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Eucalyptus water use greater than rainfall input—a possible explanation from southern India

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Abstract

Hydrological and silvicultural studies carried out in southern India on the effects of plantations of *Eucalyptus* and other fast growing exotic tree species have determined the impacts of these plantations on water resources, erosion, soil nutrient status and growth rates at sites of differing rainfall and soil depth in Karnataka. Whilst providing new information on these issues, the studies also raised two important questions: what was the explanation for the anomalous result that the water use of 3400 mm from *Eucalyptus* plantations at Hosakote over a three year period exceeded the rainfall of 2100 mm over the same period and why were growth rates of woodlots on most farmer's fields higher than those of plantations on land owned by the Karnataka Forest Department? The records of the soil moisture depletion patterns under these plantations from the day of planting provide the basis for the answers to both questions: i) whilst roots are penetrating into deeper soil layers, they are able to extract from a reservoir of water additional to that available from the rainfall each year, ii) farmer's land on which short rooted agricultural crops have been grown previously is likely to have a much higher soil water status than land previously under forest or scrub vegetation. These new studies have also established that the development of the drying front under the *Eucalyptus camaldulensis* plantations is very rapid, indicating average root extension rates in excess of 2.5 m per year, whilst those under *Tectona grandis* and *Artocarpus heterophyllus* advanced at approximately half the rate. These results have obvious implications for the long term sustainability of growth rates from these plantations and the recharge of groundwater.

The authors believe that this study may be the first to report neutron probe soil moisture depletion observations, from the date of planting, beneath tree plantations in a dry climate. The extent to which the roots were able to penetrate raises the question of whether other studies, which have estimated water use from soil moisture observations in dry climates, may have seriously underestimated both the actual soil moisture depletion and the water use through having soil moisture measurements located to insufficient depth.

Introduction

To investigate the environmental effects of plantation forestry using fast growing tree species, and in particular *Eucalyptus* species, a programme of field studies was initiated in 1987 by the Karnataka Forest Department and Mysore Paper Mills Ltd in the state of Karnataka, southern India. The Institute of Hydrology and the Oxford Forestry Institute, both of the UK, provided technical support for the hydrological and silvicultural aspects of these studies. The initial findings from these studies were presented at an International Symposium held in Bangalore in February 1991 (Calder *et al.*, 1992) and the further hydrological findings were presented in a summary report (Calder, 1995).

The hydrological studies involving *Eucalyptus* species were carried out at sites in the low rainfall zone (800 mm per annum) at the Devabal and Puradal experimental plantations managed by Mysore Paper Mills Ltd, near Shimoga and at the Hosakote experimental plantations managed by the Karnataka Forest Department, near Bangalore. The soils are of different depths, approximately 3 m at Devabal and Puradal and in excess of 8 m and possibly as much as 30 m at the Hosakote site.

Measurements were made of the meteorological and plant physiological variables, soil water status, rainfall interception and of the direct water uptake of individual trees using tracing measurements. Measurements were also made of the growth rates of the trees. Estimates of water use from the different experimental methods, physiological studies (Roberts *et al.*, 1992), soil moisture studies (Harding *et al.*, 1992) and tracing studies (Calder *et al.*, 1992) were generally in agreement at the different sites. The main findings were (Calder *et al.*, 1992):

1. The water use of young *Eucalyptus* plantation on a medium depth soil (approximately 3 m depth) was no greater than that of the indigenous, semi-degraded, dry deciduous forest.
2. The annual water use of *Eucalyptus* and the indigenous, semi-degraded, dry deciduous forest approximated the annual rainfall (within the experimental measurement uncertainty of about 10%).
3. At all sites, the water use of forest was about twice that of a commonly grown annual agricultural crop, ragi *(Eleusine coracana)*.
4. At the deep soil site (> 8 m) there were indications that the water use over the three (below average rainfall) years of measurement was greater than the rainfall. Model estimates of evaporation, calibrated using the deuterium tracing method, were 3400 mm as compared with 2100 mm rainfall for the three year period.

The studies also established (Calder, 1992) a close relationship between growth and transpiration rates and showed that at all sites the principal limit on growth rate was water availability.

Forest mensuration studies (Adlard, 1992) also established that, of the 120 permanent sample plots monitored within both industrial and farm forestry plantations, those with the highest growth rates generally were owned by private farmers rather than either Karnataka Forest Department or Mysore Paper Mills Ltd.

