EMPIRICAL MODELS EVALUATED FOR PREDICTION OF FINE FUEL MOISTURE IN AUSTRALIAN *PINUS RADIATA* PLANTATIONS

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ABSTRACT

The performances of McArthur's models, that use screen temperature (T) and relative humidity (H) to predict the moisture contents of dead fine fuel (FFM) in eucalypt forest and grassland, were assessed when they were applied to (i) six common types of dead eucalypt and pine fine fuel exposed to atmospheric conditions in a meteorological screen and (ii) dead needle fuels in canopies and litter of *Pinus radiata* D.Don plantations.

In the screen, diurnal range of FFM in pine needles was wider and reached lower afternoon values than in other fuels. When H was within the domains applicable to model inputs, the moisture contents of both pine and eucalypt fuels were, to varying extents, under-predicted by McArthur's models. The predictions of the FFM model developed for control burning operations in eucalypt forest (the CBEF model) were most closely correlated with observed FFMs; but, to achieve the best possible accuracy, the CBEF model required calibration to the different fuel types.

Early afternoon moisture contents of dead needles in tree canopies (aerial FFM) and needlebed litter (litter FFM) of unthinned-unpruned (UTUP) and thinned-pruned (TP) pine plantations were (mostly) under-predicted by McArthur's models, the mean error varying with fuel location and stand management.

Where the domains for model inputs were observed, the diurnal performance of the CBEF model calibrated to aerial fuel of the UTUP pine plantation matched the performances of the AERIAL and SCREEN models specific to such fuels. All three models may be recommended for prediction of aerial FFM.

For prediction of litter FFM, the performance of the CBEF model calibrated to needlebed litter was comparable to that of a pine litter FFM model that included a soil moisture factor. Where T and H only are available as inputs, the use of the calibrated CBEF model is recomended for the most accurate prediction of litter FFM in UTUP plantations.

Prediction of FFM was generally more accurate for aerial fuel than for litter fuel. No model at present is capable of the accuracy of FFM prediction required for forecasting fire behaviour when FFM is low. A technique for rapid measurement of FFM is needed for such times.

Keywords: fine fuel moisture; fuel moisture modelling; moisture prediction; *Pinus radiata*.

INTRODUCTION

Chandler *et al.* (1983) noted that "Fuel moisture relationships are quite complex and the history of attempts to accurately predict the moisture contents of forest fuels ...[created]... an endless series of beautiful theories demolished by ugly facts". Accurate prediction of the moisture content of dead fine fuels (FFM) is required for most fire behaviour models and fire danger rating systems. The precision of FFM prediction is most critical when fuels are relatively dry (<7% of oven dry weight (ODW)) because, at such times, quite small errors in FFM introduce considerable uncertainty into estimates of the rate of fire spread (Trevitt 1991).

In Australia, FFM is predicted using simple empirical models developed for eucalypt litter (e.g., McArthur 1962, 1967; Sneeuwjagt & Peet 1985) and grass fuels (e.g., McArthur 1960, 1966, 1977; Noble *et al.* 1980) that require only air temperature (T) and relative humidity (H), measured at 1.5 m height, as inputs; but user confidence in such models has been limited by the intriguing absence or unavailability of the data from which they were derived, and by the fact that little has been published on model validation. Hence, the results of a recent comparison made of the predictive capabilities of existing FFM models applied to eucalypt fuels (Viney & Hatton 1989) in which McArthur's models outperformed more sophisticated North American models such as the BEHAVE model (Rothermel *et al.* 1986; Andrews 1986) and the Fine Fuel Moisture Code of Van Wagner (1977) and Van Wagner & Pickett (1985) were very encouraging for users of the simpler Australian models. However, the same study showed that the accuracy of model predictions varied in relation to fuel type (i.e., twig, leaf, or bark) and time of day. Pook & Gill (1993) also found wide contemporaneous variation of FFM (i) between several common types of pine and eucalypt fuel exposed to the same environmental conditions and (ii) between pine fuels in different locations, that may militate against the general application of empirical models, such as those of McArthur; but the need to calibrate the models to different fuels or environments has seldom been recognised.

As yet, there are no published data verifying the application of the available Australian FFM models to fuels of fire-prone *Pinus radiata* plantations that comprise a highly valuable component (c. 0.5 million ha) of the forest resource in the southern states of Australia (Booth 1984). However, a recent investigation of variation of FFM, focused mainly on fuels of *P. radiata* plantations (Pook & Gill 1993), yielded data highly suited to the testing of McArthur's and similar models. Some potentially useful pine FFM models were also devised by Pook & Gill (1993) for specific pine fuel locations.

In this study, an assessment was made of the capabilities of McArthur's (1962, 1966, 1967, 1977) models for prediction of FFM in a range of fuel types and fuel locations. Independent tests were also carried out, comparing the performances of McArthur's 1962 model (calibrated to pine needle fuel) and those of pine FFM models (after Pook & Gill 1993), in order to identify the model(s) best suited to prediction of fuel moisture in unthinned-unpruned *P. radiata* plantations.

METHODS

Acquisition of FFM and Environmental Data

Measurements of FFM and environmental conditions were carried out during warm periods from spring 1988 to autumn 1992 (inclusive) (Table 1). Data obtained from

P. radiata plantations at Stromlo Forest in the Australian Capital Territory during 1988–89, and from an *ex situ* study of fuels in a meteorological screen during 1989–90, provided the basis for a description of variation of FFM (Pook & Gill 1993) and the derivation of empirical pine FFM models. All such data were suitable for the testing of McArthur's FFM models. Diurnal weather observations and measurements of FFM made during summer-autumn 1990–91 and 1991–92 provided independent data to test the performances of McArthur's 1962 model calibrated to pine fuels and the pine FFM models.

TABLE 1–Schedule of measurements.

Seasons	Observation time (AEST)*	Location†	Fuel type and exposure	Data‡
1988–89 Spring, summer, autumn (Sept–Feb)	1400–1500	UTUP and TP pine stands, Stromlo Forest	"Old" dead needles from canopy (*aerial* fuel) and "new", recently downed, dead needles from surface litter (*litter* fuel)	T and H at 1.5 m height; SM; FFM.
1989–90 Spring, summer (Sept–Feb)	Diurnal; 0600–2400 3-hourly intervals	Stevenson's screen, Black Mountain, Canberra	"Old" and "new" pine needles; pine twigs; eucalypt leaves, twigs, and bark suspended in terylene bags	Screen T and H; FFM.
1990–91, 1991–92 Summer, autumn (Jan–Apr)	Diurnal; 0600–2400 3-hourly intervals	UTUP pine stand, Stromlo Forest	Dead needles, *aerial* and *litter* fuel	T and H at 1.5 m height; SM; FFM.

* AEST = Australian Eastern Standard Time
† UTUP = unthinned and unpruned; TP = thinned and pruned
‡ T = air temperature and H = relative humidity;
SM = available moisture in topsoil (%vol);
FFM = moisture content of fine fuel (% ODW)

Ex situ Study of Pine and Eucalypt FFM

Differences between models and between fuels influence the accuracy of FFM predictions. McArthur's models differ in mathematical form and fuel application, but all require the same inputs of screen T and H. Hence, a comparison made between model predictions based on screen T and H and the moisture contents of fine fuels exposed to the atmosphere in a screen environment provided a convenient method for evaluation of model performances.

