

# **The water use of plantation forests and montane grassland in summer-rainfall forestry regions of South Africa**

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## **Introduction**

Recent droughts in many of the summer rainfall regions of South Africa have fueled the long-standing debate over the influence of forest plantations on streamflow arising from mountain catchments. This debate has become clouded recently by highly divergent claims and counter claims of the rate of water use by trees. The resultant confusion has seriously impeded understanding of the likely hydrological impact of land use changes, especially among those who lack a biological or hydrological background. The purpose of this paper is to review some of the reasons why water use estimates vary so greatly, and to point out important considerations which should be borne in mind when assessing likely changes in water use rates following changes in land use.

## **Factors to consider in evaluating estimates of water use rates**

1. Indirect estimates of water use should be used with caution.

Direct measurement of the rates of water use by plants is often technically difficult, and so estimates have frequently been based on indirect methods such as observed rates of soil water depletion. The use of such indirect estimation methods can easily lead to erroneous results. For example, soil water depletion rates are seldom recorded from the entire root profile depth beneath forests, since measurements become difficult in the deeper, often rocky, subsoil horizons. Since it is well documented that tree roots may penetrate into deep subsoil strata, soil water abstraction recorded only from the true soil profile may often be an underestimate of the total water used by trees.

Our understanding of evaporation rates from plantation forests and grasslands has been greatly improved in recent times through the use of the heat pulse velocity method for measuring sap flow in trees, and the Bowen ratio micrometeorological method for measuring evaporation from uniform and extensive mixed-species canopies. These methods have provided the data used to illustrate this paper. The former method is well suited to measuring water use rates in even-aged forest plantations, and has been successfully tested in both eucalypts (Olbrich, 1991) and pines (Dye *et al*, 1992) in the Eastern Transvaal. The Bowen ratio method has been used for long-term monitoring of evaporation rates in indigenous montane grasslands and a *Eucalyptus smithii* plantation in the Cathedral Peak area of KwaZulu/Natal (Everson, 1993). Full descriptions of these techniques are given in the quoted references, and are therefore not repeated here.

2. Average annual water use rates must adequately represent both daily and seasonal variation

in evaporative conditions

Figure 1 shows the mean daily sap flow measured in four 3-year-old *Eucalyptus grandis* trees over a 13 month period on Frankfort State Forest in the vicinity of Sabie, Eastern Transvaal. The data clearly show large day-to-day variation in water use which is caused primarily by changes in air humidity. Figure 2 shows the relation between average daytime vapour pressure deficit (between 05h00 and 19h00) and the measured mean daily sap flow of the same four sample trees for November and December 1992. A second series of data from four 9-year-old *E. grandis* trees on the same plantation and for the same period, are also shown. The function was fitted to the data applicable to the 3-year-old trees, but adequately describes the older trees as well. Both age classes of trees respond in a similar fashion to the average air humidity, limiting their transpiration rate to a relatively constant maximum rate as the average daily air vapour pressure deficit (VPD) rises beyond approximately 1 kPa. This control is exerted through stomatal control of leaf transpiration.

Marked seasonal changes in water use are also apparent in figure 1. Lowest water use occurs during winter when day length is short, solar radiation is relatively low, and when low temperatures inhibit the occurrence of excessively dry air. A marked increase in water use is seen in early September. This reflects the rapid increase in temperature at this time of year, which is also linked to lower air humidity and higher wind speeds. The sharp increase is also a reflection of a physiological change in the leaves of this species during spring (Dye and Olbrich, 1993) which results in higher rates of transpiration for given air humidity levels. The underlying physiological mechanism remains unknown. Highest daily water use occurs on dry, hot days around mid-summer when day length is longest.

### 3. Normal water use rates may decline during times of significant soil water deficit

Under conditions of non-limiting soil water availability, transpiration occurs at a potential rate governed by weather conditions and a relatively high rate of water diffusion through the open stomata of the leaves. However, if soil water is in short supply, the rate of transpiration drops as the leaf stomata close to reduce the rate of water loss. An example of a rapid decline in daily water use was recorded in eucalypt clones growing in an irrigation trial at Mkuzi, Zululand. Sap flow rates were monitored at a time when a severe drought forced the abandonment of irrigation (Fig 3). The rapid reduction in tree water use was brought about by increased stomatal control of water evaporating from the leaves, especially around midday and in the afternoon (figure 4), when the evaporative demand in the air is highest. Thus, water use may be substantially less than the potential rate over periods when significant soil water deficits occur.

Soil water deficits may also account for seasonal differences in water use among different species. An example of such a difference, brought about by differences in rooting depths has been recorded for *E. grandis* and *P. patula*. Patterns of soil drying beneath both species were measured with a neutron probe moisture meter at various Eastern Transvaal sites characterized by deep granite-derived soils. These data have shown *E. grandis* to have an extremely deep root system. Figure 5 shows the soil drying pattern recorded under a stand of 3-year-old trees on Frankfort State Forest near Sabie. Soil water abstraction is clearly taking place down to the maximum recorded depth of 8 m, and probably to a still greater depth.