Explanations for how the water use of plantations at the Hosakote site could exceed the rainfall input, known as the 'Hosakote anomaly', and why the growth rates should be higher from plantations grown on the farmer's fields could not be provided at the completion of the original studies. However, both questions raised important issues about the long term sustainability of the forest growth rates and the impacts of these plantations on water resources and groundwater recharge. Hypotheses proposed to explain the high water use were:

One hypothesis invokes soil water 'mining'. If, from the day of planting, roots penetrate successively deeper layers in the soil each year, at a rate exceeding about one metre per year, the water 'mined' from existing storage in successively deeper soil layers would account for most of this extra water. This implies that the trees are drawing on water stored in the soil from years with higher than average rainfall. The original measurement period, from 1987–1990, had much lower than average rainfall. Hence unless roots continue to penetrate deeper each year to access stored water until they reach the water table (at 30 m), present rates of growth will not be sustainable in the long term.

The explanation for the higher growth rates of plantations on farmer's fields was also thought to be linked to soil water storage. The moisture status of land under an annual agricultural crop such as ragi, is much higher than that under forest or scrub because of its reduced annual evaporative loss as a consequence of its shorter rooting depth. Soil moisture observations (Harding *et al.*, 1992) indicated that the soil returned to field capacity each year under ragi but rarely, if ever, under forest. The hypotheses that needed to be tested were therefore:

1. that the higher growth rates of plantations on farmer's fields were the result of the greater soil water storage within the profile following annual agricultural crops: this was available to the trees in addition to that supplied by the rainfall;
2. that the large excess in the evaporation over the rainfall supply at the Hosakote site was being supplied from the soil moisture reservoir and that during dry years a greater proportion might be supplied from the soil.

To test these hypotheses, the Farmer's Field Experiment was initiated at Hosakote in 1992. The study involved the monitoring, from the day of planting, of growth rates and soil moisture depletion for three tree species on land which had previously been used for growing short rooted agricultural crops for at least ten years. Tree species in addition to *Eucalyptus* were investigated in the study because, although the water use and deep rooting nature of *Eucalyptus* had been established during the earlier studies, it was not known whether the high water use and deep rooting behaviour were unique to *Eucalyptus* or whether they would be similar for other commonly planted, commercially important, tree species.

Site description

The location of the experiment was adjacent to the Karnataka Forest Department's nursery and experimental plantation at Hosakote (77° 49′ E, 13° 07′ N), 30 km due east of Bangalore, the capital of the state of Karnataka. The farmer's field used for the study has dimensions of approximately 250 m × 50 m, sufficient to accommodate six square plots of trees, each 25 m × 25 m. The field is located about 500 m from the original site at Hosakote where the water use studies of *Eucalyptus camaldulensis* were conducted and about 600 m from the site where the ragi water use studies were carried out; it lies on the border between the mostly forested land owned by the Karnataka Forest Department and the largely arable fields owned by the surrounding farmers. The soil type, a deep laterite is the same at all sites. It can exceed 8 m in depth and may extend to 30 m or more.

Fig. 1 shows the layout of the randomised plot design at the Hosakote site where six plots were installed with three treatments and two replications. The three treatments comprised the three tree species: *Eucalyptus camaldulensis*, Teak, *Tectona grandis* and Jackfruit, *Artocarpus heterophyllus*, known locally as 'Jack', a fruit tree which is widely planted in both State and private orchards. Teak accounts for nearly 15% of all man-made plantations and is a major source of revenue for the State. Tree spacing for all three

