil moisture; but, in shaded locations, an even lower value may be reached in late summer (Figure 7).

Conclusions

A knowledge of variation of FFM in forest fuel arrays is crucial to prediction of fire behaviour and fire danger rating. Future progress in modelling and prediction of FFM will, in large part, depend on better descriptions of the spacial and temporal variation of FFM influenced by fuel types and environmental conditions.

The results of the present study suggest that model predictions of FFM based on meteorological variables (T and H) are more accurate for aerial fuels than for surface litter. Litter FFM, which is much more variable than aerial FFM, may be predicted with similar accuracy to aerial FFM by models that incorporate both meteorological and soil moisture variables. However, litter FFM models, in particular, would have to be calibrated or modified for application to different fuel types and environments.

As fire behaviour models are most sensitive to error in low FFM, direct measurement, rather than prediction of FFM from models, may be necessary to obtain fuel moisture data of the required accuracy.

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