Comparable data recorded beneath a stand of 9-year-old *E. grandis* trees demonstrated that nearly all the water requirement by these unstressed trees was abstracted from below 8 m (Dye, 1993b). In contrast, figure 6 depicts a comparable situation under a stand of 9-year-old *P. patula* trees, and shows substantially less uptake of soil water below 5 m. These trees have less soil water available to them during the dry winter months, and are therefore more likely to experience soil water deficits and exhibit reduced transpiration rates than the deeper-rooted eucalypts. This difference has been demonstrated (figure 7) by comparing the pre-dawn water status of both eucalypts and pines in different seasons of the year. Measurements of pre-dawn xylem pressure potential (mean of five trees) were recorded in four different pine compartments with trees aged 5, 7, 10 and 12 years. The trees in all four compartments showed distinctly more negative water potentials in winter, contrasting with the measurements for 3-year-old eucalypts.

#### 4. Deep soils may buffer the reaction of plantation trees to drought.

Where eucalypts grow on deep soils in areas of relatively high rainfall, they show an extraordinary ability to obtain sufficient soil water to maintain normal transpiration rates in the face of drought. In June 1992 (following the severe drought of 1991/92), a stand of trees on Frankfort State Forest were subjected to an artificial drought by covering the soil surface with plastic sheeting. Soil water recharge was entirely prevented to a radius of 15 m from four monitored trees at the centre of the plot. The plastic remained in place for 13 months. At the end of this period, the monitored trees had still not shown any marked drought symptoms, due to the ability of the deep root systems to access a large store of soil water from the approximately 30 m deep profile.

Additional evidence for the large buffering capacity of deep soils came from the Mokobulaan hydrological research catchments on Uitsoek State Forest in the Lydenburg district of the Eastern Transvaal. Deep drilling at two localities within these catchments revealed moist permeable profiles to depths of 30 and 45 m respectively (Dye and Poulter, 1992). Streamflow in one of the originally grassland catchments which was planted to *E. grandis* gradually diminished after the second year, and entirely ceased flowing after 10 years from the time of planting. In 1985, the trees were clearfelled, and measures were adopted to control regrowth. Despite minimizing evapotranspiration in this way, it was four years before the stream reappeared again.

The implication of a large buffering subsoil moisture store is that deep-rooted trees may be highly resistant to drought until such time as the store of soil water is depleted to the maximum rooting depth. Tree water use over this time may not be constrained by the amount of annual rainfall falling on the site. Conversely, once the subsoil moisture store has been depleted, several years of soil water recharge may be required before the original streamflow is regained. Thus, streamflow response to land use changes may be lagged by several years.

## 5. The amount of green leaf area affects the water use of plants

The total functional leaf area on a tree determines the amount of transpiring surface, since very little water is lost directly through the branches and trunks. Within forest plantations, the competition among trees for light, water and nutrients is high. Consequently, such trees have a lower total leaf area than trees of similar size growing along the compartment edge or in the open, where competition for resources is reduced. Such trees develop a deeper crown and higher leaf area, and may use much more water than trees within plantations. For example, the sap flow within a large, north-facing *E. grandis* tree with a particularly high leaf area was measured on a warm, dry spring day on Frankfort State Forest, and found to total 722 litres. Similarly, a very large *E. grandis* tree growing in an open area close to the Sabie river in the same vicinity was found to use 664 litres on a warm summer day. Such high sap flow rates are not encountered in plantation trees.

The leaf area of plantation trees changes naturally during the course of a growth cycle, and is also altered by management activities such as thinning. Figure 9 shows how leaf area index (the ratio of leaf area to ground area) changes in a *Eucalyptus* plantation managed for sawtimber. There are clearly large changes in leaf area index over the rotation, and a broadly similar change in stand water use can be expected. Considerably less change in LAI takes place in *Eucalyptus* stands managed for pulpwood, since thinning is not practiced, and the rotation length is relatively short. These differences raise the interesting possibility that plantations managed for sawtimber may use less water over the long term than those managed for pulpwood.

The leaf area index of *E. grandis* has been observed to decline in response to severe drought stress, and this behaviour represents a further means by which this species reduces transpiration.

Montane grasses exhibit a steady increase in green leaf area from early spring to mid summer, and a corresponding decrease into autumn and winter. These changes are reflected in figure 10 which depicts a two year record of daily evaporation measured in montane grassland at Cathedral Peak. Evaporation rates during summer are as high as those recorded from forest plantations, but are considerably reduced by mid to late winter, when much of the evaporation is from wet soils and plant surfaces following dew or occasional light rain. Winter evaporation rates from grasslands are likely to be even less at lower altitudes which are characterized by lower mean annual rainfall and warmer, drier weather. The difference in winter transpiration rates between grasslands and forest plantations is believed to be the principle reason for reduced streamflows following afforestation of grasslands.

## 6. The density of trees must be considered when scaling up tree water use figures to whole stands of trees.

A wide range of tree spacings is found in forest plantations. Initial planting densities and thinning operations vary according to the species planted and the use to which the timber will be put. Comparisons of the water use of stands with different densities of trees are best made not on the basis of individual tree sap flows, but by expressing water use in terms of the equivalent depth of water. In the case of plantation trees, an average water use per tree

(litres) is multiplied by the number of trees per given area, and divided by the area in square metres. Figure 1 shows that peak mid summer transpiration rates approached 7 mm per day for trees growing at a density of 740 trees per hectare. By contrast, a group of 9-year-old *E. grandis* trees displayed peak mean sap flow rates of approximately 140 litres per day, but this was equivalent to just over 4 mm per day since the trees grew at a density of 314 trees per hectare.

