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WATER RELATIONS AND ROOTING DEPTHS OF SELECTED EUCALYPT SPECIES

Jose Kallarackal
C.K. Somen

KERALA FOREST RESEARCH INSTITUTE
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List of abbreviations and symbols used

D Vapour pressure deficit

g_s Stomata1conductance

MPa Megapascals

N Number of observations

P_n Net Photosynthesis

r.h. Relative humidity

VPD Vapour Pressure Deficit

WUE water use efficiency

ψ Water potential

ABSTRACT

An earlier study on the water use and photosynthesis of eucalypts, commissioned by the Ministry of Environment and Forests, Government of India, has shown that the eucalypts can consume excessive amounts of water. In this study, water relations of six eucalypt species *(E. tereticomis, E. camaldulensis, E. urophylla, E. brassiana, E. pellita* and *E. deglupta)* have been compared. Also the rooting depth of the commonly planted eucalypt species, *E.tereticornis* in Kerala, has been studied.

Diurnal variations in leaf water potentials, stomatal conductance and net photosynthesis have been measured at monthly intervals in all the six species during the course of three years. Rooting depth of *E. tereticornis* was studied by excavating the root system in a 20-year-old plantation.

Leaf water potential measurements gave a predawn value greater than -0.5 MPa, indicating the absence of any serious water stress for any of the species, throughout the year. The lowest midday water potential did not fall below -2.0 MPa These observations indicate that the root system of all the species go very deep in the soil because of the continuous dry period for 4 to 5 months.

The study on stomatal frequency reveals the presence of stomata on the abaxial and adaxial side in all species except *E. pellita* and *E. deglupta.* The stomatal frequency (number mm^{-2}) varied between 150 and 485 in all the species.

There were significant variations between species in the magnitude of the stomatal conductance values. *E. urophylla* showed the lowest values and *E. camaldulensis* showed the highest. There was no midday closure of stomata in any species except *E. deglupta.* There were significant variations between premonsoon and postmonsoon stomatal conductance values. The stomatal closure in response to increasing atmospheric VPD was most developed in *E. tereticornis* and *E. deglupta.* In all other species, probably the leaf water potential played a major role in stomatal closure.

Although the stomatal conductance showed much reduction in the premonsoon period, this did not affect the net photosynthesis values greatly except in *E. urophylla* and *E. camaldulensis.* This probably indicates that the stomatal component is not much significant in photosynthesis. The A_{max} in the different species varied between 15 and 25 μmol m^{-2} s^{-1} , *E. camaldulensis* showing the maximum. In all the species A_{max} occurred between PFD 800 and l000 μ mol $m^{-2}s^{-1}$. When net photosynthesis values were plotted against stomatal conductance values, most of the species showed similar photosynthesis values during the premonsoon compared to postmonsoon period at lower conductance values. This is an indication of the higher water use efficiency in these species. However, *E. tereticornis* and *E. deglupta* did not show this character.

Root excavation studies in *E. tereticornis* showed that the roots in a 20-year-old plantation were traceable up to 9.3 m depth. Roots with diameter above 5.0 mm were present within 2 m below ground level. The root length density and root weight density

showed much variations in different layers of the soil. The phreatic aquifer in the locality was found between 9.0 and 12.0 m during the summer season showing that the roots have access to this zone.

Based on the above observations, a number of conclusions have been drawn and recommendations given. Water stress is minimal in all the species due to probably a deep rooting system. The stornatal closure in response to VPD was well developed in all the species, but most in *E. tereticomis* and *E. deglupta*. The water potential also played an important role in this. The photosynthesis is not limited by partial stornatal closure in any of the species. It is found that *E. camaldulensis* is the most drought tolerant species out of the six species studied. Water conservation is most accomplished in *E. urophylla*. In *E. tereticornis*, the roots penetrate to nearly 10 m depth in the soil, indicating extraction of water from the phreatic aquifer.

It is recommended that *E. camaldulensis* may be used in very dry locations. *E. urophylla* can be a promising species as far as water conservation is concerned. More silvicultural studies are recommended in this species. The root excavation studies confirms the deep extraction of water. Hence wider spacing (3 x 3 m) is recommended in plantations to save the water table.