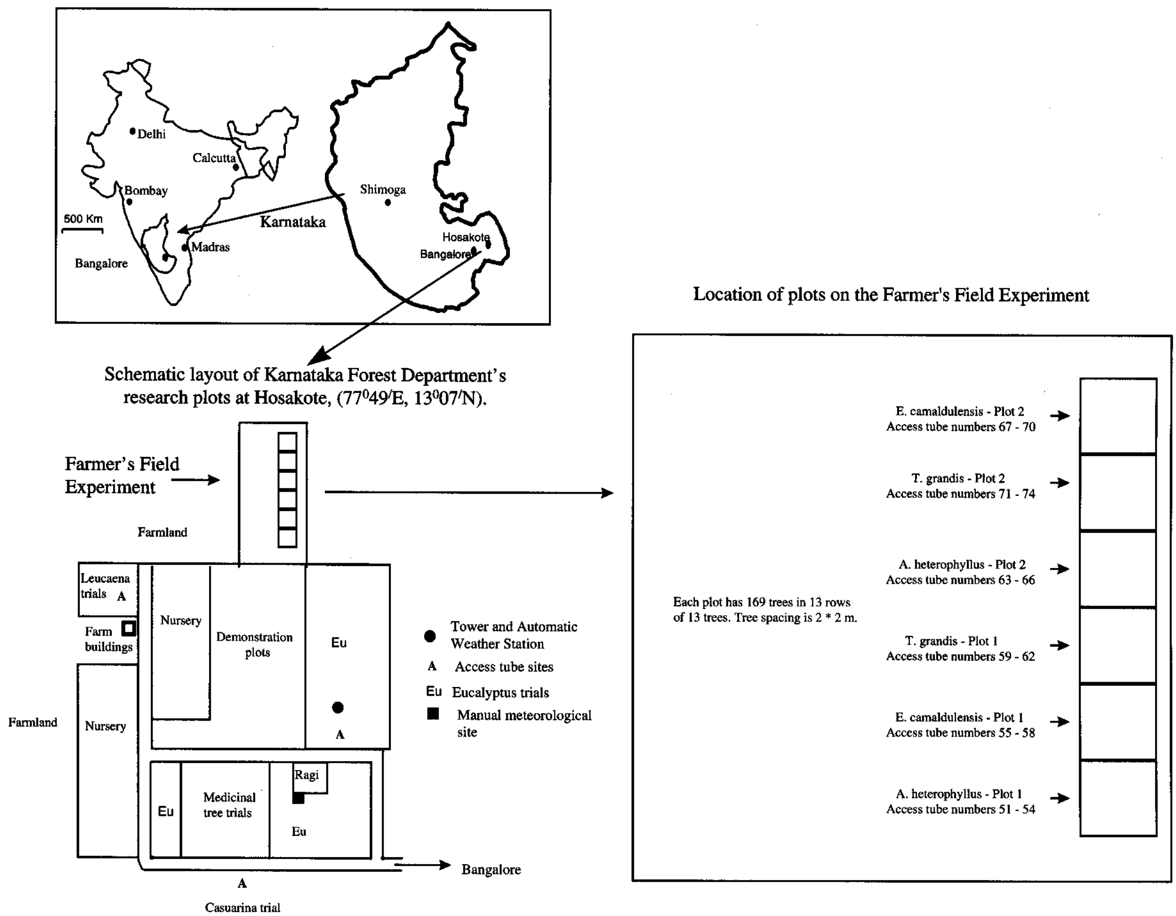

Fig. 1 *Layout of the Farmer's Field Experiment at Hosakote.*

species was 2 m × 2 m. Planting took place during July and August 1992, using the standard forest department practice of placing saplings in pre-dug holes of about 50 cm depth. Small bunds about 10 cm high were made around the saplings to retain any surface runoff during rainfall and to encourage infiltration.

For soil moisture measurements, a network of access tubes, manufactured from locally produced 8 m long 45 mm thin walled aluminium tubing, was installed in August-September 1992. Trampling of the soil surface during installation and subsequent monitoring was minimised through the use of duck boards in the immediate vicinity of each access tube. Four tubes were installed in each plot using a hand auger and steel guide tube. To minimise disturbance to the soil structure, the soil was augured out ahead of the guide tube wherever possible. The access tubes were located close to the four innermost trees of each plot and were positioned at increasing distance away from each tree. The position of all access tubes within the replicate plots was the same. The measurement programme was started immediately after installation of the access tubes.

Soil moisture methodology

Soil moisture measurements were made using Didcot Instrument Company's 'IH II' neutron probe (Bell, 1976).

Neutron probe readings were taken once a week at all tubes from August 1992 until November 1993 and from August 1995 until December 1995. Readings were taken every 10 cm to 200 cm and then every 30 cm to the last reading depth of 740 cm. The volumetric water content (θ) for each reading depth was calculated from the linear equation:

$$\theta = aR/R_w + b$$

where R is the neutron probe reading, R_w is a reference reading taken in a large drum of water every day that readings were made and a and b are calibration constants. For the soil at Hosakote, standard values of a = 0.8 and b = −0.02 were used. Confirmation of these values was made from a determination using a neutron bombardment technique (Vachaud *et al.*, 1977) on a soil sample from Hosakote, which gave a value of 0.83.