7. Water use by understorey vegetation may comprise a significant proportion of the water use of forest plantations.

Understorey plants may contribute a significant fraction of the total water loss from forest plantations, especially at the start and towards the end of a rotation when the leaf area index of the trees is low. No information is available on the water use rates of understorey plants in South African forest plantations. Studies based on heat pulse velocity measurements only measure the water use of the trees, while Bowen ratio studies have recorded combined evaporation rate from both the trees and the understorey. Research overseas has shown that understorey plants may account for a major proportion of the water loss from forest plantations (mostly conifers), particularly under warm and dry conditions. Thus, Tan and Black (1976) showed that understorey plants in a Douglas fir plantation in Canada could account for up to 70% of evaporation from the total forest plantation. Roberts *et al* (1980) showed that bracken growing beneath a Scots pine in England could contribute up to 60% of forest transpiration under dry conditions, and 25% under normal conditions. Greenwood *et al* (1985) found that evaporation from the lower and middle storeys of a *Eucalyptus marginata* forest accounted for 32-36% of annual rainfall at the site. Black and Kelliher (1989) summarized the percentage of forest stand evaporation accounted for by understorey transpiration or forest floor evaporation in 11 separate studies, and showed it to average 29%.

8. The magnitude of canopy interception losses in forest plantations

Studies in temperate forests have generally shown that the rapid evaporation of intercepted rainfall from tree canopies is an important loss, comprising 20-40 % of gross rainfall. This loss is substantially smaller in grasslands and heaths, and the difference accounts for much of the observed increase in evapotranspiration following afforestation in temperate climates. Two rainfall interception experiments were undertaken in the Sabie area, in a 4-year-old *E. grandis* and in a 9-year-old *P. patula* stand (Dye, 1993a). For each rainfall event, the difference between gross rainfall measured above the canopy, and throughfall and stem flow beneath the canopy, was ascribed to canopy interception. These studies revealed that canopy interception loss amounted to 13 % of gross rainfall in the *P. patula* stand (based on 125 rainfall events), and only 4.1 % in the *E. grandis* stand (based on 56 rainfall events). These losses are much less than those reported in many temperate forests, but reflect the less frequent and more intense rainfall characteristic of most summer rainfall forestry regions. Both these features ensure that interception loss is a relatively small proportion of gross rainfall. From these results, we conclude that transpiration from dry canopies is the dominant evaporation process. Rainfall interception loss on grassland canopies is likely to be similar to *Eucalyptus* plantations, but less than in pine canopies.

9. Following a change of land-use, the difference in rate of water use between the original vegetation and the replacement vegetation determines the net change in water use

A frequent, erroneous assumption is that by clearing plantation trees, the entire previous transpiration rate is saved and is available to downstream users. It is important to remember that some type of replacement plant community is eventually established, and that the water use of this community must be deducted from that of the original plantation to determine the net decrease in evapotranspiration.

10. An upper limit to water use rates is set by the availability of energy for evaporation

Measurements of net radiation above forest canopies indicate the amount of energy available to satisfy the latent heat demand for the conversion of water to vapour during the process of evaporation. A theoretical maximum evaporation rate was calculated on the basis of hourly net radiation readings recorded above a 6-year-old *E. grandis* canopy on a cloudless day close to the summer solstice (8 December) near Sabie. By assuming that net radiation was entirely converted to latent heat, a total daily evaporation of 9 mm was calculated. This is only an approximation of the upper limit of such a stand, since stomatal and canopy boundary layer resistances and energy storage in biomass would tend to reduce evaporation rates, while advective energy input from surrounding areas could permit higher evaporation rates. The influence of advected energy on crop evaporation rates is particularly marked in irrigated plants growing under arid conditions. Advection is likely to be less important in afforested regions where the difference in evaporation between plantations and surrounding vegetation is likely to be less extreme, but may be significant under berg winds conditions, for example. Peak water use estimates much greater than 9 mm per day should be treated with caution. The corresponding value for a cloudless, mid-winter day was 3.6 mm, reflecting lower net radiation values and a shorter day length.

## Conclusions

The rate of water use by forests and grasslands is shown to be highly variable, responding to changes in weather conditions, season, soil water availability, leaf area, plant density and species. All these factors must be considered when assessing the long-term hydrological consequences of land use changes.

## Acknowledgements

Research results from a range of studies have been drawn on for this review, and the Water Research Commission, the Department of Water Affairs and Forestry, and Mondi Forests are gratefully acknowledged for funding these studies.

