Water loss from tree plantations in the tropics

Jose Kallarackal* and C. K. Somen

This article reports the water use characteristics of a few important tree species used in raising plantations in Kerala, located in the warm humid tropics of peninsular India, which experiences variable and seasonal rainfall. Five tree species (Eucalyptus tereticornis, E. grandis, Acacia auriculiformis, Anacardium occidentale and Tectona grandis) have been investigated in five different sites experiencing different microclimates and rainfall. All the species except T. grandis are exotics in this location. Their transpirational water loss (Et) was estimated from measurements of microclimate and physiological parameters and applying them in the Penman–Monteith equation. The reference evapotranspiration (ET₀) calculated using the FAO Penman–Monteith equation was used to evaluate transpiration between the tree species and between the different sites. Ecophysiological parameters such as stomatal conductance, leaf area index, leaf water potential, etc. were also measured to relate them with water use. The root system in a plantation of E. tereticornis was excavated to study the rooting depth and pattern, and also to verify the allegation that they extract water from the phreatic aquifer. The five investigated species showed variations in transpiration. These variations are explained in terms of their rooting depth, leaf area index, stomatal conductance and soil water availability. The study points out the fact that not only the quantity of water loss through transpiration, but the ecophysiological features also play an important role in evaluating a species for plantation development in the tropics.

Keywords: Ecophysiology, Penman–Monteith equation, rooting depth, transpiration.

EVAPOTRANSPIRATION is the major form of water loss from a catchment. It is comprised of transpiration from the leaves, interception and evaporation of water by the canopy and evaporation from the ground. Several studies in the temperate parts of the world have shown that water loss in the form of evapotranspiration can be normally 65% of the total precipitation in a catchment[1]. Evapotranspiration from forests and tree plantations in the temperate countries has been a widely discussed topic[2–5]. However, not many attempts have been made in the tropics towards any meaningful comparisons. The different components of evapotranspiration are difficult to be measured in a natural forest mainly because of the species variations. Even in a monoculture plantation, transpiration by trees is difficult to be measured and quantified because of the technical problems involved in scaling-up the leaf-level or plant-level measurements to stand-level data. Hence, generally water use of trees by transpiration has been estimated using micrometeorological methods such as Bowen ratio and Eddy correlation methods or by integrated micrometeorological and physiological models such as the Penman–Monteith equation[6].

Several tree species were raised in plantations in the tropics, which include indigenous and exotic trees. Some of them form vast areas in the tropical catchments. The question of what species to plant in a selected area is always an important issue in forestry practices. This question has aroused much interest among the environmentalists in general and hydrologists in particular, with regard to the water use and evapotranspiration of different plantation species. Many of the exotic species, especially the eucalypts, have been criticized for their excessive water consumption in the tropics[7].

In this study, our main objective was to quantify the water use by transpiration in a few commonly used exotic plantation species that include *Eucalyptus tereticornis, E. grandis, Anacardium occidentale* (cashew), *Acacia auriculiformis* and an indigenous tree species, *Tectona grandis* (teak). Also, a few ecophysiological characteristics of the above species have been investigated. It was not possible to get all the above species together at any one location because of their varying habitat requirements. Such a situation would have helped us in quantitatively comparing their water use in the most ideal manner. However, we have been able to compare their transpiration based on the reference evapotranspiration ET_0 calculated using the FAO Penman–Monteith equation. This study reports the quantity of daily transpiration in comparison with refer-

The authors are in the Sustainable Natural and Plantation Forest Management Division, Kerala Forest Research Institute, Peechi 680 653, India.
*For correspondence. (e-mail: jose@kfri.org)

| Site no. | 1 | 2 | 3 | 4 | 5 |
Parameter	Et	Eg	Aa	Ao	Tg
Altitude (m)	100	750	20	30	180
Root-stock age (yrs)	13	15	5	18	12
Coppice age (yrs)	4	4	NA	NA	NA
DBH (cm)	9.0	9.9	6.5	38.5	14
Density (stems/ha)	1800	2500	4440	169	800
Tree height (m)	10	11	10	9	8
Leaf area index	2.17 (1.95)*	2.75 (2.45)	3.15 (1.80)	2.60 (2.55)	2.81 (0.55)
Study period	90–91	92–93	90–91	91–92	1992
Annual rainfall (mm)	2837	1302	2361	3176	1832
Temperature (maximum) (°C)	36.7	32	36.7	36.9	32.3
Temperature (minimum) (°C)	20.8	12	20.8	20.9	23.1

Et, Eucalyptus tereticornis; Eg, Eucalyptus grandis; Aa, Acacia auriculiformis; Ao, Anacardium occidentale; Tg, Tectona grandis.
*Figures in parenthesis represent the premonsoon (dry season) values.
NA, Not applicable.
The temperature data are based on monthly averages taken at each site during the study period.
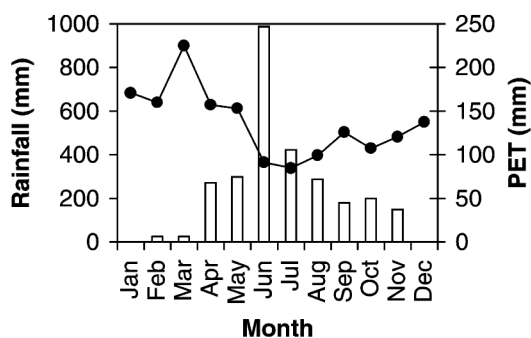
Figure 1. Rainfall (bars) and potential evapotranspiration (line) at Site 1. The bimodal rainfall showing two peaks is visible with the two monsoons operating during the year. This pattern is applicable for all the study sites, with changes in the amount of annual rainfall.

ence evapotranspiration, and the ecophysiological characteristics of the species in the different sites, both of which are important in judging their suitability for plantation development.

Materials and methods

Site description

The six plantations chosen for this study were located between latitude 10°5′N and 11°2′N, and longitude 76°2′E and 76°6′E. The elevation of the locations ranged between 100 and 750 m asl. The soil of the study site was intergraded between ferrallitic and fersiallitic soils.