1. Introduction

This study on the water relations of six eucalypt species and rooting depth of *Eucalyptus tereticornis* has been taken up as a follow-up project of a previous study on the water use and photosynthesis of two eucalypt species, commissioned by the Ministry of Environment and Forests, Government of India (Kallarackal, 1993). The salient findings of the erstwhile project are:

i) Water loss by transpiration from *E. tereticomis* plantation with 1800 stems ha^{-1} was nearly twice when compared to another plantation of the same species, but with half the number of stems ha^{-1}. This means that the per tree consumption of water is nearly the same in both the plantations, ii) The two species studied, namely, *E. tereticornis* and *E. grandis* maintain relatively high leaf water potentials, indicating the penetration of roots to deeper layers of the soil, iii) The stomatal conductance measurements showed that there was no complete stomatal closure in *E. tereticomis* even at high vapour pressure deficits (VPD). But in *E. grandis,* nearly complete stomatal closure was observed, iv) The transpiration figure of 1563 mm of water by *E. tereticomis* plantation per annum requires a rooting depth of approximately 12 m by calculation. However, for confirmation this requires excavation of the root system, and v) The water use efficiency (WUE) showed difference in both the species during premonsoon and postmonsoon periods.

The above findings led us to do further studies in *Eucalyptus*, which is a major genus in plantation forestry in Kerala State. Thus, the present study was taken up on six eucalypt species *(E. urophylla, E. camaldulensis, E. brassiana, E. pellita, E. deglupta* and *E. tereticomis)* with the following objectives:

1. To study the water relations parameters of six eucalypt species found successful in a trial conducted in Kerala.
2. To examine the stomatal control of transpiration in the above six species.
3. To quantify the instantaneous water use efficiency of the above six species.
4. To analyse the photosynthetic efficiency in stressed and unstressed conditions.
5. To examine the rooting depth of *E. tereticornis* and *E. grandis* in plantations.
6. To study the root length density of the above two species at different soil depths.

The selection of the six species is based on the result of a small scale trial of 20 different eucalypt species conducted at Nilambur, Kerala. The above species were found to be growing well in the trial.

Diurnal variations in leaf water potentials, stomatal conductance and net photosynthesis have been measured in the above six species for three years from August 1994, completing measurements on two species in a year. It would have been more ideal if all the six species were studied simultaneously. This was necessitated because of the limitations in the number of scaffold towers to reach the tall top canopy of the trees.

The excavation studies were done to physically verify the extent of root system in *E. tereticornis.* Although water loss estimations by transpiration can predict the depth of root system to some degree of accuracy, physical verification will help to confirm it. The root length density at different depth levels will also help us to classify the roots based on their functional role. The estimation of root biomass at different depths has been also done. The number of samplings in the excavation study was limited by considerable depth of root (≈10 m) and the paucity of funds.

2. Materials and Methods

2.1 Experimental site and species

An experimental plot having 14 different species of eucalypts at the subcentre of the Kerala Forest Research Institute at Nilambur (Lat:11^{o}7'N Long:76^{o} 14'E; Elevation : 50 m above msl.) was chosen for the study (Figs.1&2). The experimental plot had been planted on 5 September 1983. Each species had 30 seedlings each planted in rows at a spacing of 2x2 m. Except for weeding no other management practices were followed in these plots.

The growth measurements taken at 6-monthly intervals, kept from the date of planting formed the basis of selecting the species for this study. On the basis of growth and general performance, the following six species were selected from among the 8 surviving species in the above plot.

Eucalyptus tereticornis Sm. (Forest red gum)

Eucalyptus camaldulensis Dehn (River red gum)

Eucalyptus urophylla S.T. Blake (Timor white gum)

Eucalyptus brassiana S.T. Blake (Capeyork red gum)

Eucalyptus pellita F. Muell. (Large fruited red mahogany)

Eucalyptus deglupta Blume (Kamarere)

2.2 Weather parameters

The year-round weather parameters like rainfall and temperature were recorded near the experimental plot. The rainfall data measured during the period of study is shown in Fig.3.

2.3 Canopy measurements

The physiological measurements were made on top of the canopy using a scaffold tower, approximately 12 m tall, erected temporarily in the centre of each subplot.