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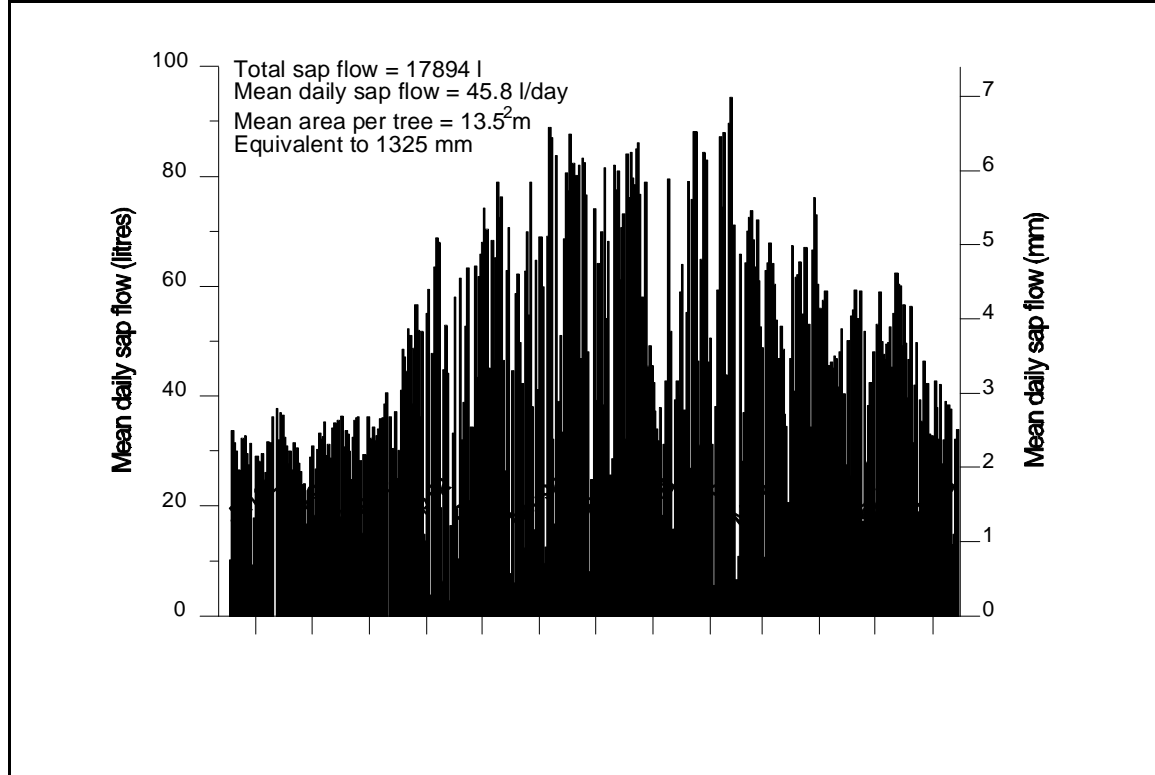


Figure 1. Average daily sap flow of four 3-year-old *E. grandis* trees growing on deep granite-derived soils in the Sabie area, Eastern Transvaal.

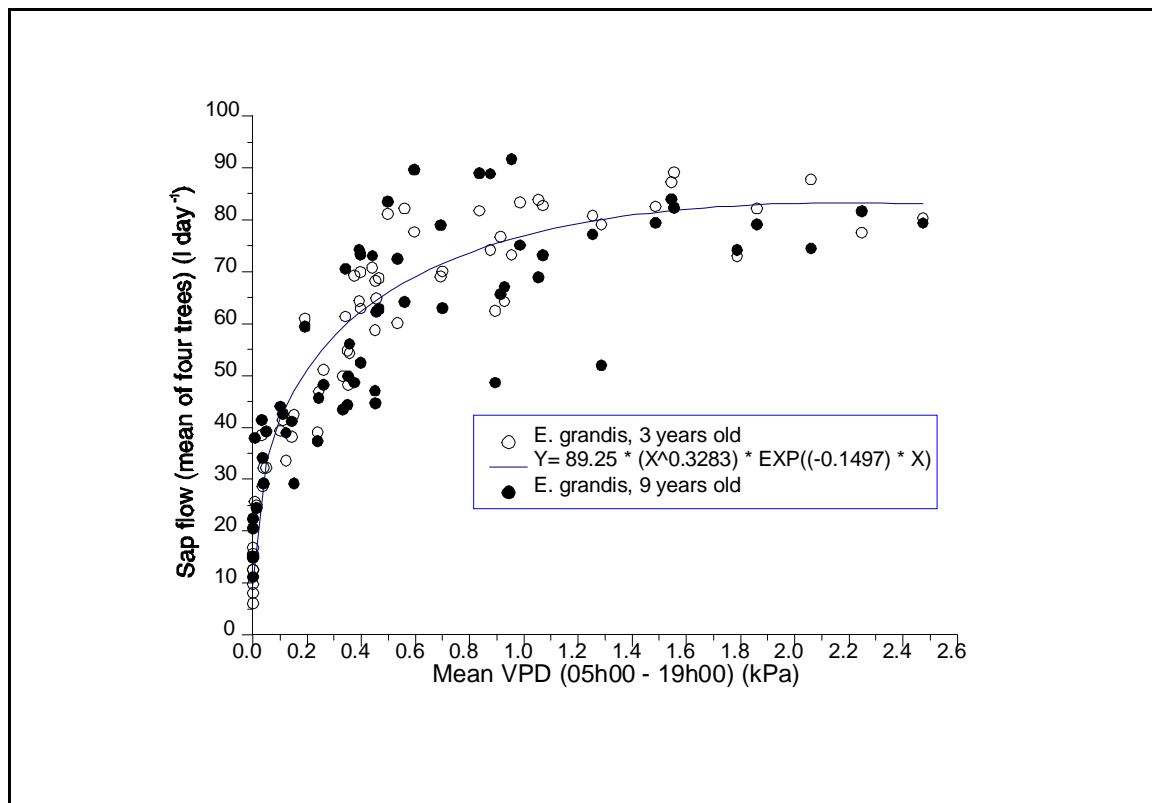


Figure 2. The relation between mean daytime vapour pressure deficit and daily sap flow (average of four trees) in a 3-year-old *E. grandis* stand and a 9-year-old *E. grandis* stand in the Sabie area, Eastern Transvaal.