The annual average rainfall for the sites ranged between 1300 and 3350 mm. Almost 85% of the rainfall at all the sites occurred during June–November as a result of two monsoons, namely, the southwest monsoon followed by the northeast monsoon. This left the rest of the

year relatively dry, with scanty rainfall, giving rise to wide variations in the potential evapotranspiration (PET). The patterns of rainfall and PET at Site 1 are shown in Figure 1 as a typical example. All the sites had a phreatic aquifer, anywhere within a depth of approximately 15 m. Details of the sites and the species are given in Table 1.

Transpiration

Transpiration (Et) was estimated at all the sites using the Penman–Monteith method. Using a scaffold tower, 12 m tall, an automated weather station was fixed 2 m above the canopy level in the plantations to collect hourly meteorological data. Details of the sensors are given elsewhere[8]. Simultaneously, stomatal conductance measurements were made at hourly intervals at two canopy levels using a Steady State Porometer (LI-1600, LI-COR Inc., Nebraska, USA). The above measurements were repeated several times a year, each visit lasting 2 to 3 days, covering the two major seasons of the area, namely postmonsoon season (August–November, relatively wet with intermittent rainfall, and with high soil water content) and premonsoon season (December–April, dry period with drying soil). Both microclimate and stomatal conductance data were used to parameterize the Penman–Monteith equation to work out the hourly and daily transpiration as follows[9].

$$\lambda Et = \frac{s_* \varphi_n + g_a \rho c_p D}{s_* + \gamma (g_a / g_c)}, \tag{1}$$

where λ is the latent heat of vapourization of water (2.47 × 10^6 J/kg), Et the flux density of water vapour (kg/sq. m/s), g_a the aerodynamic conductance (cm/s), φ_n the net radiation or radiant energy absorbed by the leaves(W/sq. m),

c_p the specific heat of air at constant pressure (J/mol), ρ the air density, γ the psychrometer constant (kPa/C), D the vapour pressure deficit of the ambient air (mb), s_* the slope of the saturated vapour pressure versus temperature curve (kPa/C) and g_c the canopy conductance (cm/s).

In eq. (1), φ_n and D were obtained from the microclimate measurements. g_c was obtained using the equation,

$$g_c = \Sigma g_s L, \tag{2}$$

where g_s is the porometer value for stomatal conductance (g_s was parameterized using its relation with D and L the leaf area index (LAI) measured by the light interception method using a Canopy analyzer (LAI-2000, Li-Cor, Nebraska, USA). Since transpiration in forests is sensitive to canopy conductance, direct multiplication of g_s with L slightly overestimates the canopy transpiration.

g_a was obtained from the following equation[10]:

$$g_a = (k^2 u)/\ln^2[(z-d)/z_0], \tag{3}$$

where k is the von Karman's constant (0.41), u the mean wind speed measured 2 m above the canopy (m/s), z the anemometer reference height, d the zero plane displacement calculated as 0.64 h (where h is the crop height in m) and z_0 the roughness length (= 0.13 h). The values for d and z_0 have been approximated for a range of relatively dense vegetation[11].

The hourly averaged wind speed data formed the most important variable for the calculation of g_a. s_* was calculated using the equation:

$$s_* = \frac{\lambda_{es}(T)}{R(T+273)^2}, \tag{4}$$

where e_s is the saturation vapour pressure at temperature T, and R the universal gas constant (8.314 J/mol/K).

The values of Et were worked out on an hourly basis for each site for each visit. The values obtained were converted to depth equivalents (mm) for convenience.

Daily transpiration was obtained by cumulating the hourly transpiration values measured during the different seasons of the year.

Reference evapotranspiration

The reference evapotranspiration for each study site was computed using the FAO Penman–Monteith equation[12].

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \tag{5}$$

where ET_0 is the reference evapotranspiration [mm/day], R_n the net adiation at the crop surface [MJ/sq. m/day], G the soil heat flux density [MJ/sq. m/day], T the mean daily

air temperature at 2 m height [°C], u_2 the wind speed at 2 m height [m/s], e_s the saturation vapour pressure [kPa], e_a the actual vapour pressure [kPa], $e_s - e_a$ the saturation vapour pressure deficit [kPa], Δ the slope vapour pressure curve [kPa/°C] and γ the psychrometric constant [kPa/°C].

The reference evapotranspiration provides a standard to which evapotranspiration at different periods of the year or in other regions can be compared. Evapotranspiration of other crops can be also related. The equation uses standard climatological records of solar radiation, air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements made above the canopy were converted to 2 m height using standard methods[12].

Ecophysiological parameters

Besides stomatal conductance, other ecophysiological parameters such as leaf water potential, ψ, using a Scholander-type pressure chamber (Soil Moisture Equipment Corporation, Ohio, USA) and LAI, using a Canopy Analyser (LAI-2000, Li-Cor Inc., Nebraska, USA), were measured to gain an understanding of the water-use characteristics of the species in relation to environmental changes. For measurements of ψ, the leaves were collected before sunrise in polythene bags and sealed before inserting in the pressure chamber, and the readings made soon after collection. LAI measurements were made either in the early morning or late evening when the sky was uniformly lit. Only two sets of measurements, the first during the post-monsoon season and the second during the premonsoon season were made in a year for each species. Several readings were taken at each site and the values were averaged.

Root excavation studies

Excavations at plantation Site 1 of *E. tereticornis* were done to investigate the root length and weight density at different depths in a plantation. Two pits, each having a diameter of 2 m were made, one around a tree stump and the second between four trees, collecting roots of all size classes at every 30 cm depth. The length and dry weight of the roots were later determined separately for every 30 cm depth and the values were averaged for the two excavations.

