Scheduling irrigation in plantations of *Eucalyptus globulus* and *E. nitens*: A practical guide

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Abstract

The ratio (crop factor, k*) of evapotranspiration to pan evaporation of* Eucalyptus globulus *and* E. nitens *was calculated for the first five years in a plantation established on a low rainfall site in south-eastern Tasmania. The plantation was irrigated with water from an adjacent dam using microsprinklers. Soil water deficits were maintained at a level where available water did not limit growth but remained sufficient to accommodate moderate rainfall events and to minimise the chance of run-off. There were no significant differences in* k *between the two species despite* E. globulus *having a larger leaf-area index at canopy closure. Evapotranspiration, and hence* k*, increased rapidly as canopy closure was approached and then stabilised at a value equal to potential evaporation. A prescription for scheduling irrigation on the basis of Class A pan evaporation and basal area is presented for use by plantation managers.*

Introduction

Sites with a mean annual rainfall of greater than 1000 mm are recommended for eucalypt plantations in Tasmania (Forestry Commission 1990). To date, most plantations in the State have been established on land above the 1000 mm isohyet, and also at elevations above 300 m where growth is limited by low temperatures and annual evaporation is similar to or less than rainfall. However, even in these wetter areas, eucalypt forests can rely heavily on stored soil water during summer to avoid drought stress (Nicolls *et al.* 1982).

Further expansion of the plantation estate will necessitate establishment on water-limited sites. Water stress reduces growth, and irrigation is one option for realising the full potential for growth at such sites. Effective use of water, applied alone or as sewage or factory effluent, requires a precise knowledge of patterns of demand by the trees throughout the course of the rotation. Over-irrigating can result in tree death due to water-logging and disease entry, as well as leaching of nutrients and salt into, and raising of, the water-table. Under-irrigating will result in lost capacity for disposal of waste water as well as reduction in growth potential.

In this study, irrigation schedules are developed for *Eucalyptus globulus* subsp. *globulus* Labill. and *E. nitens* (Deane and Maiden) Maiden, the two eucalypt species most commonly established in plantations in Tasmania. These schedules are based on the crop factor (*k*) or ratio of a measurement of actual evapotranspiration (*Et*) of the

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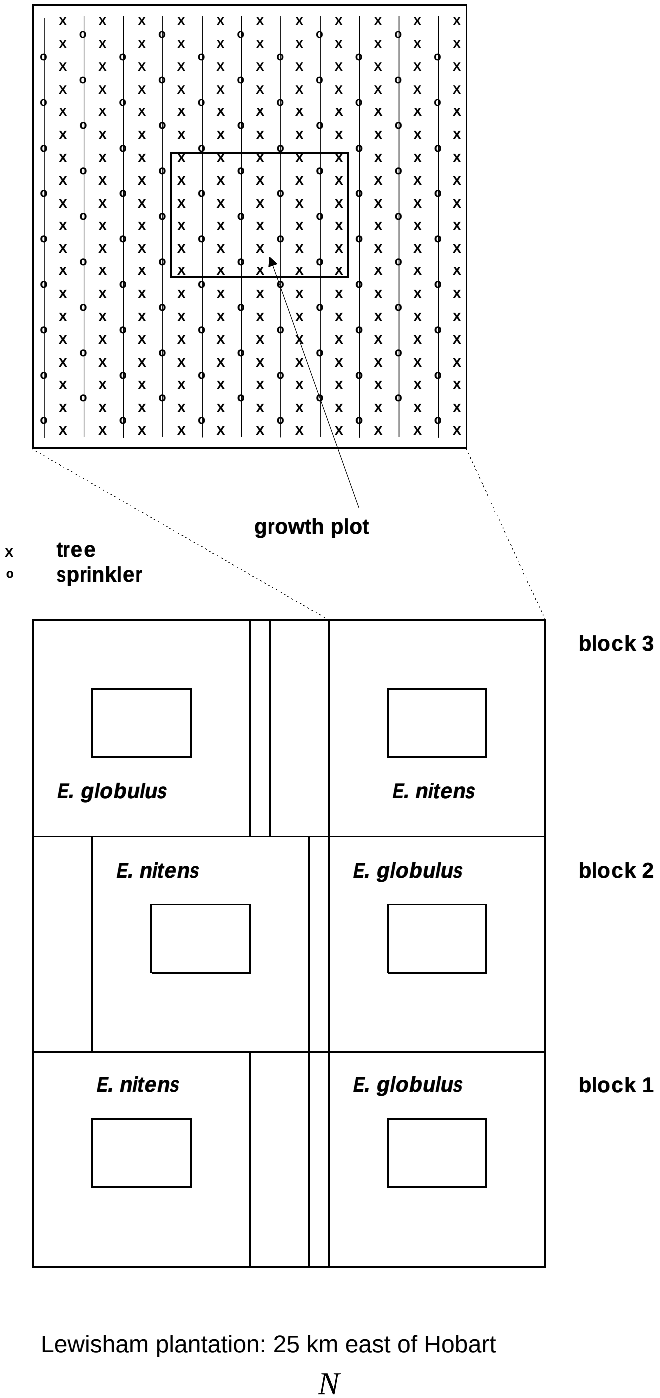