2.4 Stomata1 frequency

The number of stomata per mm^2 of leaf was measured for all the six species. Impressions of the abaxial and adaxial surfaces of the leaves were taken using a cellotape. This was later examined using a microscope and stomatal counts made. The area was measured using a micrometer.

2.5 Gas exchange measurements

Diurnal patterns of stomatal conductance (g_s) were measured on sample days chosen at approximately one month interval over a full year. Measurements were made using a Portable Photosynthesis System (Li-6200, Li-Cor. Inc. Nebraska, USA). Field measurements were done on days which were not rainy or fully overcast. The measurements had to be abandoned for two months, June and July, during the South-west Monsoon. The relative humidity was >80% during these two months, making porometer measurements erroneous. The sampling of the leaves were done from the top of the canopy layer. Only mature and well exposed leaves were used for measurements. Measurements were initially made on the upper and lower sides of the leaf using a steady state porometer (Li-1600, Li-Cor. Inc. Nebraska, USA) to determine the presence of stomata on either side of the dorsi-ventral leaves. This data were used to programme the portable photosynthesis system.

Net photosynthesis (P_n) and stomatal conductance *(gs)* were measured simultaneously using the portable photosynthesis system.

For both g_s and P_n measurements, a leaf laminar area of 12 cm2 was enclosed in a 1-litre chamber. The time of enclosure inside the chamber during the measurement was always less than a minute. Hourly diurnal measurements were made in natural daylight.

Both g_s and P_n were calculated using the software available with the instrument. Along with this, the PFD available to the leaf at the time of measurement was measured using a PAR sensor attached to the chamber. The atmospheric VPD at the time of enclosing the leaf was also measured using the temperature and humidity sensor attached to the chamber.

2.6 Leaf water potentials (ψ)

The water potential of the leaves at hourly intervals was measured using a Scholander pressure chamber (Soil Moisture Equipment Corporation, Ohio, USA). The leaves were enclosed in a plastic bag just before detachment from the tree. The leaves were subjected to pressurisation immediately after detachment. At least five leaves were sampled at hourly intervals, starting from predawn to dusk. All the precautions recommended by Turner (1988) were followed during sampling of the leaves for water potential measurement.

2.7 Root studies

The root length density and root biomass density were studied in *E. tereticornis* by excavating the root system. Two pits were dug, first one with 2 m diameter and the root bole at the centre of the pit (Fig.4a), and the second one, again 2 m diameter in between the root boles (Fig.4b). Excavation using hand tools was done, carefully collecting the roots by sieving out the loose soil.

The collected roots were classified according to their diameters using the classification of Bohm (1979) and modified by Watson (1990). Accordingly, the roots were divided into eight classes (Table 1)

Table 1. Classification of the roots according to Bohm (1979) and modified by Watson (1990).

Description	Diameter (mm)
Central root bole at base of stem	--
Coarse structural roots	>100
Very large structural roots	50-100
Large structural roots	20-50
Medium structural roots	10-20
Small structural roots	5-10
Very small structural roots	2-5
Fine roots	<2

Roots in all the classes were measured for their length using a meter scale. Later, they were oven dried at 85 ^{o}C to constant weight. When the root mass was high in certain layers, only allometric samples were dried for the purpose of determining the root biomass. The root length density and biomass density were expressed as m m^{-3} and g m^{-3} of soil respectively.

3. RESULTS

Based on the rainfall pattern and water availability to the trees, three periods were identified. They are the premonsoon, monsoon and postmonsoon periods. It is in the premonsoon period that the water is least available to the trees. This period is from January to May, when there is only scanty rainfall. During the monsoon period, which lasts from June to August, the rainfall is almost continuous and heavy. The soil is fully saturated and solar radiation is low during this period because of the overcast sky. The relative humidity is also at saturation or near saturation point. The postmonsoon period is characterised by bright sunshine and sufficient soil water availability. This period is from September to December. During this period another brief monsoon, named North-east Monsoon operates in the study location. However, the rainfall is only in the evenings and not continuous as in the South-West Monsoon.

3.1 Leaf water potentials (Ψ)

Measurements of Ψ at hourly intervals during the daytime are depicted in Figures 5 to 7. The predawn Ψ values indicate that in all the six species, they did not fall below -0.5 MPa during any period. The premonsoon values were only slightly lower than the postmonsoon values. This indicates that for all the investigated species, the water stress was apparently minimal during the premonsoon period. The Ψ values during the rest of the day showed more differences in magnitude between premonsoon and postmonsoon values.