Results

Hourly transpiration values measured during pre- and post-monsoon periods in all the investigated species are given in Figure 2. The daily cumulated values for both the above periods along with the reference ET_0 calculated using the FAO Penman–Monteith equation are given in Table 2.
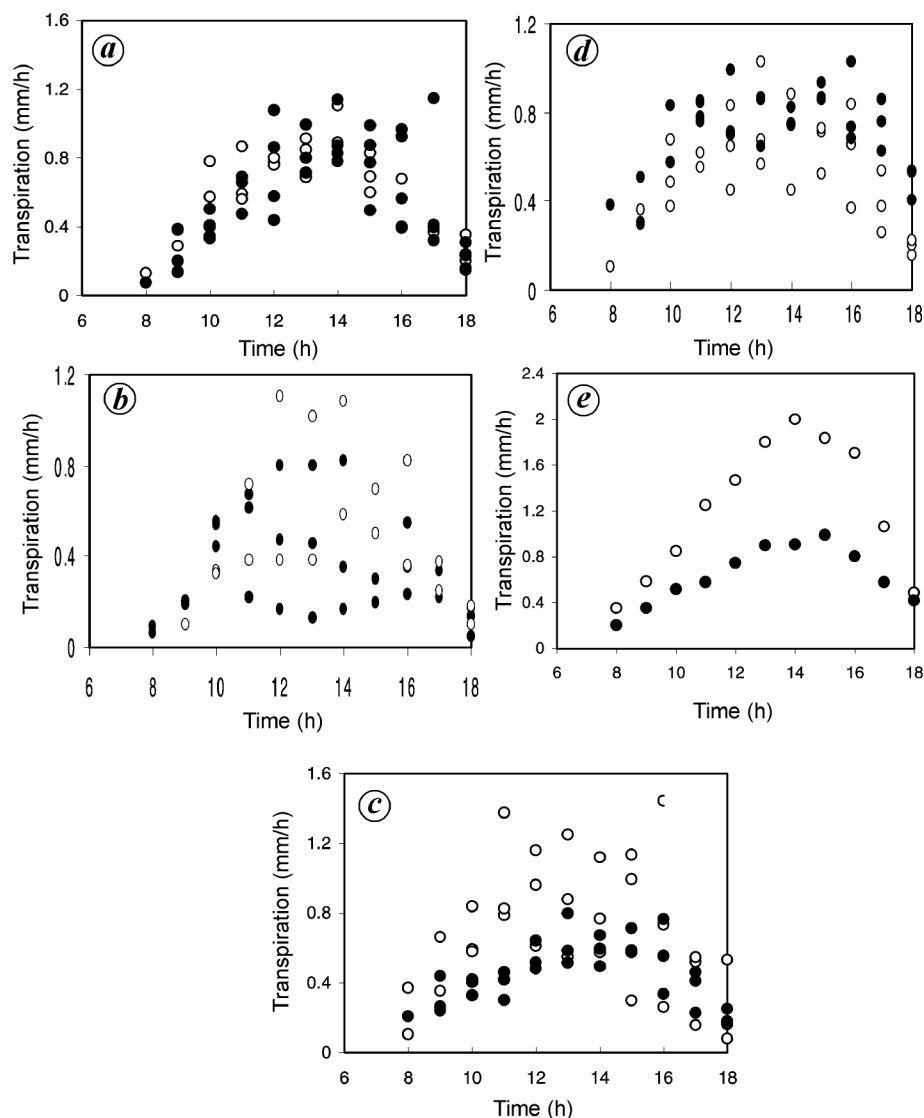
Figure 2. Hourly transpiration in (*a*) *Eucalyptus tereticornis*, (*b*) *E. grandis*, (*c*) *Acacia auriculiformis*, (*d*) *Anacardium occidentale* and (*e*) *Tectona grandis* presented as a scatter plot. Data were taken on days when field measurements were done. Open symbols represent postmonsoon period and closed symbols the premonsoon period.

Table 2. Daily transpiration (*Et*) and reference evapotranspiration (*ET*$_0$) (mm) in the different plantation species

Species	*Et* Postmonsoon	*Et* Premonsoon	*ET*$_0$ Postmonsoon	*ET*$_0$ Premonsoon	*Et*/*ET*$_0$ Postmonsoon	*Et*/*ET*$_0$ Premonsoon
E. tereticornis	5.44 ± 1.25	6.04 ± 1.08	2.78 ± 0.58	4.17 ± 0.75	1.96	1.45
E. grandis	4.52 ± 1.29	4.42 ± 1.40	1.60 ± 1.08	2.71 ± 0.78	2.81	1.63
A. auriculiformis	7.04 ± 1.53	5.32 ± 1.23	3.93 ± 0.53	5.97 ± 0.68	1.79	0.89
A. occidentale	5.56 ± 1.08	6.80 ± 0.89	3.54 ± 0.82	5.69 ± 1.05	1.57	1.19
T. grandis	10.19 ± 2.13	Leafless	5.06 ± 0.86	6.12 ± 1.03	2.01	Nil

The daily *Et* was estimated using the Penman–Monteith equation. The reference *ET*$_0$ was calculated using the FAO Penman–Monteith equation.

The stomatal conductance measurements made on the trees during the two seasons are given in Figure 3.