Figure 1. Layout of the experimental site and an expanded diagram showing microsprinkler placement in the plots and subplots used for measurement of growth.

plantation to a measure of potential evaporation (*Ep*, Class A pan). The experiment was done at a relatively warm site near sea-level in south-eastern Tasmania and was used to define maximum growth rates for eucalypt plantations in the region.

Methods

Study area

A two-hectare plantation was established in August 1990 on an ex-pasture site near Lewisham (*Prosser* 8412: 501602, Tasmania 1:100 000 Series Map; latitude 42°49'S, longitude 147°36'E). The long-term (35 years) meteorological averages at Hobart airport, 9 km west of the site, indicate the mean January maximum / minimum temperature is 22.3 / 11.8°C; mean July maximum / minimum temperature is 12.2 / 4.0°C; and mean annual rainfall is 512 ± 115 mm. Mean Class A pan evaporation for the past five years at the airport was 1320 mm / yr. The site has a westerly aspect and an average slope of 5°.

The soil has a shallow red-brown loam A-horizon and a light–medium clay B-horizon, occasionally overlaying light yellow-brown gritty loam from decomposing rock (type: chocolate soil, Stace *et al.* 1968). Parent material is largely basalt and mean soil depth to bedrock or rock floaters is 0.6 m. The site originally supported dry sclerophyll forest.

The irrigated area of the plantation was 1 ha. A randomised block design was used to divide this area into three blocks (replicates, Figure 1). Within each block, two seedlots of *E. globulus* and *E. nitens* were planted in plots (Honeysett *et al.* 1996). For measurements of growth and soil water content, only the King Island provenance of *E. globulus* and a second generation (improved) seedlot of *E. nitens* were used. Each occupied 11 rows per block and there were 209 trees in the plot.

Management

Prior to planting, the rows were ripped in both directions to a depth of 0.5 m. Rows were 3.5 m apart and seedlings were planted 2 m apart within the rip-lines to give a stocking rate of 1428 stems / ha.

Six weeks after planting, phosphorus (P) was applied as triple superphosphate at 120 kg / ha elemental P. Nitrogen (N) was applied as urea at 100 kg / ha elemental N / yr in three applications (40% in August, 30% in both December and March) in 1990 / 91 and 1991 / 92 and at 60 kg / ha N / yr in August 1992, 1993 and 1994.

Post-planting weed control was limited to the one-metre, intra-row strip in the first year and was maintained by hand hoeing and application of glyphosate using hand-held wick-wipers (2:1 water:glyphosate, with 0.1% Pulse as a wetting agent). The inter-row area was slashed periodically to prevent shading of trees and interference with sprinkler irrigation by long grass. Subsequent annual control was by backpack sprayer with a shielded nozzle, using a mixture of simazine (6 kg / ha) and glyphosate (1.5 kg / ha) with 0.1% Pulse and 2% Liase as anti-antagonist.