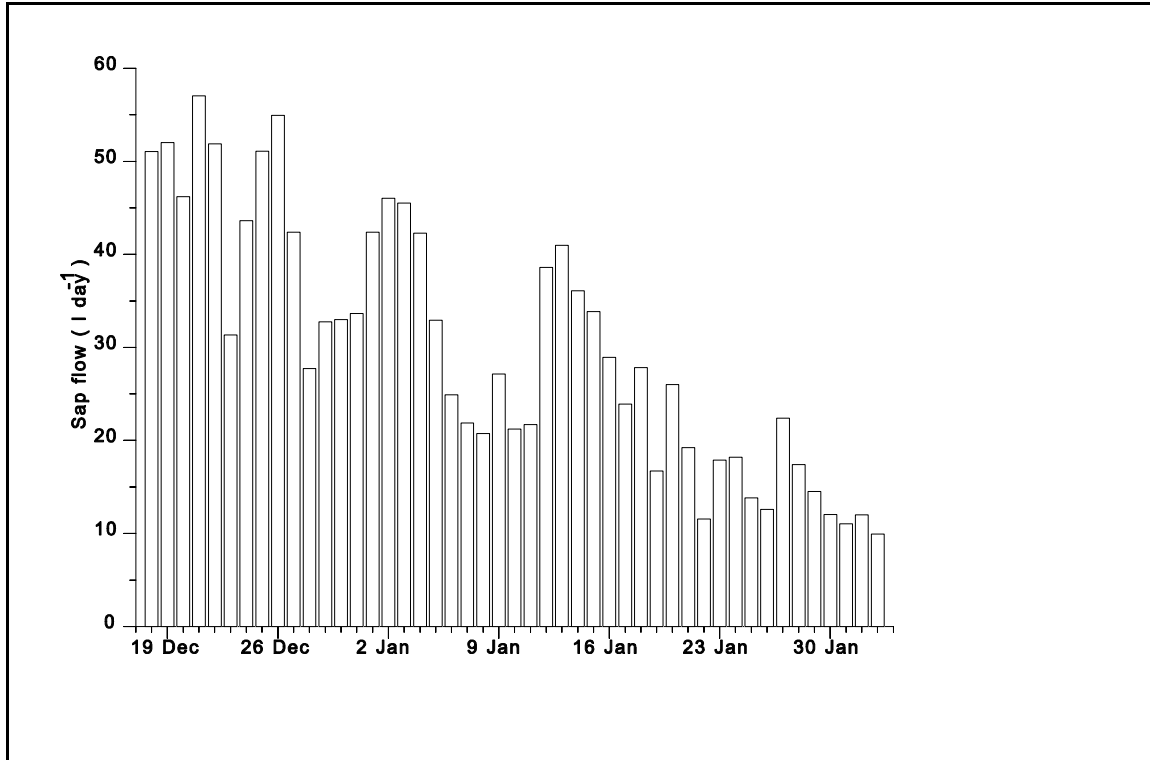


Figure 3. Daily sap flow recorded in the *Eucalyptus* clone GC540 (mean of four trees) growing in an irrigation trial at Mkuzi, KwaZulu/Natal, during 1992/1993.

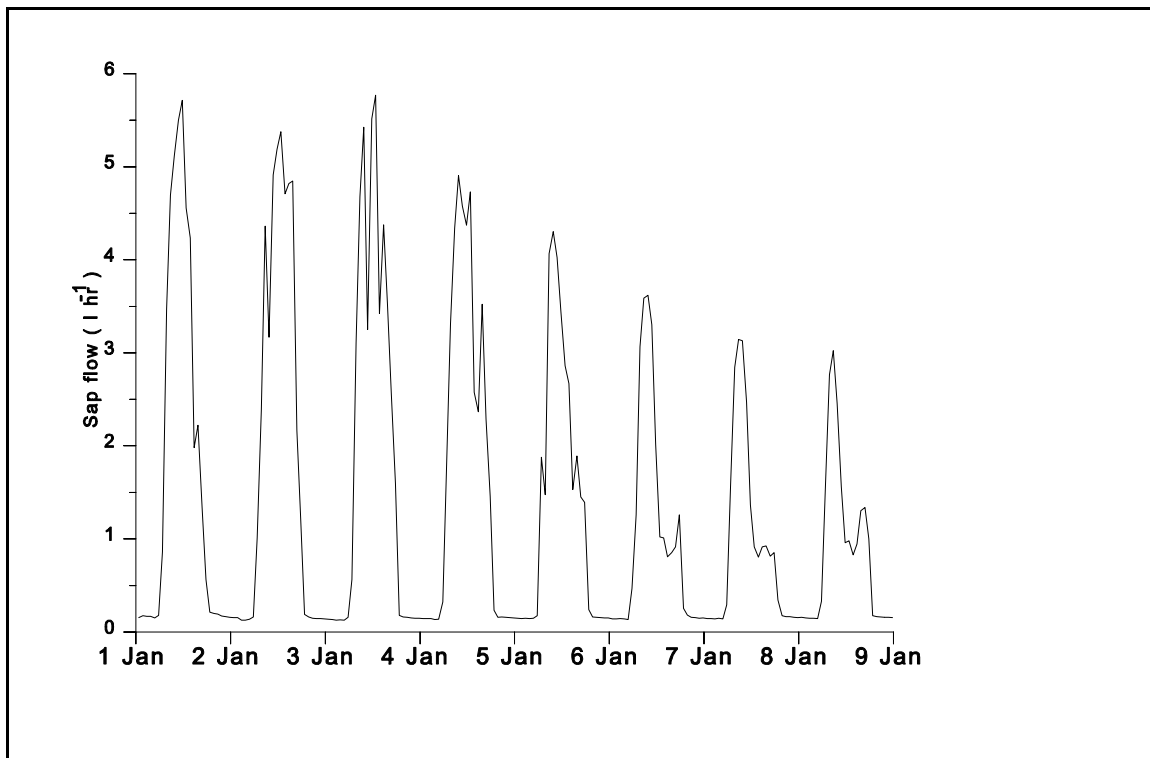


Figure 4. The hourly pattern of sap flow recorded in the *Eucalyptus* clone GC540 (mean of four trees) growing in an irrigation trial at Mkuzi, KwaZulu/Natal, during 1993.