Samples of fine fuel (fuel particles <6 mm thick) suspended in terylene bags were continuously exposed to the atmosphere in a large Stevenson's screen (instrument shelter) outside the laboratory at Black Mountain, Canberra. During suitable weather periods the fuel samples were weighed and screen T and H were recorded at intervals between dawn and midnight to explore the range of FFM related to diurnal changes of atmospheric conditions. After screen exposure, the fuel samples were dried in a forced-draught oven at 95°C for 24 hours, equilibrated in desiccators, and then weighed to determine oven dry weight. The mean moisture content (% ODW) of each fuel type was then calculated for each observation made in the screen.

Initially, the behaviour of five samples each of two types of dead pine needle fuel only was monitored from September to December (inclusive) 1990. However, as McArthur's models were originally designed for eucalypt fuels and the diurnal sorption behaviour of pine fuels relative to eucalypt fuels was not well known, five samples each of the same two types of pine needles plus pine twigs and three types of eucalypt fine fuel were exposed in the screen during January and February 1990.

The two types of pine needles studied were (a) old, well-weathered, dead needles that had persisted *in situ* for several years in tree canopies (aerial fuel), and (b) recently downed and lightly weathered needles from the surface of the needlebed (litter fuel) in an unthinned-unpruned (UTUP) pine stand. The average thickness of the pine needles was 0.4 mm, but the old needles tended to be thinner and shorter than those from litter. The dead pine twigs (average thickness 3.6 mm) were obtained from weathered slash heaps in a thinned-pruned (TP) pine stand. The three types of eucalypt fuel used were leaves, twigs, and bark fragments (averaging 0.26, 2.2, and 1.5 mm thickness, respectively) of *Eucalyptus rossii* R.T.Bak. & H.G.Sm. from surface litter of a native dry sclerophyll forest on Black Mountain, Canberra. The rough-textured bark of the pine twigs contrasted with the smooth bark of eucalypt twigs. Sample sizes were similar within, but varied between, fuel types. Oven dry weights of pine needle and eucalypt leaf samples averaged c.18 g, those of eucalypt twig and bark samples averaged c.72 g, and those of pine twig samples averaged 62 g.

Most of the diurnal data for the pine needle fuels (Table 1) were obtained from measurements made at approximately 3-hourly intervals on 14 days. Additional data were also obtained from measurements made at 1400 to 1500 hours on 10 other days. Diurnal data for leaf, twig, and bark fuels (Table 1) were based on measurements made at 3-hourly intervals on 8 days.

Study of FFM in Pine Plantations

Descriptions of the pine plantation characteristics, study sites, and methods of data collection given by Pook & Gill (1993) are briefly summarised here. In 1988–89, environmental data and samples of dead needle fuel for determination of FFM were obtained between 1400 and 1500 hours Australian Eastern Standard Time (AEST) in three *P. radiata* stands (one UTUP and two TP) at Stromlo Forest, 15 km to the west of and at about 30–40 m higher elevation than Canberra Airport (571 m a.s.l.) in the Australian Capital Territory (Table 1). The stands were situated on slopes of north-easterly aspect with gradients of 3° to 6°. The UTUP stand was planted in 1975 and the TP stands were planted in 1967 and 1972.

No measurements were made within 24 hours after a significant rainfall. Three 40- to 50-g samples of dead needles for determinations of FFM were collected from (a) tree canopies at 1.5 to 2 m above ground (aerial fuel), and (b) the surface of needle beds (litter fuel) in the pine stands. The samples from each fuel location were bulked and sealed in a plastic bag. Air temperature (T) and relative humidity (H) at 1.5 m height were measured on-site with an Assmann psychrometer. The neutron depth gauge technique (I.A.E.A. 1970) was used to measure the available moisture (volume %) in the topsoil at 0–40 cm depth (mean of three profiles). The moisture contents of fuel samples were determined by standard laboratory weighing and oven-drying methods soon after collection.

During the summer-autumn periods of 1990–91 and 1991–92 similar measurements of environmental conditions and dead-needle fuel moisture were made in the UTUP stand at 3-

hourly intervals on 15 days, and at 1500 hours on 7 other days. Sampling of the TP stands was not attempted because fuels had been strongly disturbed by new thinning operations.

FFM Models

McArthur's models

McArthur's FFM models, devised for eucalypt litter fuels (McArthur 1962, 1967) and grassland fuels (McArthur 1966, 1977), were originally presented as graphs, tables, or slide rules. They have been given mathematical expression as follows (Table 2):

(1) The FFM model for control burning of litter fuels of eucalypt forest (the CBEF model) consisting of two graphs, one each for desorption (a.m.) and adsorption (p.m.) conditions, relating FFM to H at various isotherms (McArthur 1962) was mathematically formulated by Viney & Hatton (1989).

(2) The relationship between the FFM of standing dead grass and screen T and H presented by McArthur (1977) with the Mark 5 (linear slide rule) version of the Grassland Fire Danger Meter (the GFDM model) was formulated by Noble *et al.* (1980). The grass curing factor, C, may be set at 100% to apply the model to dead fine fuel.

(3) McArthur's tabular model for the relationship of FFM to T and H, devised for the Forest Fire Danger Meter (the FFDM model) (McArthur 1967), was analysed by Viney (1991). This model was intended to be a guide to FFM of eucalypt litter in the early afternoon at the height of summer.

TABLE 2–Algorithms for McArthur's models relating FFM to air temperature (T) and relative humidity (H) measured at screen height (1.5 m).

Model	Algorithm	Domains
CBEF (McArthur 1962)	Desorption (0600–1200) $FFM = 0.113H - 0.281T + 12.5$ Adsorption (1200 onwards) $FFM = 0.132H - 0.168T + 6.8$ (Viney & Hatton 1989)	T=10–32°C H=20–70% FFM=6–16% ODW
GFDM (McArthur 1977)	$FFM = \frac{(97.7 + 4.06H)}{(T - 6)} - 0.00854H + \frac{3000}{C} - 30$ (Noble *et al.* 1980)	T=10–43°C H=5–80%
FFDM (McArthur 1967)	$FFM = 5.658 + 0.04651H + \frac{(3.151 \times 10^{-4}H^{3})}{T} - 0.1854\,T^{0.77}$ (Viney 1991)	T=10–41°C H=5–70% FFM=3–19% ODW

Pine FFM models

Empirical FFM models for pine fuels were derived from the analyses of relationships between afternoon (1400–1500 hours AEST) pine needle FFM and environmental conditions measured in *P. radiata* plantations at Stromlo Forest during spring-summer-autumn 1988–89 (Pook & Gill 1993). The models relating pine FFM to atmospheric T and H measured at screen height (Pook & Gill 1993) were initially in the form of multiple regressions. However, subsequent analyses and comparisons revealed that linear relationships between pine FFM and the difference between T and H, (T – H), (Fig. 1a, b) provided alternative models of equal precision and, possibly, greater utility for field use. (T – H) appears as a variable in a