Juvenile foliage of both species was attacked by autumn gum moth (*Mnesampela privata*) and that of *E. globulus* by bluegum psyllids (*Ctenarytaina eucalypti*). Adult foliage of both species was attacked by a range of chrysomelid beetles and larvae, and sawfly larvae. The trees were sprayed with mixtures of Nuvacron 400 (0.5 l / ha) and Dominex (0.25 l / ha) as required.

Measurement

Growth.—Subplots were established in the centre of the plots of both species in all replicates. These subplots comprised 30 trees (5 rows x 6 trees, Figure 1). Height and diameter at breast height over bark (DBHob) of trees in all subplots were measured regularly (intervals varied between one and three months) from age two years. Height was measured using a telescopic height pole for trees up to 8.2 m, and sectional height poles up to 12 m. From January 1995, trees in the 30-tree subplots were divided into five diameter classes, and one tree from each class was selected: height was measured using a hypsometer (Forestor Vertex, Forestor Instrument AB, Sweden) on selected trees only. Basal area [πr^2 (m^2 / ha)] and stem volume (Opie 1976) were calculated as a mean for each growth plot.

Weather.—The weather station was at the same elevation (20 m a.s.l.) as the plantation on an exposed adjacent hill, 500 m south-west of the plantation. A maximum and minimum thermometer and thermohygrograph housed in a Stephenson screen were reset weekly on Friday at 0900 h, Australian Eastern Standard Time. A Class A pan evaporimeter, wind-run anemometer at 2 m and manual rain gauge were read two to three times per week.

Soil water.—Four access tubes for measurement with a neutron moisture meter (NMM, CPN503, Pacheco, California) were installed within each of the six subplots. The tubes were placed immediately opposite the midpoint between a randomly selected pair of trees, the first two at 0.5 m and 1.0 m and the other two at 1.75 m from the rip-line. The first two and one of the latter were advanced to soil depth by augering inside the tube to bedrock. The fourth tube was placed in an oversize hole mechanically drilled into the rock base to a total depth of 3.0 m and set in a slurry of kaolin and cement (Prebble *et al.* 1981). Soil water content (θ) was measured at 0.15 m intervals down to 1.0 m and at 0.3 m intervals below 1.0 m, and calculated as a mean of the four tubes at each depth using a calibration for the site.

Soil water content was calculated as total soil water content (mm) in zone 1 (0–1.0 m) and zone 2 (1.0–3.0 m) for each of the six plots and is reported as species means. Soil water deficit (*ΔW*) and evapotranspiration (*Et*, total water use including canopy interception) were calculated using a soil water balance equation (Honeysett *et al.* 1992). Measurements were generally taken every two weeks during the period October to March, and at longer intervals at other times. The assumption was made that there was negligible deep drainage due to the impervious nature of the underlying solid basalt. A spoon drain across the bottom of the plantation was inspected after heavy or prolonged rainfall events to detect run-off.

Irrigation system

The irrigated hectare was divided into four zones of equal area and an automatic controller (Richdel 600 PR series, USA) communicated with four solenoid valves, one for each zone. The water was delivered from an adjacent dam by a pump (Grundfos CRI6-50, Denmark) with filter to the top of the irrigated area through 50 mm poly pipe. From this main line, 19 mm laterals ran down the centre of each inter-row. Microsprinklers (Daan, Israel) were positioned every 4 m along the laterals, on 0.3 m spikes. The sprinklers in every second row were offset by 2 m to provide total ground coverage (Figure 1). The sprinklers were pressure compensating and, at pressures greater than 200 kPa, they delivered 70 l / h (—5 mm / h). Irrigation was applied routinely in 10 mm applications between 2000 and 0400 h (i.e. 2 h per zone). This was done to maximise infiltration and to minimise evaporation. An in-line flowmeter (Arad, Israel) was installed to confirm that irrigation was applied as programmed and to determine the volume of water (m^3) applied.

Irrigation was scheduled on the basis of weekly pan evaporation and fortnightly NMM readings. Frequent application of small amounts of irrigation, once the entire soil profile was wet, was considered a more efficient form of water management. This facilitated uptake by near-surface roots (Clothier and Green 1994) and allowed flexibility to cancel applications when rain occurred. The frequency of 10 mm applications of irrigation varied in rain-free periods from 0–1, 1–3 and 3–5 per week in winter, autumn / spring and summer, respectively.