The error introduced by the loss of neutrons from the surface layer measurement is insignificant compared with the measured changes with time of the total profile water content and no corrections were applied.

The water content of each metre depth of the profile and the total water content of the profile to the deepest measurement depth were then obtained by numerical integration.

Results

The time series of total soil moisture deficits within the soil profile to 7.4 m depth recorded beneath the eucalypt, teak and jackfruit plots are shown in Fig. 2. The deficits shown are the mean of the four neutron probe soil moisture access tubes in plot 1 for each tree species. The tubes in the replicated plots showed similar patterns. Also shown on Fig. 2 are the soil moisture deficits recorded under ragi, at an adjacent field. The differences in the soil moisture depletion patterns between species are clear. Under ragi deficits of the order of 100 mm were observed during the dry season but the soil invariably returned to field capacity during the monsoon. The trees were planted during July and August 1992, about 2 months after the start of the monsoon, and by about October/November (the end of the monsoon), the soil moisture on all the plots had returned to field capacity. During the dry season (1993), the soil moisture depletion rates were highest under the eucalypts, similar but less under teak and jackfruit and considerably less under ragi. During the 1993 monsoon, the soil moisture on the land planted with the ragi returned to field capacity quickly; for the teak and jackfruit plots, the soil moisture content increased but did not reach field capacity, whilst the soil moisture on the eucalypt plots increased only briefly before continuing to decrease.

The time series of volumetric water contents, averaged for each metre depth of soil, recorded beneath the eucalypt plot are shown in Fig. 3. Also shown in Figs 4a–4c, for selected days, are the profiles of volumetric water contents recorded at each measurement depth. These figures show clearly the (spatially averaged) movement of the drying front beneath the different plots. The movement of the front beneath the eucalypts indicates that the spatially averaged eucalypt root extension exceeds 2.5 m per year, a rate of extension which, alone, is sufficient to explain the 'Hosakote anomaly'. The drying fronts, and associated root extension, develop at about half the rate beneath the teak and jackfruit plots.

The growth of the different tree species on the Farmer's Field Experiment are given in Table 1, expressed in terms of stand volume ($m^3\ ha^{-1}$), together with those recorded from Mysore Paper Mills' plantations. The stand volumes for all species on the Farmer's Field Experiment were calculated from measurements of tree height and girth on the assumption that the trunks were conical (i.e. the form fac-