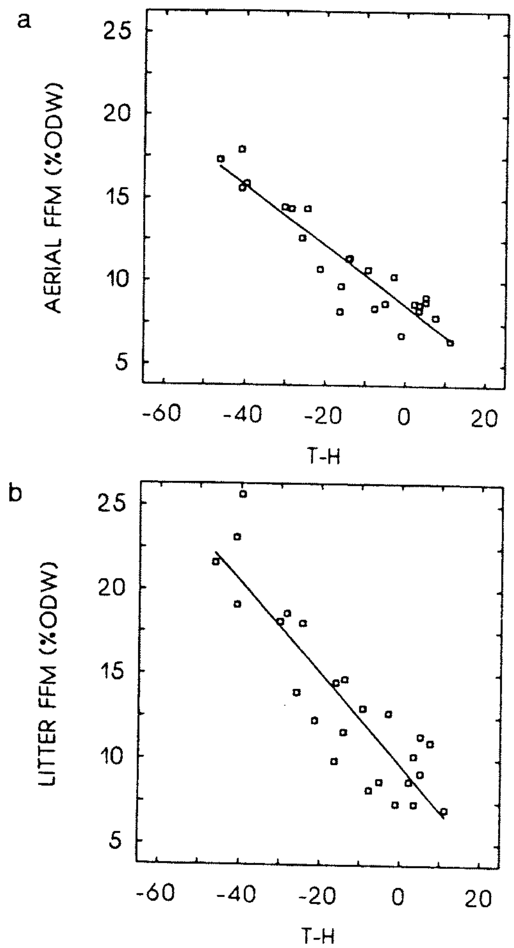

FIG. 1–The relationship of dead needle FFM to (T – H) for (a) aerial fuel and (b) litter fuel in UTUP *Pinus radiata* plantations. T and H were measured at 1.5 m height. Regression equations are included in Table 3.

simplified form of the equation for the forest fire danger index of the Mark 5 version of McArthur's (1967) forest fire danger meter (Noble *et al.* 1980). The FFM models for dead needle fuel in tree canopies (AERIAL; Fig. 1a) and for the surface litter of needle beds (LITTER1; Fig. 1b) in UTUP pine stands are listed in Table 3. The latter table also includes a similar model (SCREEN) for the relationship between FFM of old (aerial) pine needle fuel and (T – H) based on diurnal measurements made in the Stevenson's screen, and a multiple regression model (LITTER2) relating afternoon litter FFM to (T – H) and available moisture in topsoil (SM) in the UTUP pine plantation.

Statistical criteria, similar to those used by Viney & Hatton (1989), were employed to assess the predictive capabilities of the models. Mean error (rather than mean absolute error) and the root mean square error between prediction and observation were calculated. Where appropriate, predictions that were within 1%, 2%, and 3% (ODW) of observed FFMs were also collated.

TABLE 3–Models for the prediction of moisture content of dead pine needle fuels, FFM (% ODW), in UTUP and TP *P. radiata* plantations at Stromlo Forest—T (°C), H (%), SM (% vol), other abbreviations and symbols as for Table 1.

Model	Algorithm	Corrected R^2	Domains
AERIAL	FFM = 8.56 – 0.18 (T – H)	0.86	T 9–32; H 17–60; FFM 6–18.
SCREEN	FFM = 9.11 – 0.14 (T – H)	0.82	T 10–40; H 10–70. FFM 5–19.
LITTER1	FFM = 9.67 – 0.27 (T – H)	0.78	T 9–32; H 17–60; FFM 7–26.
LITTER2	FFM = 8.1 – 0.13(T – H) + 0.69SM	0.88	T 9–32; H 17–60; SM 0.3–14.0; FFM 7–26.

Calibrated CBEF Models

Evaluation of McArthur's models applied to pine plantation fuels suggested that the predictive capability of the CBEF model, in particular, might be improved by calibration. An appropriate calibration factor for the model applied to a particular fuel was inferred from the mean error between predicted and observed FFMs revealed by the assessments of model performance (using 1988–89 data) in which the domains for T and H inputs and FFM (Table 2) were strictly observed. In practice, the calibration factor is simply added to the predictions of the model. The calibration factors for the CBEF model applied to aerial fuel and litter fuel of the UTUP plantation were +3.0% and +4.7% (ODW), respectively.

RESULTS

Model Predictions Related to Different Fuel Types

Warm to hot weather conditions were experienced in Canberra during the first few days of January 1990. In the afternoon of 3 January, a day of extreme fire danger rating, screen T and H approached 40°C and 15%, respectively (Fig. 2a). The average moisture contents of the pine fuels and the eucalypt fuels, continuously exposed to the atmosphere in the Stevenson's screen, were highest at dawn (c. 17–18% ODW) and differed by less than 1% ODW during most mornings up to noon; but, as fuel moistures generally decreased during the afternoon, the pine fuels became drier than the eucalypt fuels by up to 2% ODW (Fig. 2b). Amongst all six types of fine fuel, the variation in moisture content was between 2 and 4% ODW between dawn and midnight. About dawn, when H was high, there was a wider range of moisture content amongst pine fuels (3.4% ODW) than amongst the eucalypt fuels (2.1% ODW). In the afternoon, at low H, the range of variation of FFM decreased and was only slightly greater in eucalypt fuels (1.5% ODW) than in pine fuels (1.2% ODW) (Table 4).

Fuel rankings, in terms of moisture content, changed between dawn and mid to late afternoon (Table 4). Amongst the eucalypt fuels, twigs had the lowest moisture contents at all times. However, around dawn, eucalypt bark moisture content was slightly higher than that of eucalypt leaves. The reverse was true at low H in the afternoon. Amongst pine fuels, dawn moisture contents were highest in old needles and lowest in twigs, but in the afternoon moisture content of twigs was the highest and that of new needles was the lowest. Amongst all six fuels, the highest dawn moisture contents were observed in old pine needles and the lowest afternoon moisture contents were found in the new pine needles. Comparisons based on the measurements made between 0800 and 2200 hours (AEST) also revealed that the mean difference in moisture content (% ODW) between the two types of pine needles (0.97,

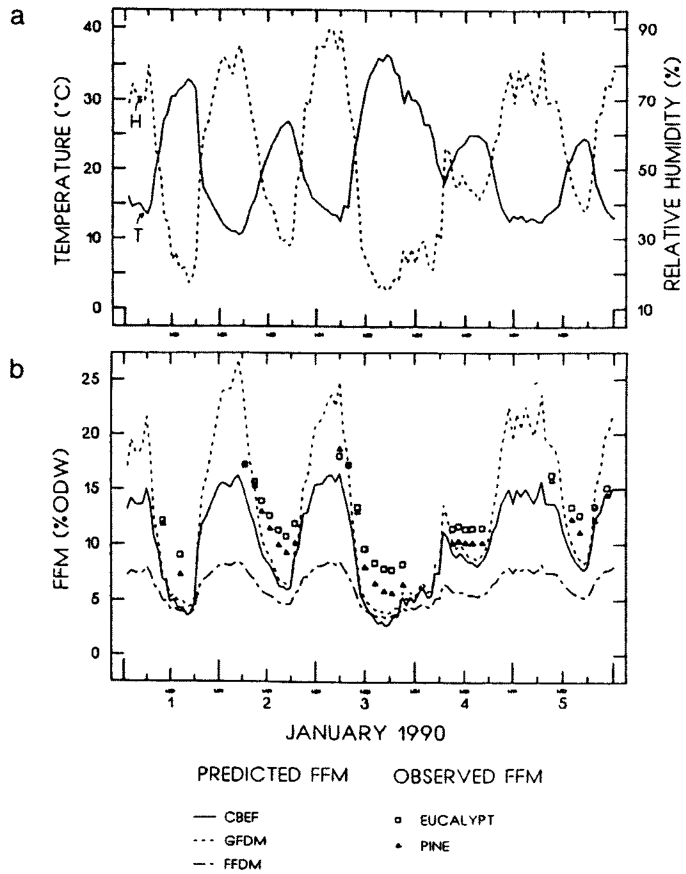

FIG. 2–(a) Hourly averages of screen T and H during the first 5 days of January 1990, at Black Mountain, Canberra; (b) CBEF, GFDM, and FFDM model predictions of FFM (based on average hourly screen T and H) compared to average moisture contents of pine and eucalypt fine fuels exposed to the atmosphere in a large Stevenson's screen over the same period. MD = midday; MN = midnight.