The hourly transpiration values in *E. tereticornis* plantation at Site 1 sometimes reached 1.2 mm/h during mid-day (≈ 7.7 mm/d). The transpiration rates during pre- and postmonsoon seasons were not significantly different in this species. However, the *ET*$_0$ at this locality showed significant differences for the two periods. The stomatal
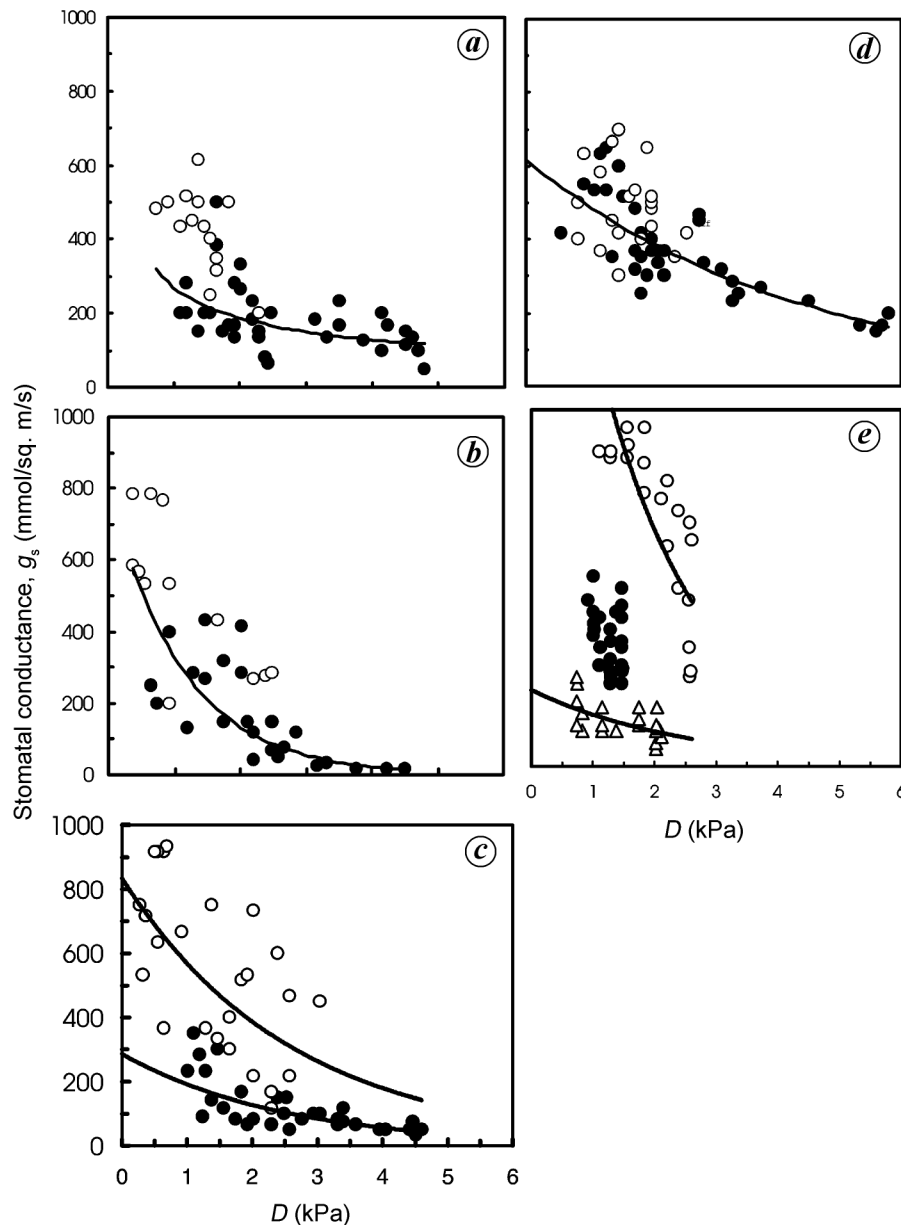
Figure 3. Stomatal conductance, g_s plotted against the atmospheric vapour pressure deficit, D in (**a**) *E. tereti-cornis*, (**b**) *E. grandis*, (**c**) *A. auriculiformis*, (**d**) *A. occidental* and (**e**) *T. grandis*. The postmonsoon (○), premonsoon (●) and monsoon (△) values (only in *T. grandis*) are indicated and trendlines have been fitted.

conductance measurements in this species indicated that the stomatal closure in response to vapour pressure deficit, D, although negatively exponential at lower D values, became relatively stable as the value of D increased (Figure 3 *a*). The stomatal closure in this species is only partial even at higher values of D. A vertically oriented canopy with drooping leaves having stomata on both sides gives an ideal transpiring surface for this species. In *E. tereticornis*, the predawn values of leaf water potential (ψ) rarely dropped to less than −0.5 MPa in a year (Figure 4 *a*). Out of the twelve months measurements in a year, only once (in May) ψ was found to be less than −0.5 MPa.

It may be also noted that the LAI of *E. tereticornis* did not show significant variation between the post- and premonsoon seasons (Table 1).

In *E. grandis* plantation, grown in a relatively lower rainfall area and higher elevation at Site 2, the transpiration reached a higher value of 1.2 mm/h and 6.3 mm/d (Figure 2 *b*). As in the other eucalypt species, there was no significant difference in transpiration between postmonsoon and premonsoon values. However, the reference ET_0 values were significantly different for both the seasons (Table 2). Stomatal conductance measurements have shown that *E. grandis* has a well-developed mechanism
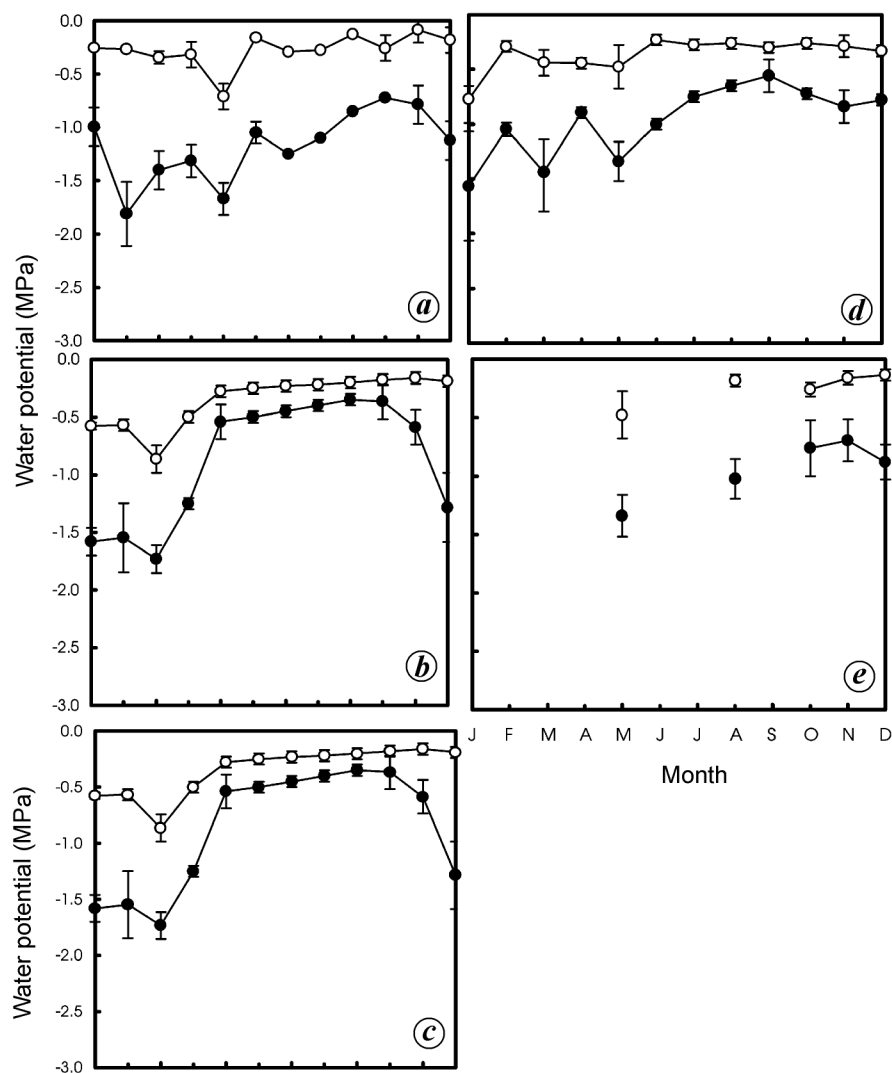
Figure 4. Leaf water potential, ψ in the different species. (**a**) *E. tereticornis*, (**b**) *E. grandis*, (**c**) *A. auruculiformis*, (**d**) *A. occidentale* and (**e**) *T. grandis*. The predawn (○) and midday (●) water potentials are shown.