In *E. urophylla,* the lowest midday water potential obtained was -1.5 MPa, whereas in *E. camaldulensis,* this was a little <-2.0 MPa. *E. brassiana* and *E. pellita* also showed midday water potentials <-2.0 MPa. In *E. deglupta,* the midday Ψ values did not fall below -1.5 MPa and in *E. tereticornis,* these were between -1.5 and -2.0 MPa. In all the species studied, the diurnal Ψ values during the premonsoon period were less than the postmonsoon values. However, the differences were less apparent in *E. pellita* and most apparent in *E. camaldulensis.*

3.2 Stomatal frequency

The stomatal frequency in the six species is reported in Table 2.

Table 2. Stomatal frequency (No. mm^{-2}) in the leaves of the eucalypt species under investigation

Species	Abaxial side	Adaxial side
E.urophylla	365 ± 13	148 ± 8
E.camaldulensis	248 ± 11	184 ± 10
E.pellita	304 ± 19	Nil
E.tereticornis	241 ± 9	216 ± 7
E.deglupta	484 ± 21	Nil
E.brassiana	199 ± 4	159 ± 8

± s.e. is indicated ; N=10

3.3 Stomatal conductance (g_s)

The diurnal variations in g_s in the six species studied are depicted in Figures 8 to 10. The g_s in *E. urophylla* showed considerably lower values when compared to other species. They hardly exceeded 600 mmol m^{-2} s^{-1}. In all the other species the maximum g_s values sometimes reached 1000 mmol m^{-2} s^{-1} or even slightly more. However, the premonsoon values in all species were nearly half of those measured during the postmonsoon period. There was no tendency for the midday closure of stomata in any of the six species except in *E. deglupta.* In all the other species diurnal variations in g_s were minimal during the postmonsoon period. However, the premonsoon period showed some diurnal variations.

To know the atmospheric factor regulating the g_s in each of the six species studied, g_s values were plotted against atmospheric VPD values. The results are shown in Figures 11 to 13. In *E. urophylla* and *E. camaldulensis,* the increasing VPD had no effect on stomatal closure even up to a VPD value of 5.0 kPa, especially in the premonsoon period. In *E. brassianu* and *E. pellita,* the stomatal closure due to increasing VPD was a little more apparent. Out of the six species studied, the stomatal closure in response to increasing VPD was most developed in *E. tereticornis* and *E. deglupta.* In *E. tereticornis* partial closure of stomata was apparent when the VPD crossed 3.0 kPa. It is interesting to note that even at very high VPD levels, only partial stomatal closure occurred in *E. tereticornis.* In *E. deglupta,* near to complete stomatal closure occurred at VPD values >2.5 kPa. As seen in the Fig.14, VPD values in the study location reached a highest value of *5.5* kPa during the premonsoon period. The postmonsoon VPD values rarely crossed 3.0 kPa.

3.4 Net photosynthesis (P_n)

The diurnal values of P_n did not show much differences in the premonsoon and postmonsoon periods (Figs.15-17). The higher values were noticed during the forenoon hours. There was a gradual decrease in P_n in all the six species in the afternoon. The only exception was *E. deglupta* which showed a second peak in the afternoon also. The assimilation maximum (A_{max}) in *E. urophylla* was nearly 20 pmol m^{-2} s^{-1}. In *E. camaldulensis,* the A_{max} reached almost 25 μmol m^{-2} s^{-1}. In the other four species, it was between 15 and 20 μmol m^{-2} s^{-1}.

To determine the assimilation maximum (A_{max}) and the light response in the species studied, the P_n values were plotted against photon flux density (PFD) (Figs.18-20). The highest A_{max} was observed in *E. camaldulensis* which gave a value very near to 25 μmol m^{-2} s^{-1}. In all the other five species A_{max} ranged between 15 and 20 μmol m^{-2} s^{-1}. There were variations in the A_{max} values for the premonsoon and postmonsoon periods in some species. This was much apparent in *urophylla* and *E. camuldulensis.* In both these species, the premonsoon values were considerably lower than the postmonsoon values. In the other four species also, although the premonsoon values were scattered along with the postmonsoon values, a trend for lower premonsoon values was always apparent. In all the species the A_s occurred between PFD values of 800 and 1000 μ mol m^{-2} s^{-1}.