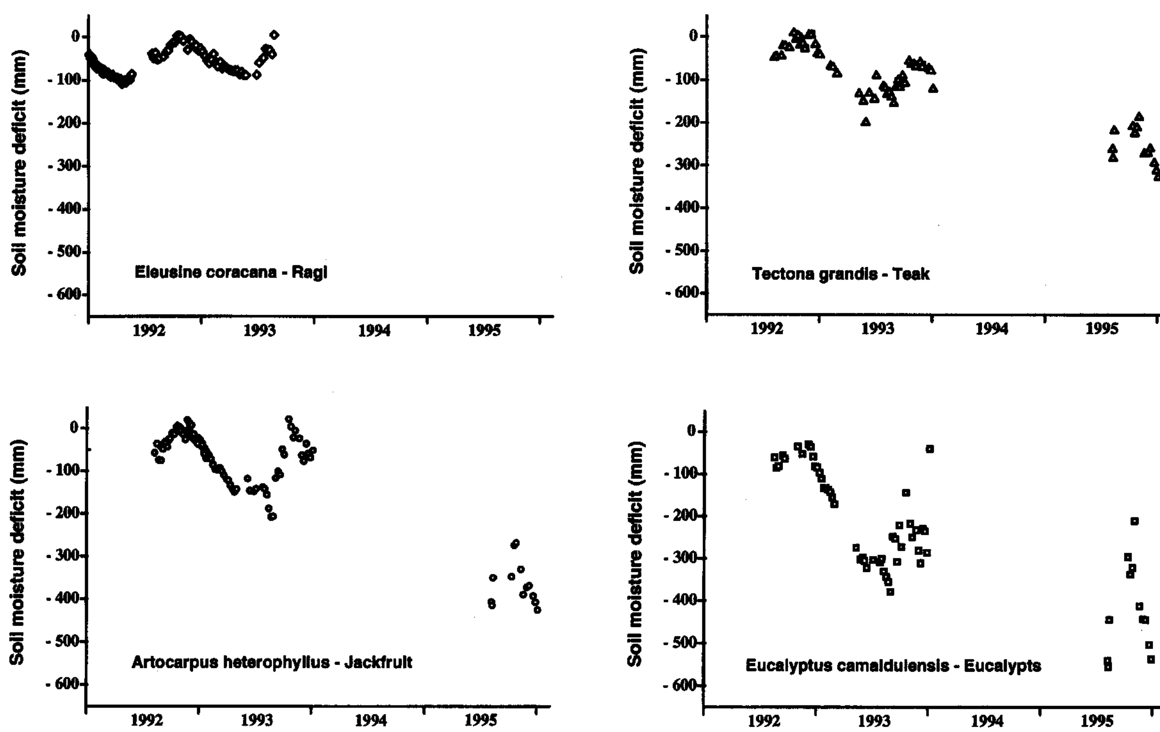

Fig. 2 *Time series of total water deficits within the soil profile to 7.4 m depth recorded beneath the* Eucalyptus camaldulensis *(Eucalyptus),* Tectona grandis *(Teak),* Artocarpus heterophyllus *(Jackfruit) and* Eleusine coracana *(Ragi) plots. The deficits shown are the mean of soil moisture measurements made from plot 1 for each species, each of which contained four neutron probe soil moisture access tubes. Measurements were stopped in November 1993 and restarted in August 1995.*

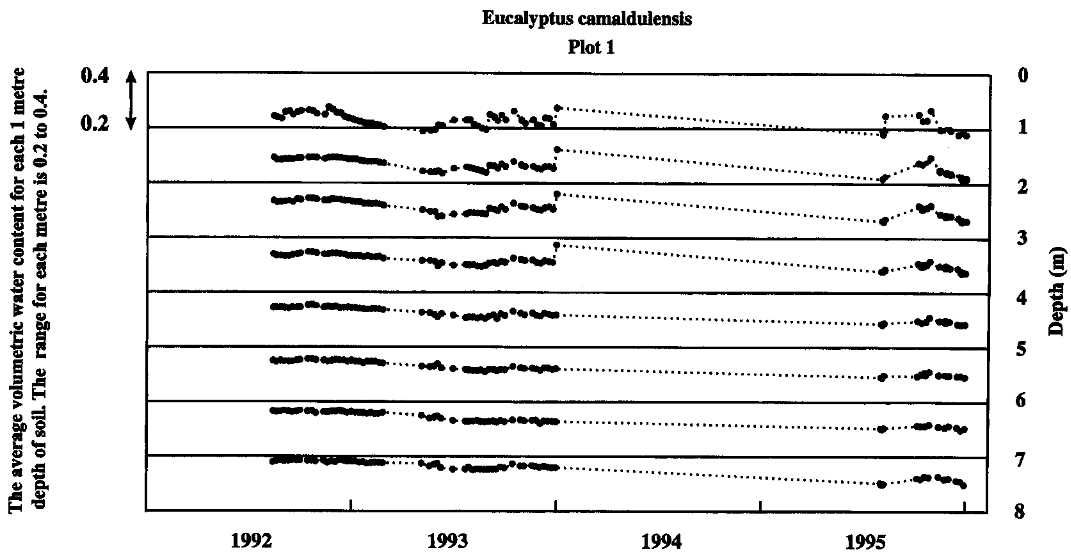

Fig. 3 *Time series of volumetric water content averaged for each metre depth of soil from access tubes 55–58 beneath* Eucalyptus camaldulensis *plot 1. The range is from 0.2–0.4.*

tor = 1/3). The growth rate of the eucalypts in the Farmer's Field Experiment is much greater than that measured from Mysore Paper Mills' plots on formerly forested or degraded land. This supports the hypothesis of extra soil water availability on land formerly under agricultural crops rather than under scrub or forest cover.

The growth rates recorded for the eucalypts are almost an order of magnitude greater than those of the other two species, teak and jackfruit.