Crop factor

The annual crop factor (*k*) was calculated for each species as the ratio of annual evapotranspiration, *Et,* over annual pan evaporation, *Ep*. Evapotranspiration was calculated as the sum of Et_i, where Et_i is the evapotranspiration for the *i*th measurement period. This had the effect of weighting the crop factor on the basis of period evaporation divided by annual evaporation. For any period *i*,

$$Et_i = (I_i + P_i) - \Delta W - R_i - D_i$$

where $I_i + P_i$ is the irrigation applied and rainfall respectively, and ΔW_i is the change in soil water deficit (*ΔW*) for the *i*th measurement period. Run-off and deep drainage for that period are given by R_i and D_i respectively. The occurrence of R_i was determined on the basis of observation. By reason of confinement by a solid basalt 'C-horizon', D_i was not measured but assumed to be close to zero. Large rainfall events in December 1993, November 1994, April and December 1995, and March and April 1996 caused run-off, and data for these periods were omitted. Thus:

$$k = \frac{\sum_{i=1}^{n} Et_i}{Ep_i} \times \frac{Ep_i}{Ep}\ , \ \therefore\ k = \frac{\Re_{i=1}^{n} Et_i}{Ep}$$

Analysis

The GENSTAT ANOVA procedure (Genstat 5 Committee 1988) was used to test for differences between species for *k* and basal area using a single factor model

$$X_{ij} = \mu + S_i + \Sigma_{ij}$$

where X_{ij} was the value of *k* or of basal area of the jth plot of the ith species and μ, S_i and $\Re_{ij}$ were the grand mean, species and residual variance respectively. A test for paired data was used to test for significant changes from one year to the next.

Results and discussion

Soil water deficit

Irrigation was scheduled to maintain soil water deficit (ΔW) in zone 1 for both species at between 20 and 40 mm (Figure 2a). This level of deficit was maintained for two reasons. Firstly, it reduced the likelihood of run-off except during very high rainfall events. Secondly, pre-dawn leaf water potential, a measure of the underlying water stress in the tree, was maintained at greater than -0.5 MPa and this ensured that water was not a factor limiting growth of either species (Honeysett *et al.* 1996; White 1996). In winter, when growth and water use were low, ΔW in zone 1 was allowed to increase above 40 mm to facilitate aeration of the root zone