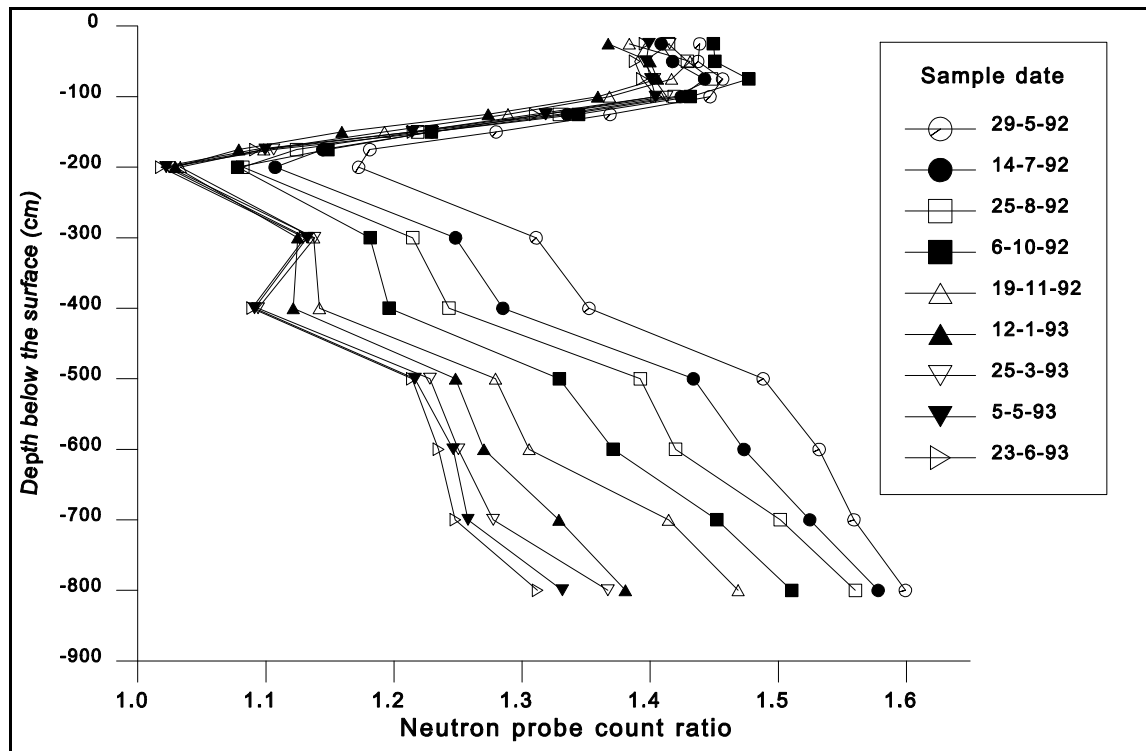


Figure 5. Changes in neutron probe count ratio (mean of ten access tubes) recorded beneath a stand of 3-year-old *Eucalyptus grandis* trees on Frankfort State Forest, Eastern Transvaal.