Conclusions

The original Hosakote findings showed that the water use by *Eucalyptus camaldulensis* exceeded the input supply of water from rainfall, albeit over a drier-than-average three year period. This result generated considerable concern regarding the long term sustainability of such plantations and the water resource implications of such a high water use in relation to the rainfall. The subsequent Farmer's Field Experiment has shown that even, over years of close to average rainfall, water use can still exceed the rainfall by about 350 mm. The rate at which the roots of *Eucalyptus* penetrate the soil reservoir, in excess of 2.5 metres per year, was considerably greater than that anticipated originally and is roughly equivalent to the annual growth in height of the trees. At this rate of root penetration, the roots will have passed through the deepest measurement depth of 7.4 m within three years from the date of planting. These measurements, together with observations made from a 5 m deep soil pit at the original *Eucalyptus camaldulensis* study plot that showed roots extending to at least the depth of the pit, contradict locally held beliefs that eucalyptus species root only to 2.5 m depth. Although the Farmer's Field Experiment shows that roots extend to more than 7.4 m, the maximum rooting depth possible at this site has yet to be determined. Unless soil moisture measurements are extended beneath the present 7.4 m depth, it will not be possible to use soil moisture depletion measurements to estimate water use.

These observations highlight the dangers of making estimates

Table 1 Growth rates of trees on the Farmer's Field Experiment at Hosakote and at Mysore Paper Mills plantations at Devabal.

Tree species	Location	Age (years)	Volume (m^3 ha^{-1})	Growth rate (m^3 ha^{-1} a^{-1})
E. camaldulensis	Farmer's Field	0.75	3.55 ± 0.24	4.73 ± 0.32
T. grandis	Farmer's Field	0.75	0.71 ± 0.06	0.96 ± 0.08
A. heterophyllus	Farmer's Field	0.75	0.42 ± 0.06	0.56 ± 0.08
E. camaldulensis	Farmer's Field	3.5	55.82 ± 2.23	15.95 ± 0.64
T. grandis	Farmer's Field	3.5	6.97 ± 1.02	1.72 ± 0.02
A. heterophyllus	Farmer's Field	3.5	4.84 ± 1.22	1.38 ± 0.35
E. camaldulensis	Devabal	5.5	21.79 ± 11.40	3.84 ± 1.84