of almost complete stomatal closure in response to increasing atmospheric D (Figure 3 *b*). Unlike *E. tereticornis*, *E. grandis* has stomata only on one side of the leaf. The predawn ψ was rarely less than -0.5 MPa during any part of the year (Figure 4 *b*). Similarly, the LAI variation between the pre- and postmonsoon seasons was negligible (Table 1).

In *A. auruculiformis*, at Site 3 the postmonsoon values of transpiration sometimes reached a maximum of 1.5 mm/h and 9.7 mm/d, whereas the premonsoon values reached a maximum of only 0.8 mm/h and 4.0 mm/d. Both Et and the reference ET_0 values showed significant differences during the pre and postmonsoon seasons (Table 2). The leafy phyllodes of this species had stomata on both sides in almost equal proportion. However, *A. auruculiformis* had a well-developed stomatal closure mechanism in response to increasing atmospheric D (Figure 3 *c*), so that

during the dry period, water loss through the leaves was greatly reduced. Besides, as progressive drying of the soil occurred, LAI also got reduced by nearly 50% of the postmonsoon LAI (Table 1). In *A. auruculiformis*, the predawn ψ during the dry season reached less than -1.5 MPa (Figure 4 *c*).

The Et loss in *A. occidentale* (cashew), at Site 4 reached a little more than 1.0 mm/h and 6 mm/d (Figure 2 *d*). Although the differences in transpiration between the two seasons were not significant, there was a trend towards higher transpiration values during the premonsoon season (Table 2). However, the reference ET_0 showed significant difference between the two seasons. The stomata remained partially open even at higher values of D (Figure 3 *d*). The predawn ψ values during the dry season were rarely less than -0.5 MPa (Figure 4 *d*). Leaf shedding in this species occurred in December; however, the

trees flushed rather fast, so that during the dry period there was not much reduction in the LAI compared to the postmonsoon season.

T. grandis, the only indigenous tree species investigated in this study at Site 5, showed transpiration values reaching 2 mm/h and 13.4 mm/d during the postmonsoon season (Figure 2 *e*). The premonsoon values shown in Figure 2 *e* are measurements taken before leaf fall, which should not be considered as dry-season values. The differences between the two sets of values were significantly different ($P = 0.05$). Since the tree was totally leafless during the premonsoon season, it was assumed that the transpiration loss would be negligible. The reference ET_0 values showed significant differences between the two seasons. The stomatal closure mechanism in response to atmospheric D was well developed in *T. grandis* (Figure 3 *e*). The predawn ψ values during the wet part of the year were relatively very high, the leafless condition during the dry season did not permit us to record any leaf ψ measurement (Figure 4 *e*).

Root excavation studies

Results of the root excavation studies in *E. tereticornis* are presented in Figure 5. The root length density measurement showed that maximum rooting occurs in the top 30 cm soil layer. However, roots were present in considerable length to nearly 10 m depth in the soil. The root weight density was also the highest at the top layer, indicating the presence of larger diameter roots in this layer. The root weight density was negligible beyond 2 m depth, which is an indication that mostly finer roots occur in the deeper layers.

Discussion

The five tree species investigated in this article are distributed in five different sites in Kerala, having variable microclimate, although all the sites are located within a narrow range of tropical latitudes. For comparing the transpiration of the different species it would have been most ideal if they were all located at one site. However, this is not possible because of the climatic and edaphic requirements of the individual species, and hence in comparing them some subjectivity is bound to occur. The reference ET_0 as calculated by the FAO Penman–Monteith equation provides a standard to which evapotranspiration at different periods of the year or in different locations can be compared. Evapotranspiration of different crops can be also related. Since this article gives the transpiration Et values alone, as estimated from the Penman–Monteith equation, and not the other components of evapotranspiration, it has not been possible to derive a crop coefficient for each species. Crop coefficient values may not have much application in forestry plantation species,

hence the relation between Et and ET_0 has been expressed as a ratio in Table 2. This ratio has been found to be useful in understanding the water-use characteristics of the different species as well as in comparing their water use, especially since the locations are different.