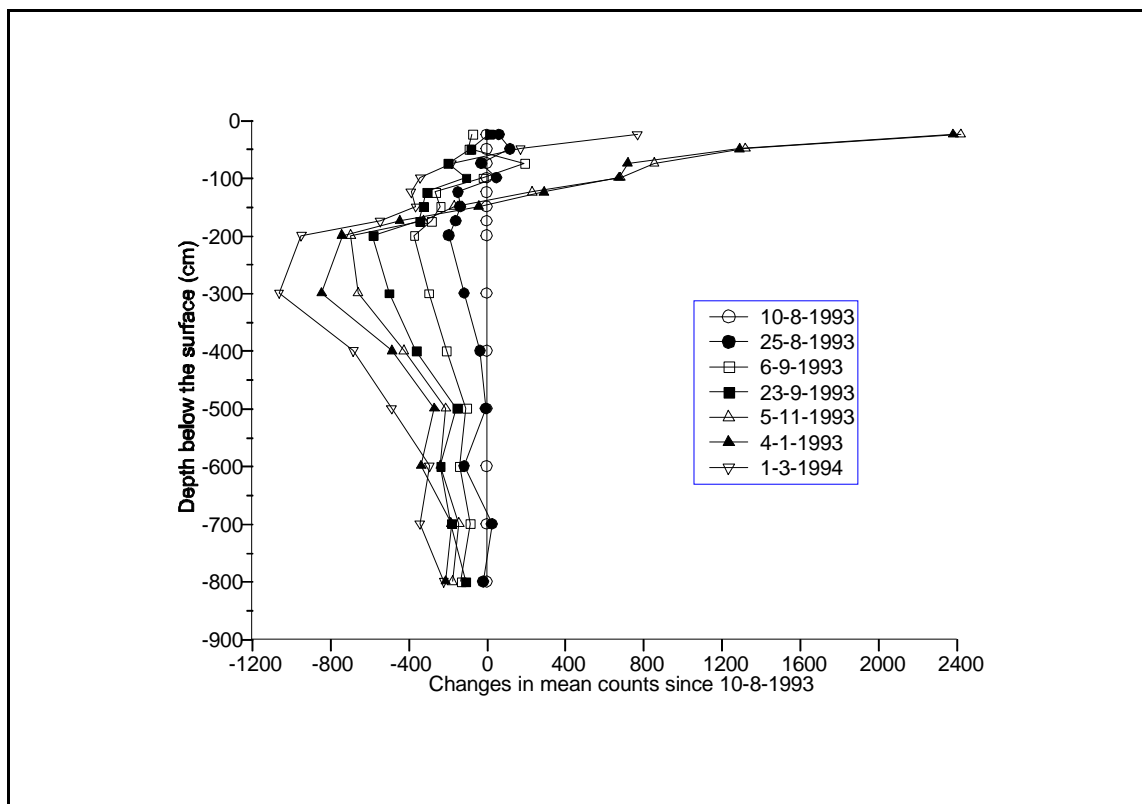


Figure 6. Changes in neutron probe count ratio (mean of ten access tubes) recorded beneath a stand of 9-year-old *Pinus patula* trees on Witklip State Forest, Eastern Transvaal.

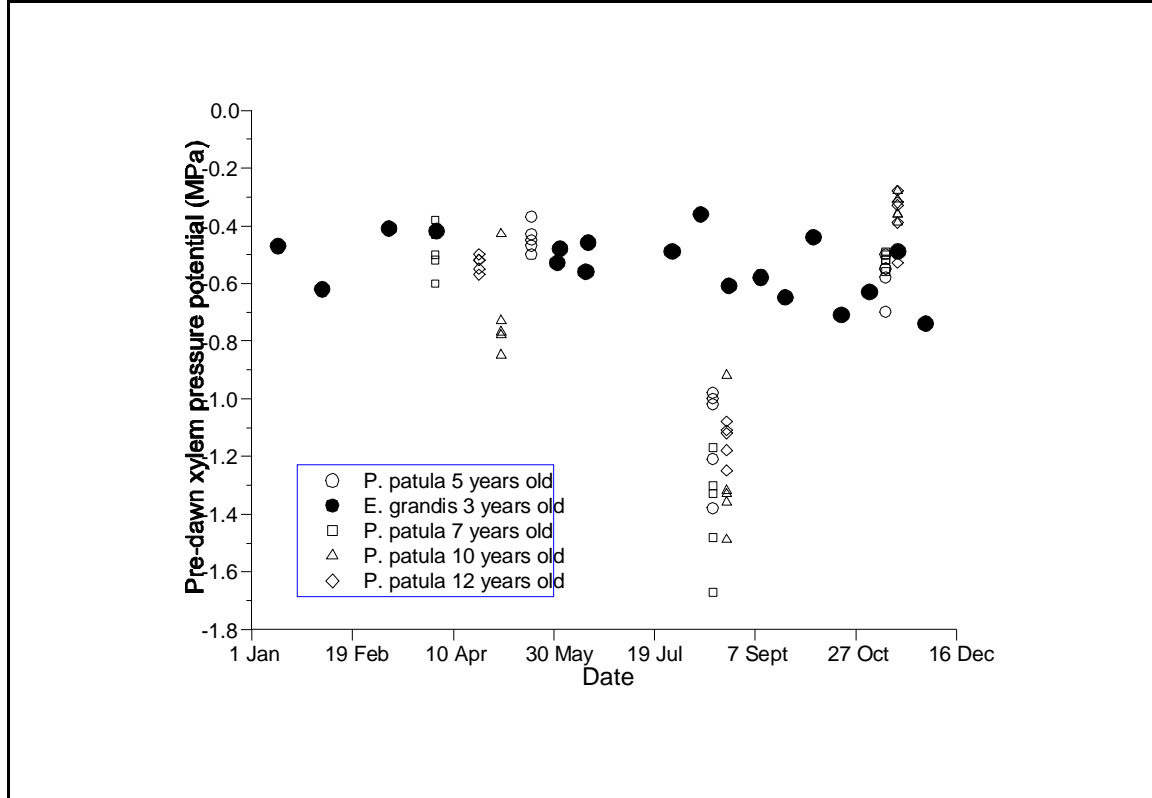


Figure 7. The annual pattern of pre-dawn xylem pressure potential recorded in a stand of 3-year-old *Eucalyptus grandis* trees, and in four different compartments of *Pinus patula* aged 5, 7, 10 and 12 years, respectively, all growing on deep granite-derived soils in the Sabie area.