TABLE 4–Ranking of six types of fine fuel in relation to their moisture contents (% ODW) at 0600 hours (when screen T and H were 15.5°C and 85%, respectively), and at 1430 hours (when screen T and H were 38.9°C and 16.5%, respectively) on 3 January 1990.

Morning ranking 0600 hours		Afternoon ranking 1430 hours	
Fuel type	Moisture content (% ODW)	Fuel type	Moisture content (% ODW)
Old pine needles	20.5	Eucalypt leaves	8.5
Eucalypt bark	18.8	Eucalypt bark	8.1
Eucalypt leaves	18.7	Eucalypt twigs	7.0
New pine needles	18.4	Pine twigs	6.5
Pine twigs	17.1	Old pine needles	5.7
Eucalypt twigs	16.7	New pine needles	5.3

s.e. 0.09), was greater than the mean difference between eucalypt twigs and pine twigs (0.52, s.e. 0.08), or between eucalypt leaves and eucalypt bark fragments (0.35, s.e. 0.12).

There were appreciable differences between the predictions of FFM based on hourly averages of screen T and H obtained from the three McArthur models (Fig. 2b). The largest variation between model predictions of FFM within the 5-day period occurred in the (predominantly) night-time intervals between 2000 hours and 0800 hours when values of H were outside the domain applicable to model inputs (Table 2). The GFDM model grossly over-predicted FFM measured at such times. When input conditions were more appropriate to model application (i.e., between 0800 and 2200 hours), all three models under-predicted observed moisture contents of the fuels. The patterns of CBEF and GFDM model predictions, that were generally in harmony with changes in FFM observed during daytime, contrasted with the conservative pattern of FFDM prediction. The minimum variation between model predictions corresponded to relatively high T, low H, and the lowest observed FFMs in the afternoon. It is significant and, perhaps, paradoxical that at such times the range of variation of observed FFMs amongst fuel types was two to three times the range of variation amongst model predictions.

Trends in diurnal performances of the models between 0800 and 2200 hours (Fig. 2b) when domains for model inputs, in particular, were observed are quantified and contrasted in Table 5. The mean errors in predictions of the CBEF and GFDM models are similar for individual fuel types. Wide variation of the mean error in prediction between fuel types is notable.

TABLE 5–Diurnal performance of McArthur's FFM models between 0800 and 2200 hours AEST applied to fine fuels continuously exposed to atmospheric conditions in a large Stevenson's screen.

Statistics	Models		
	CBEF	GFDM	FFDM
(a) Mean error, predicted minus observed FFM (% ODW)			
Eucalypt leaves	-4.12	-4.16	-7.22
Eucalypt bark	-4.74	-4.78	-7.85
Eucalypt twigs	-2.84	-2.90	-5.95
Pine twigs	-3.39	-3.42	-6.49
Old pine needles	-2.80	-2.83	-5.90
New pine needles	-1.81	-1.85	-4.91
(b) Root mean square error (% ODW)			
Eucalypt leaves	1.53	1.61	1.29
Eucalypt bark	1.49	1.77	1.93
Eucalypt twigs	1.90	2.05	1.74
Pine twigs	1.85	2.10	1.96
Old pine needles	1.50	1.90	2.33
New pine needles	1.61	1.93	2.07

Parallelism of the pattern of CBEF model predictions and observed daytime FFMs suggests that calibration of that model to individual fuel types (or groups of fuels) may be achieved quite simply by inclusion of a correction factor that produces a systematic shift in FFM predictions. The appropriate correction factors are approximated by the mean errors between prediction and observation (e.g., Table 5). Such calibrations would, however, require testing using independent data. Systematic adjustments of the CBEF predictions that simulated calibration of the model to the fuel types (paired for similar sorption behaviour) showed that on typical summer days with wide amplitudes of T and H (e.g., 1–3 January) the adjusted predictions tracked observed FFM closely between 0800 and 2100 hours. At other times (between 2100 and 0800 hours), when values of H were higher than specified for application of the model (i.e., >70%) (Table 2), the moisture contents of eucalypt fuels and pine twigs were over-predicted and those of new pine needles were under-predicted. Further to this, the simulated calibrations revealed a significant lapse in model performance associated with (apparently) unusual trends in T and H that followed the extreme fire danger weather conditions of 3 January. Relatively high T and low H persisted overnight into the early hours of the morning of 4 January (Fig. 2a). By 0600 hours T had declined to c. 20°C but H had risen to only 30%. The average moisture content of the fuels increased by only 4% ODW overnight and then responded little to the delayed (but sharp) rise of H to 56% in the morning and its decline to 40% during the day. Influenced by the "peculiar" behaviour of T and H, the "calibrated" CBEF model, to varying extent, over-predicted the more or less constant daytime FFMs on 4 January (Fig. 3).

The relationships between predicted and observed FFMs for the old pine needles, based on diurnal measurements made during spring-summer 1989–90 (Fig. 4), were typical of the performances of McArthur's models applied to the screen-exposed fine fuels when T and H were within specified domains for inputs to the (uncalibrated) CBEF and FFDM models. The performances of the CBEF and GFDM models were similar in their systematic under-prediction of FFM, but predictions of the latter model tended to be more variable than those of the former at the upper end of the FFM range. The FFDM model, by contrast, was less sensitive to changes in environmental conditions and its conservative predictions had little overlap with those of the other two models.

Model Prediction in Relation to Fuel Location in Pine Plantations

For prediction of afternoon FFMs of dead needle fuels in pine plantations, the relative performances of McArthur's models were generally similar to those obtained for the screen-exposed fuels (Fig. 5). Again, all three models tended to under-predict FFM of pine needles to greater or lesser extent depending on fuel location (canopy or needlebed surface) or stand management (UTUP or TP) (Table 6). Thus, the mean errors of FFM prediction were larger for surface litter of needlebeds than for well-ventilated aerial fuel of the canopy, and they were larger for UTUP than for TP stands. For both aerial and litter FFM, more of GFDM than CBEF model predictions fell within specified ranges of error between prediction and observation (1% and 3% ODW) but, as indicated by root mean square errors, the overall variation in GFDM compared to CBEF predictions was greater for aerial FFM and slightly less for litter FFM.