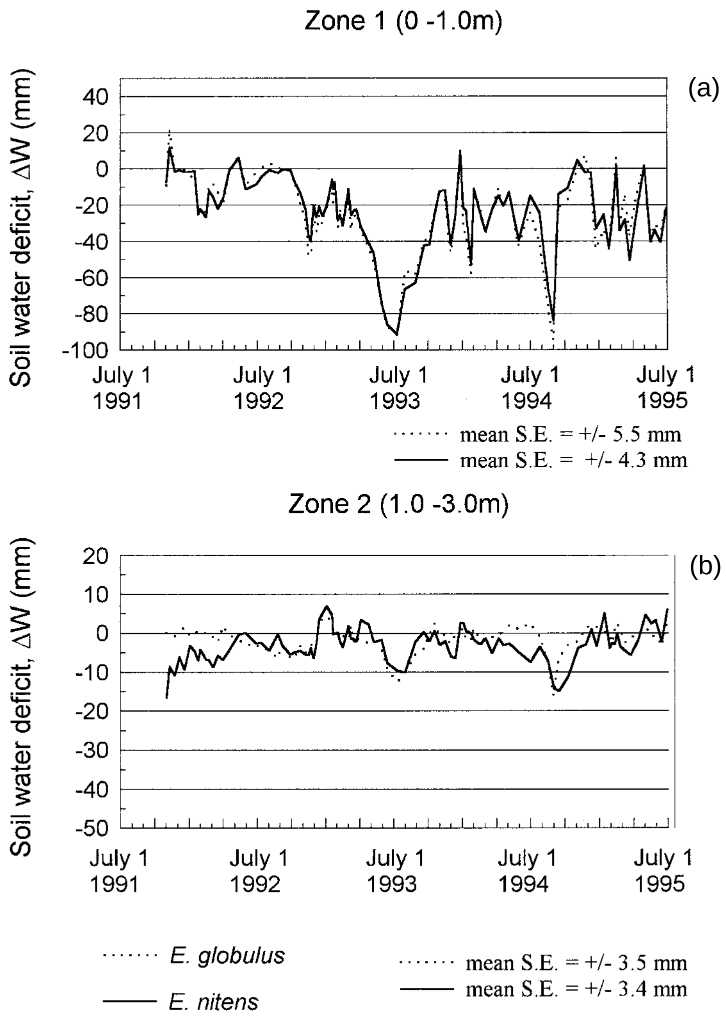

Figure 2. Changes in soil water deficit in (a) zone 1 (0–1.0 m) and (b) zone 2 (1.0–3.0 m) for Eucalyptus globulus *and* E. nitens *from July 1991 to June 1995. Note that deficits in zone 1 were maintained mostly in the 20–40 mm range and in zone 2 remained reasonably constant and showed minimal variation, even during the winter drying cycles of 1993 and 1994.*

*Table 1. Evapotranspiration (*Et*), pan evaporation (*Ep*) and crop factor (*k*) for the second to the sixth year of growth.*

	Et		*k*			
	E. globulus	*E. nitens*	*E. globulus*	*E. nitens*	Rainfall	*Ep*
Year 2[1] (1991/92)	744	734	0.74	0.73	250	1005
Year 3[2] (1992/93)	1129	1141	0.89	0.90	466	1268
Year 4[2] (1993/94)	1403	1389	0.99	0.98	496	1417
Year 5[2] (1994/95)	1518	1518	1.00	1.00	442	1518
Year 6[2,3] (1995/96)	1342	1414	1.13	1.19	700	1188

[1] from November–June only [2] from July–June [3] may include some run-off

and to encourage root development. Soil water deficit in zone 2 showed little change for either species throughout the experiment; that is, no significant soil water deficits developed in this zone (Figure 2b). Deep or lateral sub-surface drainage may have occurred but changes in θ in zone 2 indicate that this was probably negligible, justifying the assumption that D_i was close to zero. Maintaining soil water deficits of 20–40 mm below field capacity and applying irrigation in small frequent amounts was designed to reduce deep drainage. On free-draining soils, it would be necessary to monitor water-table levels and, if effluent were being used, to also monitor for water-table contamination with N, P and salt.

Evapotranspiration and crop factor

Evapotranspiration (*Et*) increased from around 760 mm in the eight-month period from November to June in the second year of growth to over 1400 mm in the fourth and fifth year of growth (Table 1). In the sixth year of growth, several high rainfall events (> 50 mm) during summer led to substantial run-off and, although data were omitted when run-off was observed, *Et* may have been overestimated. Increases in *Et* were associated with increase in canopy size and it was not until the fourth year that the canopy was closed throughout the period of measurement (White 1996). There were no significant differences in *Et* between species despite *E. globulus* having a larger leaf-area index at canopy closure (White 1996).

Because of this lack of difference in *Et* between species, there were also no differences in crop factor (*k*) between species (Table 1). Crop factor was 0.74 in the second year, 0.90 in the third year, and then approximately 1.0 after canopy closure, except in the sixth year of growth. Changes in *k* between the second and third, and third and fourth year of growth were significantly different ($P < 0.05$) but not thereafter. Thus, maximum levels of *Et* over an annual cycle were close to pan evaporation. In the sixth year of growth (1995/96), as suggested above, *k* may have been overestimated. However, stomata of *E. globulus* and *E. nitens* close with increasing vapour pressure deficit (D; White 1996). Years with cool, wet summers like 1995/96 may therefore be associated with higher *k*. For *E. grandis*, Myers *et al.* (1996) have concluded that *k* may change inversely with increasing pan evaporation.