In *E. tereticornis*, the not so well developed stomatal closure mechanism in response to increasing D, the failure to reduce the leaf area substantially during the dry season, and the relatively high predawn leaf water potentials indicate that this species is not a conservative water consumer in times of atmospheric demand. This is well illustrated in Table 2, where the differences in transpiration between the seasons are not as apparent as in other species. However, as the reference ET_0 is higher during the premonsoon season, the Et/ET_0 ratio is lower compared to the ratio of the postmonsoon season. This is certainly indicative of some stomatal control in this species, otherwise we should expect a much higher Et in response to a
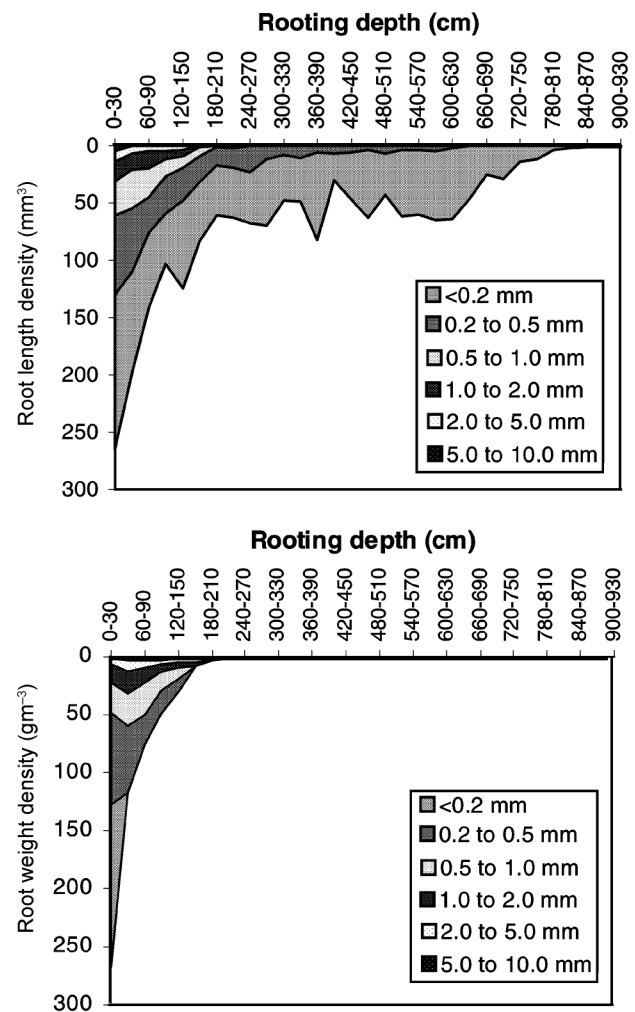
Figure 5. Root length and root weight density in *E. tereticornis*. The measurements are mean values from two excavations in a plantation, tracing roots of all size classes at 30 cm intervals. The different size classes are depicted with different shades.

higher reference ET_0. When the rooting depth studies in *E. tereticornis* are taken into account, the water use picture of this species becomes clearer. Since the species has a rooting depth of nearly 10 m, reaching the phreatic aquifer, the possibility of water extraction from deeper layers is very apparent. This could be the reason that the stomata show only partial closure during the dry season. In a location with seasonal rainfall, as in the present study site, the soil water content is depleted considerably in the surface layers after the monsoon rains. When the aquifer is relatively shallow ($\approx$10 m), there is the possibility for the root system to go in search of water. Although we have reported a rooting depth of 10 m in *E. tereticornis*, wide variations have been reported[13,14] in the literature regarding the rooting depth in eucalypts, going from 1 m to more than 30 m. It appears that as the rotation cycle of the plantation proceeds, the rooting depth simultaneously increases. Planting eucalypts with wider spacing can be expected to improve the water yield from catchments planted with this species, as the tree roots tend to have more space to spread laterally for extraction of water and minerals[15]. Although it could be argued that the more open canopy in a wider spaced plantation could promote higher soil-surface evaporation, it may be pointed out that in locations with a prolonged dry period, the soil forms a dry crest which prevents evaporation from the deeper layers[16].

The stomatal control of transpiration in *E. grandis* seems to be better developed compared to *E. tereticornis*. This is indicated by the complete closure of stomata in response to increasing D of the atmosphere. The postmonsoon and premonsoon values of transpiration are not significantly different in this species. However, the Et/ET_0 ratio shows much difference for the two seasons. The comparatively lower ratio during the premonsoon period indicates the well-developed stomatal closure mechanism in this species and therefore the adaptation for water conservation. The relatively high leaf water potentials during premonsoon and the not-so-apparent adjustment of the leaf area, as observed in some Australian studies[17], also suggest that it is mainly through stomatal control that excessive transpiration is regulated in this species in the current location. The equally high transpiration during premonsoon season in *E. grandis* is again an indication that only a deep rooting system that extracts water from the water-table can support such high water loss. Although the root system in this species has not been excavated in the present study, the authors have observed roots of *E. grandis* going deeper than 10 m at road cuttings.

In a study in Australia on tree water uptake in a pasture planted with eucalypts at different densities, it was found that in a densely planted site the water uptake was 30–40% higher compared to a low-density plantation[18]. During several months the transpiration of trees in a densely planted site was higher than the pan evaporation by more than 25%. This has been ascribed to deeper and denser root systems in the densely planted site. Researchers have also observed greater depletion of near-surface water near the more densely planted trees. However, the root length density was higher in low-density plantations. Several past studies have reported the extent of root system in eucalypts, which shows that the eucalypts have the capacity to extract water from deeper layers[13,14]. Calder[19] presented evidences for water mining by eucalypts from different parts of the world. The deep-rooting system is bound to enhance the dry season water-use in eucalypts, although the annual water use compared to other tree species may be the same. There is also a general assumption that the vegetation will tend towards structural and functional equilibrium with its environment. In the present study sites of eucalypts, it seems that the trees tend to regulate their water use only through the stomatal closure mechanism in response to both atmospheric and soil-water deficits. This mechanism is fairly well developed in both the eucalypt species studied at the two sites, though it is much better in *E. grandis*. Some observations support the higher water use of eucalypts due to wider xylem vessels compared to some other native trees growing under the same conditions[20]. We have not made any anatomical comparisons between the species to verify this point. Various studies conducted around the world, including the present study, indicate that eucalypts develop large leaf areas and transpire at high rates, when the atmospheric demand is high and water freely available in the soil[21,22].