Independent Tests of Pine FFM Models and the Calibrated CBEF Model for UTUP Plantations

Comparisons between the performances of the pine FFM models and calibrated CBEF models, tested using the independent data acquired in the UTUP plantation in 1990–91 and 1991–92, showed that the predictive capabilities of models for aerial fuel were somewhat

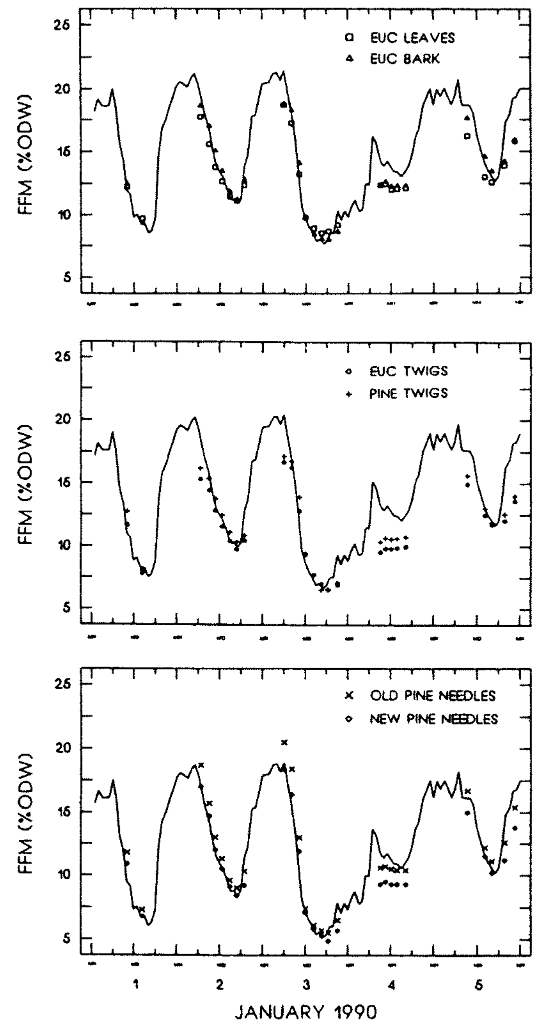

FIG. 3–The diurnal pattern of the adjusted CBEF model predictions of FFM compared to the moisture contents of fine fuels (paired for similar sorption behaviour) continuously exposed to the atmosphere in a Stevenson's screen during the first 5 days of January 1990. Adjustments of CBEF predictions of FFM: eucalypt leaves and bark, +5%; twigs, +4%; pine needles, +2.5%. MD = midday; MN = midnight.

better than those for litter (Fig. 6, Table 7). The AERIAL model performed well when applied diurnally (0500–2200 hours) to aerial fuels of the UTUP pine stand under summer conditions with T ranging from 10° to 37°C and H ranging from 14% to 98% (Fig. 6a). Similar performances were obtained from the SCREEN model (Fig. 6b) and the CBEF model calibrated to 1988–89 afternoon aerial FFM of the UTUP stand (Fig. 6c), except that both showed greater bias towards under-prediction of FFM when H exceeded 70% (i.e., between 2200 and 0800 hours). When H was less than 70%, the SCREEN model had the best overall diurnal performance with 52% of predictions being within 1% (ODW) of observed values of FFM (Table 7).

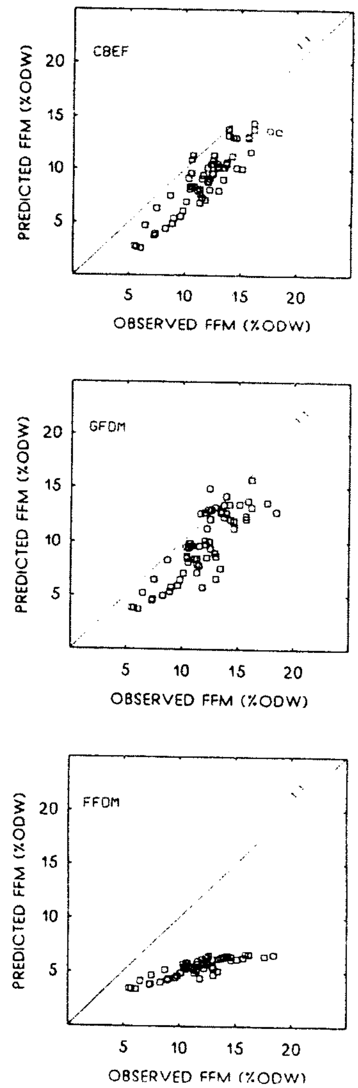

FIG. 4–CBEF, GFDM, and FFDM model predictions of FFM compared to the observed moisture contents of weathered pine needles continuously exposed to the atmosphere in a Stevenson's screen during spring and summer 1989–90.

For litter FFM, predictions of the LITTER1 model, based on (T – H), were strongly skewed towards over-prediction of FFM as H increased (Fig. 6d). Only afternoon and early evening FFMs were reasonably well approximated. By contrast, the predictions of FFM from (T – H) and available topsoil moisture, SM, by the LITTER2 model showed little bias (Fig. 6e, Table 7). The CBEF model, calibrated to 1988–89 litter FFM of the UTUP stand, over-predicted diurnal litter FFMs (on average) by about 1% ODW when it was applied to the same fuel during the 1991 and 1992 summers (Fig. 6f). Its performance was, nevertheless, comparable to that of the LITTER2 model.