Increases in *k* during canopy development have been reported for *Eucalyptus grandis* in southern New South Wales (0.7–1.0, Myers *et al.* 1996; CSIRO 1994) and for a range of eucalypt species, including *E. globulus,* in South Australia (0.9–1.3, Hanna *et al.* 1993) in irrigated plantations with higher *Ep*. In 10–14-year-old *Pinus radiata* in the Australian Capital Territory, *k* varied between 0.88 and 1.19, was highest in irrigated and fertilised plantations, and was directly proportional to foliage mass (Myers and Talsma 1992). These results point to maximum *Et* being close to, or a little above, *Ep* over a range of Australian environments. Higher values of *k* for eucalypts

(> 1.5) have been reported in some instances (Greenwood *et al.* 1985; Morris and Wehner 1987) but are associated with *Et* exceeding levels of available energy. The irrigated plantation used here was surrounded by dry pasture in summer but there was no evidence of any 'oasis' effect of advected energy on *Et*.

These values of *k* include canopy-interception losses for rainfall and sprinkler-efficiency losses for irrigation and, in the water-balance equation, rainfall and irrigation are gross inputs. However, in practical terms, these estimates of *k* form a useful basis for scheduling irrigation.

Growth

Current annual increment (CAI) in the sixth year of growth was 52.5 and 53.0 m^3/ha for *E. globulus* and *E. nitens* respectively. The corresponding mean annual increment (MAI) at age six years was 30.6 and 27.6 m^3/ha/yr (Figure 3). The higher CAIs for volume of *E. globulus* than *E. nitens* were associated with significantly larger CAIs of height growth of *E. globulus* to age three years (Honeysett *et al.* 1996). The maximum CAIs observed at this site were slightly above those reported for fertilised 60-tree plots of *E. nitens* in the Esperance Valley (Southern Forests of Tasmania, Beadle *et al.* 1994). Higher CAIs have been reported for small plots of *E. nitens* in Tasmania (Beadle *et al.* 1995) but not in a replicated trial. The results for this and the Esperance study (Honeysett *et al.* 1992) point to these maximum growth rates being associated with water use for closed canopies close to pan evaporation in these cool maritime climates.

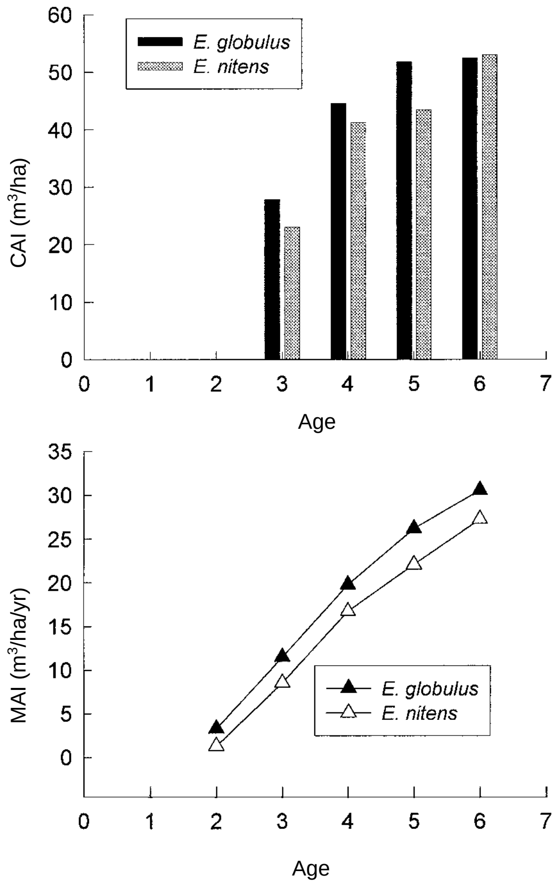

Figure 3. Current annual increment (CAI) and mean annual increment (MAI) of volume for Eucalyptus globulus *and* E. nitens *to age six years.*

Scheduling irrigation

Pan evaporation

We have seen from the results discussed above that *Ep* provides a robust estimate of *Et* over an annual cycle for closed canopies of *E. globulus* and *E. nitens*. For developing canopies over the period of a year, cumulative *Et = k(Ep)* where *k* increases to approximately 1.0 at canopy closure. Class A pan evaporation (*Ep*) was therefore chosen to schedule irrigation due to the relative ease of obtaining data.