A. auriculiformis, another exotic species widely introduced into India, has a well-developed stomatal closure mechanism in response to D, as seen from the results. This is a water-conserving feature, which will help prevent excessive water loss from the catchment during the dry period when water availability is most critical. This is apparent while examining the daily water use during the two seasons. There is a significant difference in Et between the two seasons. The vast difference in the Et/ET_0 ratio also sheds light on the great water-conserving character of this species during the dry months. Additionally, *A. auriculiformis* reduced the LAI considerably during the dry period (Table 1). A parallel study on the litter fall at the same site showed annual litter production of 10–12 tonnes/ha, of which nearly 75% occurred during the dry months (December–March) of the year[23]. The predawn leaf water potentials also decreased substantially during the dry season. All these ecophysiological features give indirect evidences to suggest that this species may not have a deep rooting system to extract water from deeper soil layers. Studies using sapflow gauges elsewhere in southern India, have also shown the conservative water-use trends in *A. auriculiformis* compared to other species[24].

A. occidentale, another exotic tree species introduced into Kerala more than three centuries ago, showed water-use characteristics similar to *E. tereticornis*. Here again, in spite of good stomatal responses to atmospheric D,

stomatal closure was only partial during the dry season. Similar observations have been made in Australia, where even at higher values of D (=7.0 kPa), the stomata were not completely closed[25]. It is because of this feature that in the present study the premonsoon Et is similar to the postmonsoon value, and the Et/ET_0 ratios are not very different. Relatively high predawn leaf water potential for this species during the dry period indicates water mining by this tree at the present site. Although the tree completely sheds its leaves at the start of the dry season, new flushes appear within two weeks and they mature during the dry period; thereby water consumption during the dry season is possibly high. Radio tracer studies conducted in identical locations have shown that the cashew trees have a deep rooting system, nearly 11 m deep, mostly reaching the water-table in these locations[26].

Et measurements in $T.$ $grandis$ have been made only during the postmonsoon period. The deciduous nature of $T.$ $grandis$ trees during the dry season does not allow any conductance measurements to be made. The postmonsoon values of Et show that it consumes a lot of water during the season, which is nearly twice that of the reference ET_0. However, the leafless nature of the tree helps conserve water during the dry period. In $T.$ $grandis$, where measurements have been made, the stomatal response to atmospheric D is also well developed. Because of the high conductance values noted in this species (which is a unique characteristic), the transpiration values are also relatively high. Similar conductance values have been observed for teak grown in Nigeria[27]. This species is also unique in shedding the entire leaves during the dry season, greatly reducing the transpiring surface. In deciduous trees, the possibility for deep extraction of water may not exist because during the dry period they are leafless and therefore water requirement by the tree is minimal. The rooting depth in a 4-year-old teak tree was reported[28] to be 1.35 m.

When we consider the different species for plantation programmes, especially in the tropics, where water conservation is also an important issue, the annual transpiration values are certainly interesting in a hydrological sense. This is especially true when we consider planting of exotic trees on a massive scale, as has been done in various forestry programmes in India[29,30]. However, the ecophysiological characteristics of the trees and the water consumption of the species during the dry season are more important while deciding the right species to be planted. The stomata of all the species investigated in this study have been found to respond to changes in atmospheric D; however, it is only in $E.$ $grandis$, $A.$ $auriculiformis$ and $T.$ $grandis$ that nearly complete stomatal closure was observed in response to increasing D. It has been shown in several other tree species that complete stomatal closure occurs only when soil water was limiting[17,31,32]. If this is true, it means that in species without stomatal closure or with partial stomatal closure, the roots are in

touch with the aquifer, as the surface soil layers will not be able to support the high transpiration rates reported in this study. Measurement of predawn leaf water potentials and excavations can help in understanding the rooting pattern of trees. In the Jarrah forests of Western Australia, it was found that seasonal patterns of predawn leaf water potential were connected to rooting depth[33]. In the present study, there were differences in the predawn leaf water potential values between the different species. For example, $A.$ $auriculiformis$ showed lower ψ values during the premonsoon season compared to other species. Since there are phreatic aquifers at all the sites, not so deep, the high predawn leaf water potential is indicative of tree roots accessing this water-table at least in some of the species investigated.

The magnitude of stomatal conductance in most of the tropical plants examined in the present study shows that they are much higher compared to temperate trees. Studies in the past have shown that the control of transpiration by the overall leaf area of a species was much more than the control exerted on a unit leaf area basis[17,34]. Our measurements and observations indicate that in water-limited situations (dry period), the stomata tend to close almost completely, especially if the roots are not in contact with the water-table. If the roots have access to water, although the stomata respond to the atmospheric D, the stomatal opening is only partially adjusted to the new environmental conditions. This is an important aspect to be investigated with regard to any species in the tropics before being considered for introduction as a plantation or agroforestry item.

Eucalypts, with a deep rooting system and access to more soil volume and phreatic aquifers, retain most of their leaf area, maintain relatively high leaf water potential and hence have the potential to consume more water during the dry period. However, the two eucalypt species investigated in this article show that the stomatal regulation of transpiration greatly helps in reducing transpiration during the dry part of the year. $A.$ $auriculiformis$ has good water-conserving features such as leaf shedding and stomatal control when it senses soil-water deficits. Hence with the added advantage of a fast-growing species, it could be introduced to locations where water conservation is also important. $A.$ $occidentale$ seems to be similar to the eucalypts in its water consumption. $T.$ $grandis$, with its deciduous habit during the dry season, is highly economical in its water use during this period, although the tree consumes a lot of water during the postmonsoon period, when water is freely available in the soil.

In general, the study points out the water-use characteristics of the different exotic and indigenous tree species generally used in forest plantations in the tropics. Measurements of transpiration by the above trees along with calculation of reference evapotranspiration help us to compare the different species growing in different locations. The study also reveals that not only transpiration, but

the ecophysiological features of the tree also play an important role in evaluating a species for plantation development in the tropics.