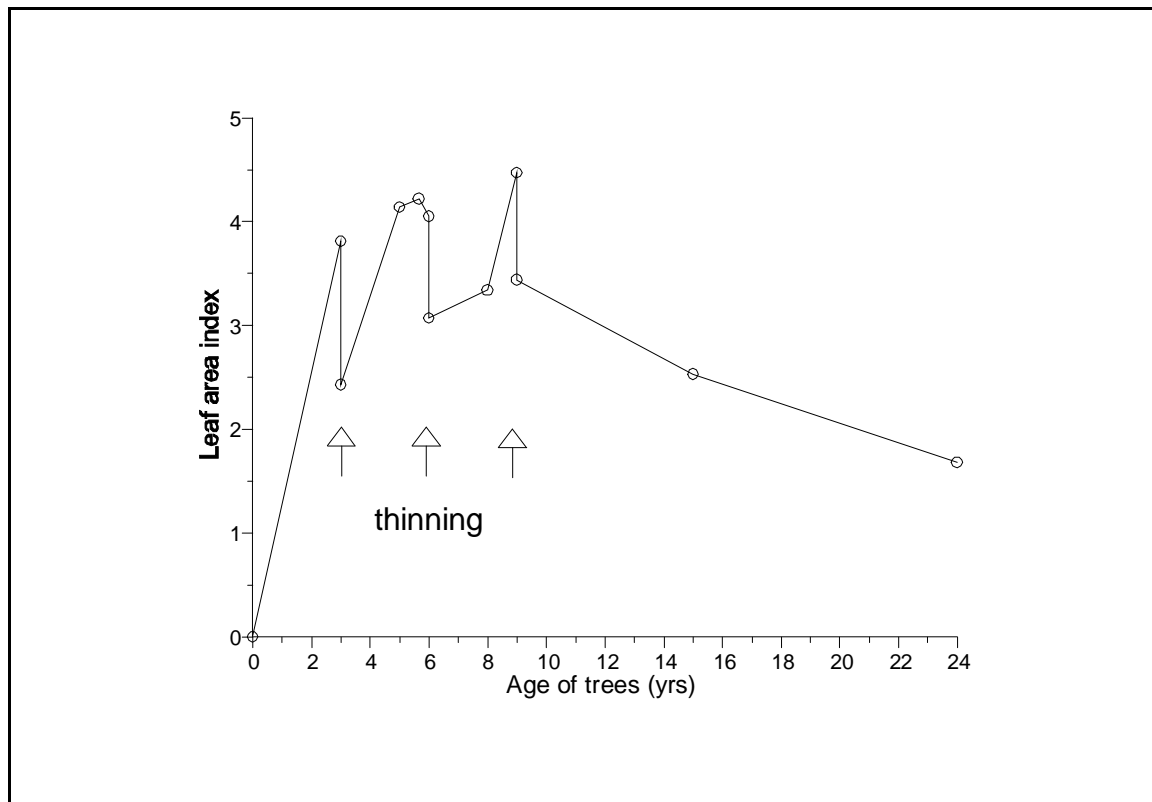


Figure 8. The trend in leaf area index recorded in different age classes of *Eucalyptus grandis* in the Sabie area. The stands were managed for sawtimber.

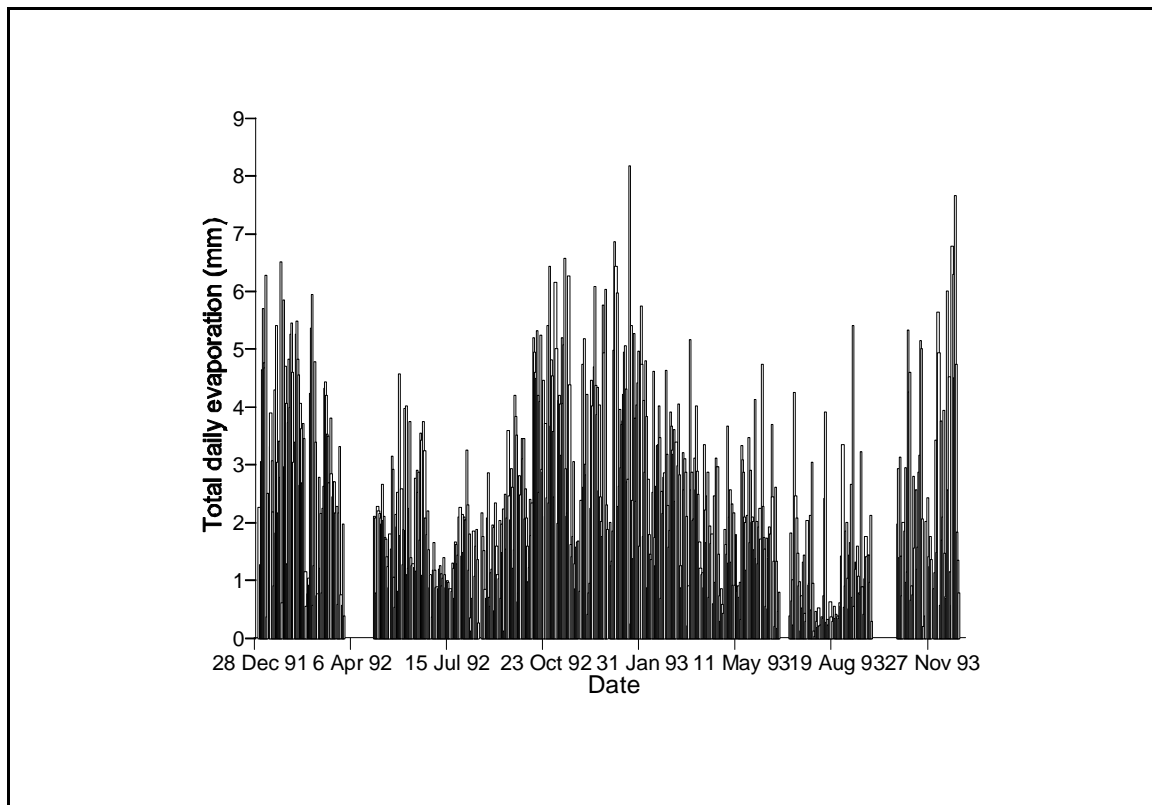


Figure 9. Daily evaporation totals recorded from montane grassland at Cathedral Peak, using Bowen ratio instrumentation.