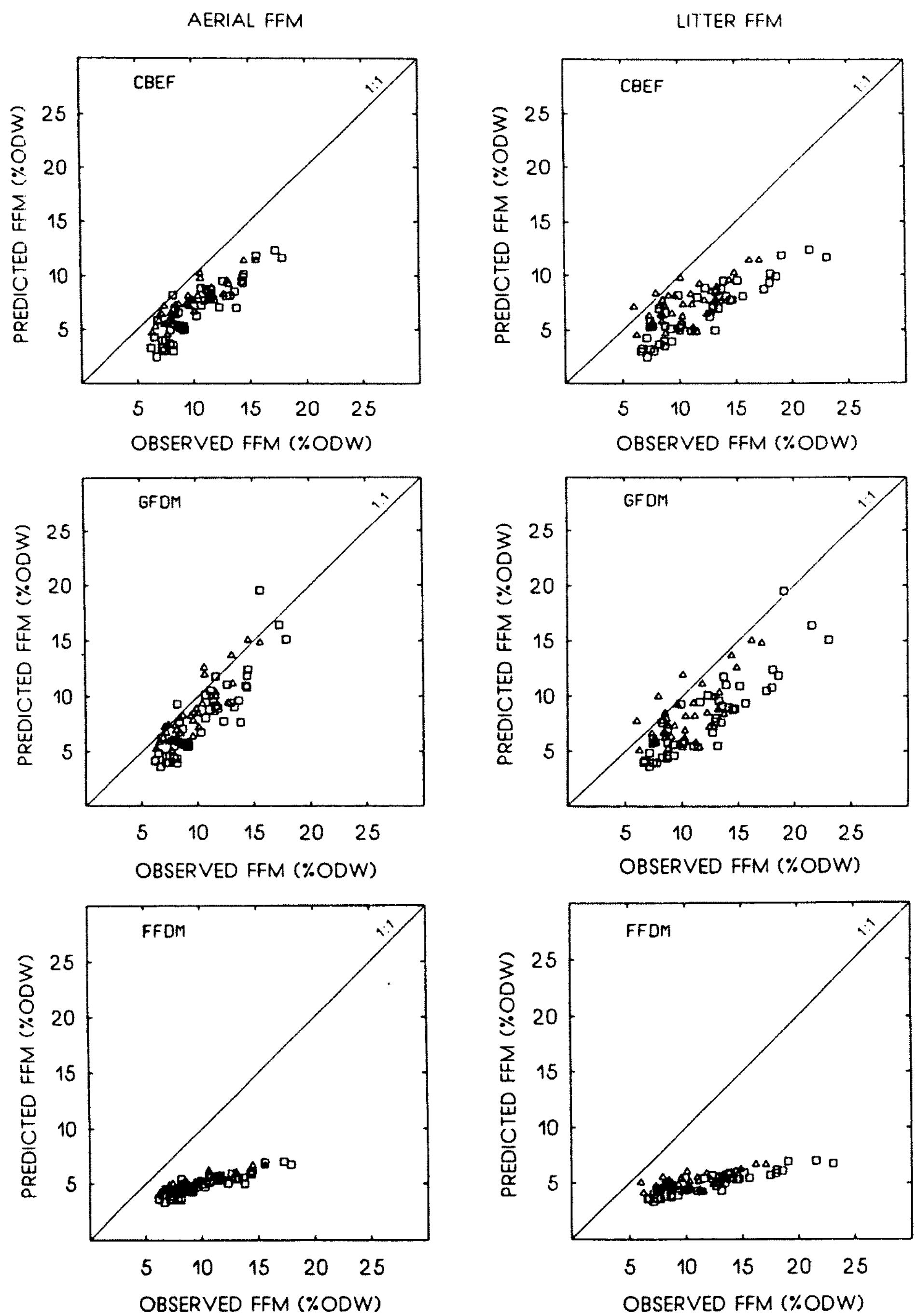

FIG. 5–Afternoon (1400–1500 hours AEST) predictions of FFM by the CBEF, GFDM, and FFDM models compared to observed moisture contents of dead aerial and litter pine needle fuels in UTUP (□) and TP (Δ) *P. radiata* plantations.

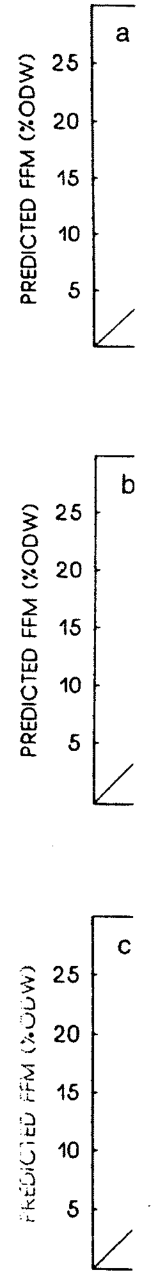

FIG. 6–Con
appl
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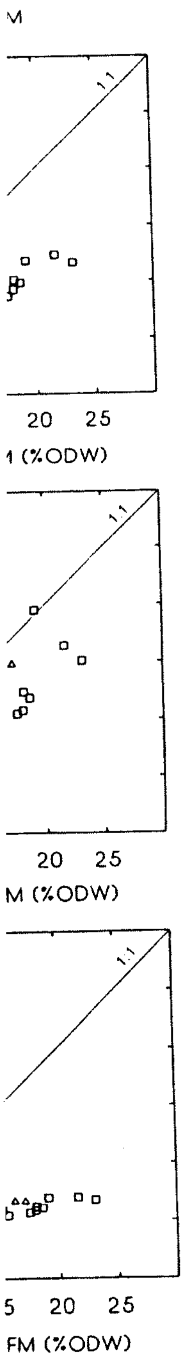

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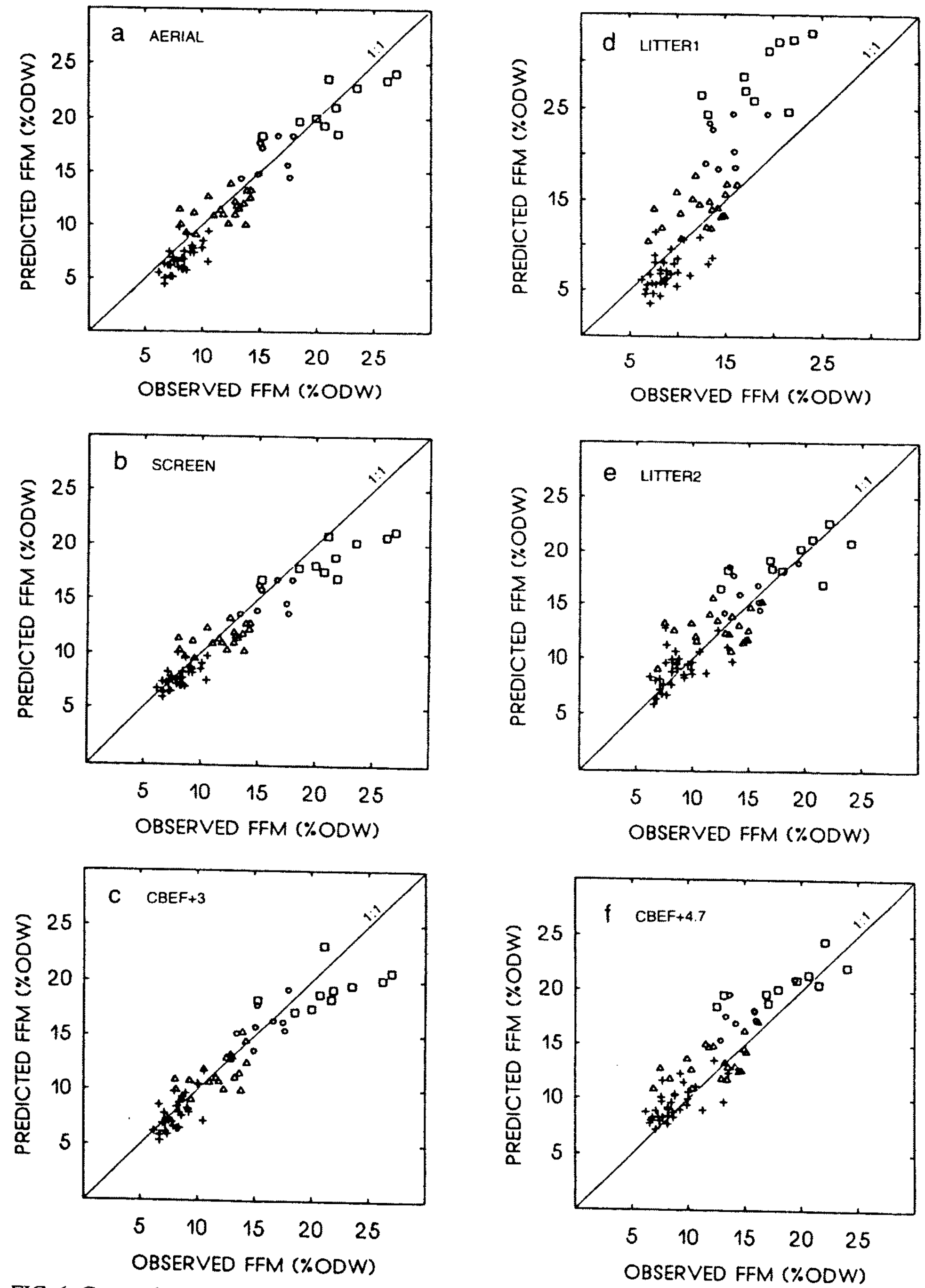

FIG. 6–Comparison of the diurnal performances of pine FFM models and the calibrated CBEF model applied to dead aerial (a–c) and litter (d–f) needle fuels of the UTUP *P. radiata* plantation in the summers of 1990–91 and 1991–92. Relative humidity at the time of observations: + = >10–30%; Δ = >30–50%; O = >50–70%; □ = >70–100%.