1. Whitehead, D. and Kelliher, F. M., A canopy water balance model for a *Pinus radiata* stand before and after thinning. *Agric. For. Meteorol.*, 1991, **55**, 109–126.
2. Stewart, J. B., Evaporation from forests. In Proceedings of the XVIII IUFRO World Congress, Kyoto, Japan, 1981, pp. 130–138.
3. Whitehead, D. and Beadle, C. L., Physiological regulation of productivity and water use in Eucalyptus – A review. *For. Ecol. Manage.*, 2004, 113–140.
4. Marshall, J. K, Morgan, A. L., Akilan, K., Farrell R. C. C. and Bell, D. T., Water uptake by two riverbed gum (*Eucalyptus camaldulensis*) clones in a discharge site plantation in the Western Australian wheat belt. *J. Hydrol.*, 1997, **200**, 136–148.
5. O'Grady, A. P., Eamus, D. and Hutley, L. B., Transpiration increases during the dry season: Patterns of tree water use in eucalypt open-forests of northern Australia. *Tree Physiol.*, 1999, **19**, 591–597.
6. Calder, I. R., Hall, R. L. and Adlard, P. G. (eds), *Growth and Water Use of Forest Plantations*, John Wiley, Chichester, UK, 1992, p. 381.
7. Poore, M. E. D. and Fries, C., The ecological effects of eucalyptus, FAO Forestry Paper No. 59. FAO, Rome, 1985, p. 75.
8. Kallarackal, J. and Somen, C. K., An ecophysiological evaluation of the suitability of *Eucalyptus grandis* for planting in the tropics. *For. Ecol. Manage.*, 1997, **95**, 53–61.
9. Monteith, J. L., Evaporation and environment. *Symp. Soc. Exp. Biol.*, 1965, **19**, 205–234.
10. Monteith, J. L., *Principles of Environmental Physics*, Arnold, London, 1973.
11. Campbell, G. S., *An Introduction to Environmental Biophysics*, Springer-Verlag, NY, 1977.
12. Allen, R. G., Pereira, L. S., Raes, D. and Smith, M., Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome, 1998, p. 49.
13. Knight, J. H., Root distributions and water uptake patterns in eucalypts and other species. In *The Ways Trees Use Water* (ed. Landsberg, J. J.), Rural Industries Research and Development Corporation, Australia, Publication No. 99/37, 1999, pp. 55–85.
14. Stone, E. L. and Kalisz, P. J., On the maximum extent of roots. *For. Ecol. Manage.*, 1991, **46**, 59–102.
15. Kallarackal, J. and Somen, C. K., Water use by *Eucalyptus tereticornis* stands of differing stand density in southern India. *Tree Physiol.*, 1997, **17**, 195–203.
16. Satterlund, D. R. and Adams, P. W., *Wildland Watershed Management*, John Wiley, NY, 1992, p. 236.
17. Landsberg, J. J., Tree water use and its implications in relation to agroforestry systems. In *The Ways Trees Use Water* (ed. Landsberg, J. J.), Rural Industries Research and Development Corporation, Australia, Publication No. 99/37, 1999, pp. 1–31.
18. Eastham, J. and Rose, C. W., Pasture evapotranspiration under varying tree planting density in an agroforestry experiment. *Agric. Water Manage.*, 1988, **15**, 87–105.
19. Calder, I. R., Water use of eucalypts – A review with special reference to South India. *Agric. Water Manage.*, 1986, **11**, 333–342.
20. Barrett, D. J., Hatton, T. J., Ash, J. E. and Ball, M. C., Transpiration by trees from contrasting forest types. *Aust. J. Bot.*, 1996, **44**, 249–263.
21. Cromer, R. N., Cameron, D. M., Rance, S. J., Ryan, P. A. and Brown, M., Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *For. Ecol. Manage.*, 1993, **62**, 211–230.
22. Myers, B. J., Theiveyanathan, S., O'Brien, N. D. and Bond, W. J., Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Physiol.*, 1996, **16**, 211–219.
23. Sankaran, K. V., Balasundaran, M., Thomas, T. P. and Sujatha, M. P., Litter dynamics, microbial associations and soil studies in *Acacia auriculiformis* plantations in Kerala. KFRI Research Report No. 91, Kerala Forest Research Institute, Peechi, 1993.
24. Graves, A., Berlinner, P. and Gev, I., Transpiration in two common tree species of Auroville, Tamil Nadu, India, using the calibrated heat pulse method to measure sap flux. *Curr. Sci.*, 1997, **72**, 196–201.
25. Schaper, H. and Chacko, E. K., Diurnal variations in gas exchange and water relations of cashew leaves (*Anacardium occidentale* L.). *Gartenbauwissenschaft*, 1992, **57**, 88–92.
26. Khader, K. B. A., Distribution of cashew roots in the laterite soils of west coast of India. *Indian Cashew J.*, 1986, **17**, 15–19.
27. Whitehead, D., Okali, D. U. U. and Fasehun, F. E., Stomatal response to environmental variables in two tropical forest species during the dry season in Nigeria. *J. Appl. Ecol.*, 1981, **18**, 571–587.
28. Kallarackal, J., Chacko, K. C. and Somen, C. K., Belowground carbon stocking potential in some tropical plantations. In Proceedings of the 2003 International Conference on Tropical Forests and Climate Change, College of Forestry and Natural Resources, University of Philippines, Philippines, 2003, pp. 150–161.
29. Rajan, B. K. C., *The Versatile Eucalyptus*, Diana Publication, Bangalore, 1987, p. 243.
30. Tewari, D. N., *Monograph on Eucalyptus*, Surya Pubs., Dehra Dun, 1992, p. 373.
31. Landsberg, J. J. and Waring, R. H., A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.*, 1997, **95**, 209–228.
32. Sands, P. J. and Landsberg, J. J., Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. *For. Ecol. Manage.*, 2001, **163**, 273–292.
33. Crombie, D. S., Tipett, J. T. and Hill, T. C., Dawn water potential and root depth of trees and understorey species in south Western Australia. *Aust. J. Bot.*, 1988, **36**, 621–631.
34. Smith, D. M., Water use by windbreak trees in the Sahel, Ph D thesis, University of Edinburgh, UK, 1995.