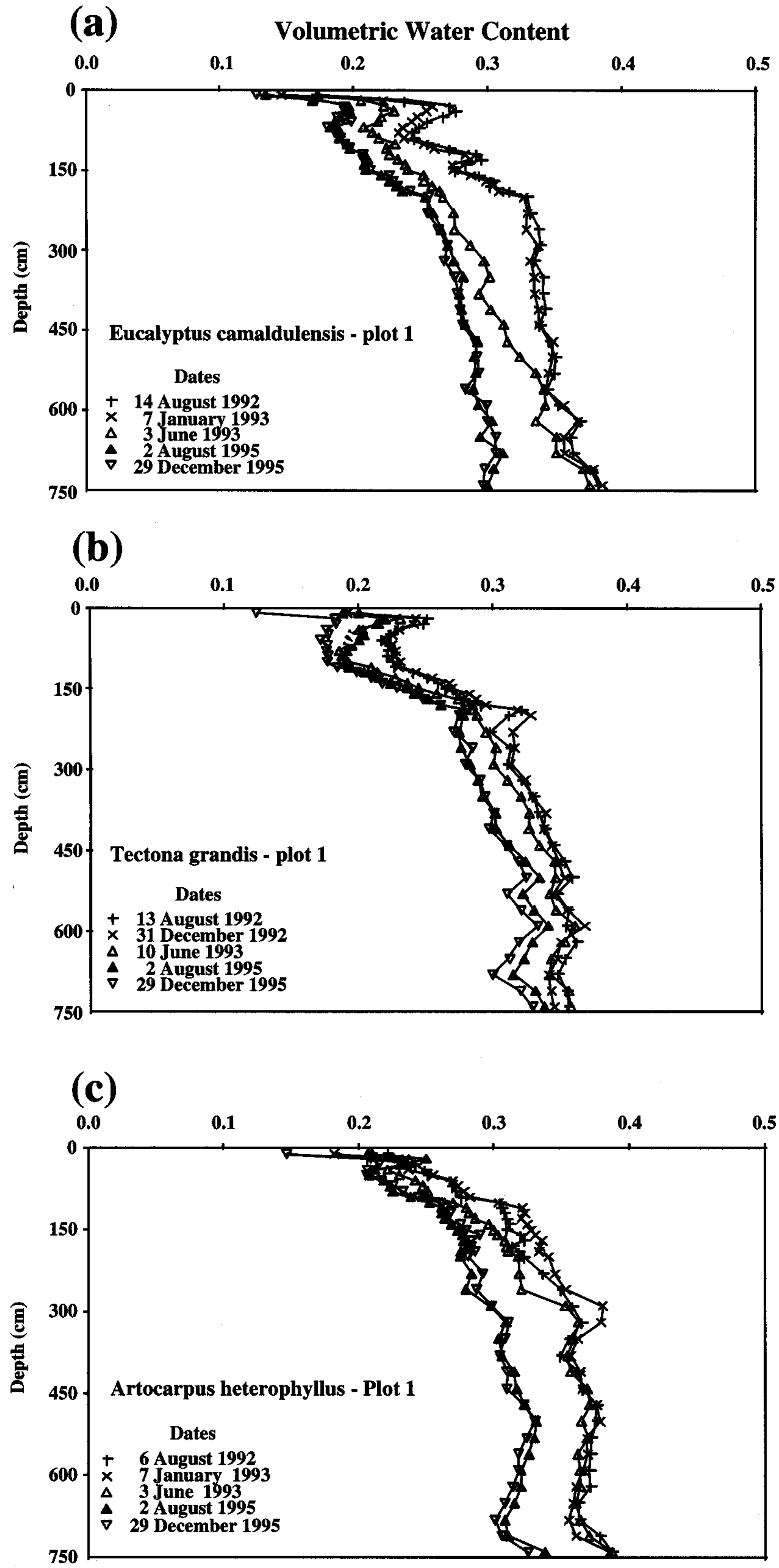

Fig. 4(a) *Profiles of the mean volumetric water content for each measurement depth for selected days; tubes 55–58 beneath* Eucalyptus camaldulensis *plot 1.* (b) *Profiles of the mean volumetric water content for each measurement depth for selected days; tubes 59–62 beneath* Tectona grandis *plot 1.* (c) *Profiles of the mean volumetric water content for each measurement depth for selected days; tubes 51–54 beneath* Artocarpus heterophyllus *plot 1.*

of water use from soil moisture observations beneath tree crops unless it can be assured that the observations extend through the full rooting zone of the crop. These observations also raise questions concerning the validity of results from other reported studies of water use from forests based on estimated soil moisture observations. Unless the full rooting zone has been monitored, the soil moisture depletion measured may represent a serious underestimate of the total water use.

The spatially averaged rates of root penetration of the two other tree species investigated, teak and jackfruit, were roughly half those of the eucalypts; this implies that soil moisture was being depleted at roughly half the rate.

The continuously increasing soil moisture deficits observed beneath the eucalypt plots indicate that the possibility of the soil returning to field capacity within the monsoon season to allow matrix flow through the profile to recharge the groundwater reservoir would be remote. Bypass flow, that is flow through cracks in the soil matrix, could occur during periods of rain of sufficient intensity to exceed the infiltration capacity of the soil but there is no evidence, from the soil moisture data, for this having occurred during the observation periods. It is also possible that during periods of high intensity rain, surface redistribution of runoff may lead to 'wet spots' reaching field capacity, thus allowing recharge; again there is no evidence, from the existing soil moisture measurements, for this having occurred during either observation period.

Recharge under the other tree species, teak and jackfruit, could possibly occur infrequently during very wet monsoons. By contrast, all observations of the soil moisture content under the agricultural crop, ragi, indicated that field capacity was attained every year, even during relatively dry years and, consequently, that recharge would occur routinely each monsoon season.

The growth rates recorded on the Farmer's Field Experiment lie in the upper spectrum of growth rates measured for rainfed plantations in the Bangalore area and lend support to the hypothesis that the extra soil water initially available on land formerly under agricultural crops rather than under scrub or forest cover contributes to these higher growth rates. Modelling studies using the WAG model (Calder, 1992) are proposed to investigate further the linkage between growth rates and water use from the Farmer's Field Experiment.

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