The Class A pan is small in area and experiences advection differently from the crop (Theiveyanathan *et al.* 1991). Scheduling irrigation using *Ep* assumes that the pan behaves in the same way as a crop with zero resistance. The crop factor (*k*), however, is subject to seasonal variation. As noted previously, during periods of high evaporative demand, stomatal closure will reduce transpiration and hence *k*. In hot summer periods, it was observed that *Et* was

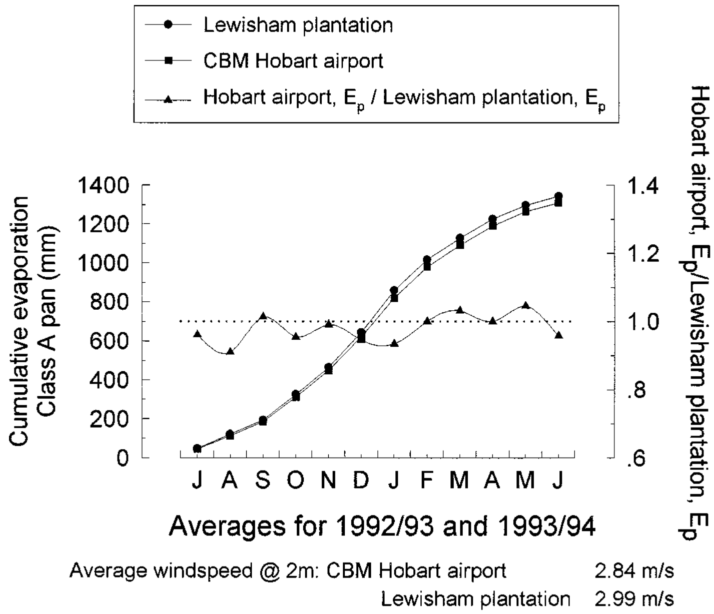

Figure 4. A comparison between two well-sited Class A pan evaporimeters at the Lewisham plantation (20 m a.s.l.), and 9 km west at the Commonwealth Bureau of Meteorology (CBM) weather station at Hobart airport (4 m a.s.l.).

less than *k*(*Ep*) whereas in cooler and calmer (low wind speed) periods in winter, *Et* was greater than *k*(*Ep*). For the purposes of scheduling irrigation, this would result in slight over-watering in summer and under-watering in winter, an outcome which is preferable to the reverse of that situation.

The siting of the Class A pan evaporimeter is critical. It should not be placed in forest clearings. The Commonwealth Bureau of Meteorology (CBM) provides written 'guidelines for the siting and exposure of meteorological instruments' (Observation specification No. 2013). It is preferable to have a well-maintained and regularly read pan on-site. If this is not feasible, *Ep* measured at the nearest CBM pan should be adequate as long as the plantation is in a similar biogeographical region (Figure 4).

Basal area

Scheduling irrigation must accommodate the period up to, as well as at and beyond, canopy closure. It is proposed here that crop factors, and hence irrigation, be assigned on the basis of basal area [πr^2 (m^2/ ha)]. In this experiment, differences in basal area between species were not significantly different ($P < 0.05$) between age two and age five years except for a period of six months from October 1992 in the third year of growth when *E. globulus* had a larger basal area than *E. nitens* (Figure 5). Measurement of basal area is a much simpler procedure than the measurement of leaf-area index (leaf area per unit ground area) or foliar dry mass, which provide direct measures of canopy size and therefore the evaporating surface. Fortunately, there is a proportional relationship between canopy size and basal area during this period of growth (White *et al.* 1998; Jane Medhurst, pers. comm.).