TABLE 6–Performances of McArthur's FFM models applied to dead needle fuels with different exposures in UTUP and TP *P. radiata* plantations in the mid-afternoon (1400–1500 hours AEST); abbreviations as for Table 1.

Statistics		Models		
		CBEF	GFDM	FFDM
(a) Mean error, predicted minus observed FFM (% ODW)				
Aerial FFM	UTUP	–3.71	–2.49	–5.54
	TP	–2.28	–1.34	–4.41
Litter FFM	UTUP	–5.25	–4.03	–7.09
	TP	–3.06	–2.12	–5.20
(b) Root mean square error (% ODW)				
Aerial FFM	UTUP	1.30	1.66	2.18
	TP	1.10	1.27	1.62
Litter FFM	UTUP	2.26	2.01	3.38
	TP	1.99	1.97	2.29
(c) Percentage of predictions within 1% of observed ODW				
Aerial FFM	UTUP	4	13	0
	TP	12	27	0
Litter FFM	UTUP	7	7	0
	TP	12	17	2
(d) Percentage of predictions within 3% of observed ODW				
Aerial FFM	UTUP	24	56	9
	TP	71	88	15
Litter FFM	UTUP	10	33	2
	TP	56	73	10

TABLE 7–Comparison of the diurnal performances of pine FFM models and the calibrated CBEF model applied to aerial and litter dead needle fuels in an UTUP *P. radiata* plantation. Domains for model application are given in Table 2 (CBEF) and Table 3 (pine FFM models); n=60.

Statistics	Aerial FFM models		
	AERIAL	SCREEN	CBEF+3
Mean error, predicted minus observed FFM (% ODW)	–0.87	0.51	–0.30
Root mean square error (% ODW)	1.57	1.37	1.41
Percentage of predictions—			
within 1% of ODW	32	52	47
within 2% of ODW	72	87	87
within 3% of ODW	93	95	97
	Litter FFM models		
	LITTER1	LITTER2	CBEF+4.7
Mean error, predicted minus observed FFM (% ODW)	0.40	0.41	1.10
Root mean square error (% ODW)	3.58	2.16	1.90
Percentage of predictions—			
within 1% of ODW	22	35	33
within 2% of ODW	47	67	62
within 3% of ODW	62	80	85

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DISCUSSION

Variation of FFM Related to Fuel Type and Exposure

As surface fuels are influenced to varying extents by radiative heating and cooling, reduced wind activity, and subsurface moisture, T and H of the litter environment may differ appreciably from air T and H at screen height (1.5 m) in plantations. Such differences will influence the predictive performance of empirical models based on relationships between litter FFM and air T and H measured at screen height. In view of this, the observations made of the moisture contents of screen-exposed fuels, influenced only by T and H, provide a criterion of FFM behaviour for such fuels exposed in other environments. For example, the afternoon moisture contents of the three types of eucalypt fuel exposed in the screen during the present study were of comparable range to those found for the same fuels in litter of dry sclerophyll forest (Hatton & Viney 1991). However, ranking of the fuels according to moisture content differs between the screen and the forest. For screen exposure the 5-day average of afternoon moisture contents of twigs (9.7% ODW) was *lower* than that of both leaves (11.0% ODW) and bark (11.3% ODW), whereas in forest litter the 4-day average of afternoon moisture contents of twigs (8% ODW) was *higher* than that of both leaves (6% ODW) and bark (5% ODW). As the litter fuels of dry sclerophyll forest were insolated (Viney & Hatton 1989), flat leaves and bark fragments that had high surface area to volume ratios were presumably heated to higher temperatures and dried out more than twigs that had relatively low surface area to volume ratios. The differences in moisture content found between the three fine eucalypt fuels exposed in the screen (Table 4, Fig. 3) and in forest litter (Viney & Hatton 1989) suggest that careful specification of fuel type and exposure is significant to FFM modelling.

Performances of McArthur's Models

Moisture contents of shaded well-ventilated fuels in the screen (Fig. 2 and 4, Table 5) and in canopies of pine plantations (aerial fuel) (Fig. 5, Table 6) were under-predicted by McArthur's models for surface litter fuels in eucalypt forest (CBEF, FFDM) or standing grass fuels (GFDM) exposed to varying levels of solar radiation. The predominantly shaded litter fuels of pine plantations were influenced, to varying extents, by subsurface moisture in duff and topsoil (Pook & Gill 1993). Thus, litter FFM was frequently higher than aerial FFM and the under-prediction of FFM by McArthur's models was, on average, of greater magnitude for litter than for aerial fuel.

The relatively low values for predictions of FFM consistently obtained from the FFDM model (Fig. 2, 4, 5) indicate that it was designed to fit a worst case scenario in forecasting fire behaviour. McArthur (1967) considered the tabulated moisture contents that form the basis of the FFDM model "to be typical of mid-summer conditions in a very dry fuel bed". However, when forest fire danger ratings were very high (1 Jan 1990) or extreme (3 Jan 1990), the predictions of mid-afternoon FFMs by the CBEF model were about the same as, or slightly lower than, those of the FFDM model (Fig. 2a). This suggests that the CBEF model may perform well under the hot dry summer conditions for which the FFDM model was designed, even though T and H may at times be outside applicable domains.

Overall, the comparisons of predicted FFMs and observed moisture contents of pine needles exposed in the screen (Fig. 3c and 4) and at various locations in pine plantations

(Fig. 5) suggest that, of the three McArthur models, the CBEF model (with calibration) has the best potential for diurnal prediction of *P. radiata* FFMs (Table 7). The GFDM and FFDM models may (if necessary) be calibrated to different fuel types and fuel locations to attain greater accuracy of FFM prediction. However, the GFDM model appears to be less reliable than the CBEF model when H increases above 50%, and the calibration of the FFDM model is more involved. The greater complexity of the model algorithms (Table 2) does not lead to a better prediction of FFM (Fig. 2b, 4, and 5).

Performances of Calibrated CBEF and Pine FFM Models

The CBEF model calibrated to aerial and litter fuels of UTUP pine plantations is able to match the performance of FFM models specific to those fuels (Fig. 6, Table 7). For aerial FFM, the performances of the AERIAL, SCREEN, and CBEF+3 models were similar and may be about the best that can be expected from such models because (significantly) T and H were measured at the same height as that of the fuel (1.5 m). Any one of the models may provide satisfactory predictions of aerial FFM in UTUP plantations.