Crop factor

Crop factor (*k*) was not calculated during the first year of the experiment when transpiration from grass in the inter-row and

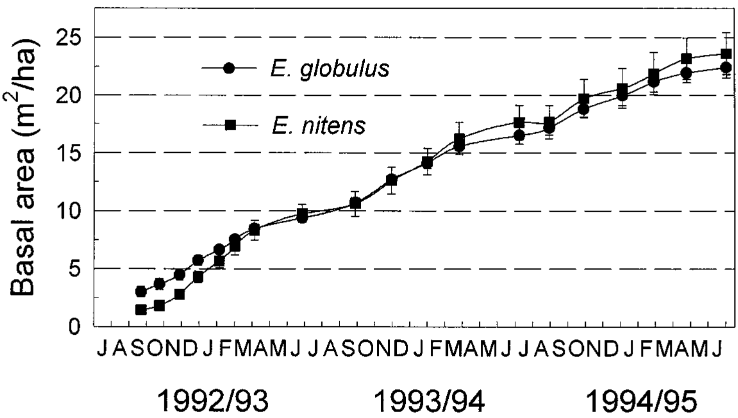

Figure 5. Basal area development between age two and age five years of growth. Diameter measurements until September 1992 were at 0.15 m and then subsequently at 1.3 m (diameter at breast height over bark).

bare soil evaporation in the intra-row areas (a one-metre, weed-free strip) would have been the main sources of *Et*. Crop factors for well-watered grass vary from 0.5 to 0.8 *Ep* (Penman 1948; Eastham and Rose 1988; CSIRO 1994). The crop factor in the second year of growth was 0.74 (Table 1). We assume here that a *k* of 0.60 can be applied in the first year and combine our observed basal area and crop factors to schedule irrigation as follows:

Year 1	0.60 *Ep*
then:	
Basal area < 2.2 m^2/ha (DBHob < ♠ 4.5 cm)	0.75 *Ep*
Basal area > 2.2 m^2/ha < 9.4 m^2/ha	0.90 *Ep*
Basal area > 9.4 m^2/ha (DBHob > ♠ 9.0 cm)	1.00 *Ep*

It should be noted that the above was developed in a plantation which was irrigated from establishment. Periods of drought stress may change the relationship between basal area and canopy size if these are prolonged or result in loss of canopy, and the above crop factors will not apply.

Application

If the soil is not close to field capacity (FC) after planting (normally in winter or early spring in Tasmania), irrigation will have to be applied. This should be done gradually over several days until the profile is saturated. After drainage for 2–3 days, FC is established. A further period of evapotranspiration of 3–4 days with no significant rainfall (> 5 mm) should be allowed to attain a soil water content equivalent to 60–80% of the available soil water at field capacity. Irrigation scheduling can now commence and post-planting fertiliser application carried out without risk of significant leaching losses. As the trees grow and the roots exploit an increasing proportion of the soil profile, it is recommended that FC be re-established each spring. Re-establishing FC also reduces the possibility of any cumulative gains or losses in soil water content, due to slightly over- or under-irrigating, over the previous growing season.

In the absence of rainfall, irrigation should be applied at the appropriate *kEp* and at intervals not greater than one week. Applying large amounts of irrigation increases the likelihood of run-off or deep drainage. Soil water content (or soil water potential if the relationship between content and potential is known) should be measured at intervals over the growing season to ensure that soil water content is being maintained at the correct level and that water stress or water-logging are avoided. This can be done by simple gravimetric sampling, a neutron moisture meter or time domain reflectometry (soil water content); tensiometers or gypsum blocks (soil water potential). Measurements need to be done over a range of soil depths and integrated to give a water content for the total profile.

Scheduling irrigation on the basis of *Ep* for the previous week, less any rain that fell in that week, will maintain the plantation at a soil water content of 20–40% below that available at FC. Thus:

$$I = k(Ep) - R$$

where *I* is irrigation to be applied and *R* is rainfall for that week. For weekly periods where rainfall exceeds *kEp*, a negative value of *I* is carried forward to the next week's calculation. In the case of very heavy or prolonged rain where the profile is saturated and run-off occurs, the soil should be allowed to drain and return to the FC point. *Ep* will determine the time required (3–4 days in summer) to return the soil profile to a soil water content of 20–40% below that available at FC before irrigation recommences.

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