For prediction of litter FFM, the performance of the LITTER1 model, derived from a relatively small set of afternoon observations made when H was limited in range (less than 60%) deteriorated when applied at other times of day (Fig. 6d). By comparison, the LITTER2 model, though also based on a limited set of afternoon observations, nevertheless had the best diurnal performance (Fig. 6e) and, thereby, indicated the important influence of subsurface moisture on litter FFM (cf. also the findings of Hatton *et al.* 1988). The fact that the volume of available moisture in topsoil (SM) may be readily determined by use of a neutron moisture depth gauge or (even more conveniently) by time domain reflectometry (e.g., Dalton *et al.* 1984) should add to the utility of the LITTER2 model.

Though it lacked a soil moisture factor, the predictive capabilities of the CBEF model calibrated to litter (CBEF+4.7), ironically, were similar to those of the LITTER2 model. This, most probably, reflects the derivation of the original CBEF model from a large and wide-ranging data set and the model's facility for adjustment to change of sorption conditions. Another factor that may also have favoured the performance of the calibrated model was the relatively low moisture status of the forest topsoil (mostly below 0.33 of storage capacity) that minimised the influence of SM on diurnal FFM. Testing of the calibrated CBEF model, therefore, needs to be extended to periods when topsoils are at higher moisture contents.

At this juncture it should be emphasised that the litter FFM models were applied to surface litter fuel of 5 to 10 mm depth and not to the full depth of the needlebeds (i.e., litter plus duff). Under local environmental conditions the needlebeds in *P. radiata* plantations at Stromlo Forest, regardless of management, are relatively shallow and seldom more than 5 cm in depth. Deep duff layers are usually associated only with weathered and decomposing heaps of slash in TP stands.

Whereas the models for prediction of aerial FFM in the UTUP pine stand may be applied to dead needle fuels in canopies of pine plantations generally, there is evidence to suggest that the litter FFM models may be much less portable (Pook & Gill 1993); somewhat different models have to be developed for the surface fuels exposed to greater wind activity and solar radiation in TP stands. Likewise the calibration of the CBEF model to the latter fuels will differ from those established for UTUP plantations. However, the calibrated CBEF models verified in the present study may provide reliable prediction of FFM in shaded fuel environments and in vulnerable dense young UTUP pine stands that are likely to create the most severe fires.

Limitations of FFM Prediction

Many factors may contribute to variation of FFM and limit the predictive capability of simple empirical models based on T and H alone. The measurement of T and H at locations remote from the fuel, in particular, may exacerbate errors in prediction. Thus, where T and H were measured at screen height (i.e., at the level of aerial fuels) in pine forest, the precision of the relationship between FFM and (T – H) of the AERIAL model was superior to that of the LITTER1 model (Fig. 1, Table 3) and, in independent tests, AERIAL model predictions were more accurate (Fig. 6, Table 7). Although the best performance amongst aerial FFM models (52% of predictions within 1% of observation for SCREEN) may be commensurate with the needs of prescribed burning and fuel reduction operations, it is inadequate for models forecasting fire behaviour during high fire-danger weather when FFMs are at the critical low end of the range (Trevitt 1991). At such times it would seem advisable to make direct measurements of FFM rather than rely only on model predictions (Pook & Gill 1993). Direct measurements might also be appropriate for a day or so subsequent to periods of extreme fire danger if unusual trends in weather conditions maintain low FFMs at night.

How rapid accurate measurements of FFM are to be achieved is obviously a formidable problem. Mechanical fracture tests appear to have potential for determination of moisture contents of relatively uniform fuels such as pine needles (e.g., Burrows 1991) but, as yet, such methods remain to be proved for non-uniform and heterogeneous fine fuels.

McArthur's models appear to have been devised as general guides only to FFM in eucalypt forest and grassland. Although they have performed as well as or better than other more sophisticated FFM models when applied to eucalypt fuels (Viney & Hatton 1989), the results of the present study suggest that, for both eucalypt and pine fuels, they require calibration with regard to fuel type, fuel location, and fuel exposure in order to attain a more useful level of accuracy in the prediction of FFM. With suitable calibration, the CBEF model, in particular, performs as well as models that are specific to pine fuels in the prediction of FFM in pine plantations.

The algorithms for the pine FFM models that accept (T – H) as input are simple and easily memorised. If the demand for accuracy is not too rigorous they may be generally useful for field approximation of moisture content of dead needle fuels in shaded environments of *P. radiata* plantations.

CONCLUSIONS

There is a considerable range of natural fuel types and environments within Australian landscapes for which there is little knowledge of spacial and temporal variation of FFM, a factor that has a major influence on fuel flammability and fire behaviour. The wide variation of diurnal patterns of moisture content observed amongst six common types of dead fine pine and eucalypt fuels influenced only by atmospheric conditions emphasises the need to determine FFM responses to environmental factors for a wider range of fuels in order to test available models and, possibly, to design new ones.

The range and amplitude of the diurnal variations of moisture content in common dead pine and eucalypt fine fuels differ. Fuels consisting of physically similar particles (e.g., eucalypt leaves and bark flakes; eucalypt and pine twigs) have similar diurnal sorption behaviour, but this may be modified by fuel age and weathering (e.g., old *v.* new pine needles).

Amongst McArthur's models, the performance of the CBEF model with respect to different fuel types and fuel locations suggests that it is most amenable to local calibration.

The CBEF model calibrated to both aerial and litter fuels in an UTUP pine plantation performed as well as pine FFM models specific to those fuels. However, FFM was more accurately predicted in aerial fuels than in litter fuels, and FFM models for the former are more portable than FFM models for the latter.

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A.M.Gill made the suggestion that relationships between FFM and (T – H) may provide more useful forms of the pine FFM models, and R.I.Forrester gave helpful advice on statistical methods. They, together with J.Gould, are thanked for constructive comments on the draft manuscript. The competent technical assistance of P.H.R.Moore and J.Armstrong at various times during the study is appreciated.

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CORRIGENDUM

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EMPIRICAL MODELS EVALUATED FOR PREDICTION OF FINE FUEL MOISTURE IN AUSTRALIAN *PINUS RADIATA* PLANTATIONS

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An error was unfortunately included in the formulation of the GFDM model presented in Table 2 on p.282 in that the divisor in the first term of the model should read (T + 6), *not* (T – 6). The correct formulation was used in testing of the model. The amended Table 2 is reproduced here in full.

TABLE 2–Algorithms for McArthur's models relating FFM to air temperature (T) and relative humidity (H) measured at screen height (1.5 m).

Model	Algorithm	Domains
CBEF (McArthur 1962)	Desorption (0600–1200) $FFM = 0.113H - 0.281T + 12.5$ Adsorption (1200 onwards) $FFM = 0.132H - 0.168T + 6.8$ (Viney & Hatton 1989)	T=10–32°C H=20–70% FFM=6–16% ODW
GFDM (McArthur 1977)	$FFM = \frac{(97.7 + 4.06H)}{(T + 6)} - 0.00854H + \frac{3000}{C} - 30$ (Noble *et al.* 1980)	T=10–43°C H=5–80%
FFDM (McArthur 1967)	$FFM = 5.658 + 0.04651H + \frac{(3.151 \times 10^{-4}H^3)}{T} - 0.1854\,T^{0.77}$ (Viney 1991)	T=10–41°C H=5–70% FFM=3–19% ODW