The relationship between p_n and g_s was plotted individually for all the six species (Fig.21-23). A nearly linear relationship was found in all the species. The separation of pre- and post- monsoon values in these figures gives interesting results. In *E. urophylla, E. camaldulensis, E. brassiana* and *E. pellita,* the premonsoon values showed a clear trend for higher P_n rates at lower g_s values. This is indicative of the higher water use efficiency (WUE) in the above four species during the dry period. In *E. deglupta* and *E. tereticornis,* the separation of pre- and post-monsoon values were not so apparent. This could be interpreted as a tendency for less water conservation during the dry period.

3.5 Root excavation study

The vertical extent of the root system in *E. tereticornis* studied from two excavations is depicted in Figs. 24 to 27. In Figs. 24 and 25, the root length density is expressed as m m-3of soil. This would give an idea on the density of the root system at different soil depths starting from the soil surface. It may be seen that roots were traced up to 9.3 m in one of the two excavations. Roots of larger size classes (structural roots) (>1.0 cm) were found to a depth of about 2.0 m from ground level. Maximum density of roots with diameter <2.0 mm was found in the upper 30 cm of the soil. Roots of lower size classes were found in all the soil layers. At depths deeper than 2 m, roots with a diameter of <5.0 mm only existed. It should be assumed that these are the absorbing roots of the plant.

In the excavation where the root bole was in the centre of the pit, the digging went up to 9.5 meters, where the roots had stopped further downward growth. The examination of the summer water table from wells in the adjacent locations showed that the phreatic aquifer existed at this depth. This indicates that the eucalypt roots are travelling down in search of water to the phreatic aquifer.

In Figures 26 and 27 the root weight density plotted as a histogram against the depth classes. They show that the root biomass is more at the top one meter of the soil compared to deeper layers.

One of the specialities to be pointed out in the present method of root excavation is the positioning of the pits. One of the pits was taken by keeping the root stump at the centre of the pit and the second pit was taken in between two plants. Each pit had a diameter of ≈2.0 m which is the planting distance between any two plants. This sampling method will help us to determine the root biomass of the trees. In the present study the root biomass is as follows:

Biomass (dry weight) of the root stump	= 37.5 Kg
Biomass of other roots in the 2 m diameter pit	= 15.3 Kg
Total root biomass	= 52.8 Kg

Since direct root biomass determination are rarely attempted, the above value would certainly contribute to our knowledge of root biomass even though the result is based on a single tree.

4. Discussion

Measurements of the soil water content, although give an idea on the water availability to the trees, are impracticable in grown up eucalypts because of the deep penetration of the root system. If they have to be meaningful, soil must be sampled from several meters deep. However, the predawn leaf water potential can indicate the soil water potential accessed by the root system (Crombie et al. 1988).

A look at the predawn water potential in the six species under investigation shows that the values ranged between 0 and -0.5 MPa. This indicates that none of the species is experiencing any severe water stress. The predawn water potentials during the premonsoon period is always lower than that of the postmonsoon values. This is indicative of a slight water stress during the premonsoon period. The slight water stress could be due to the drying up of the top, soil layers. However, it is difficult to note any difference in water stress between the species. The diurnal values of water potential vary in premonsoon and postmonsoon periods. This is most apparent in *E. camaldulensis*. In *E. camaldulensis*, *E. brassiana* and *E. pellita*, the midday water potential values came down to -2.0 MPa, whereas in all other species, this was around -1.5 MPa. Lower water potentials are indicative of the drought tolerance of a species. This means that the above three species should be preferred over the other three species for drier locations.

The stornatal conductance in all the six species showed differences in magnitude for pre- and postmonsoon periods. In all species except *E. deglupta*, the stornatal conductance showed a peak during midday. In *E. deglupta*, this peak was during the forenoon hours. In all the six species, the premonsoon values had only half the magnitude compared to postmonsoon values. In *E. camaldulensis*, some of the postmonsoon values were extremely high exceeding 1200 mmol m^{-2} s^{-1}. The lowest values were in *E. urophylla* where the maximum values hardly exceeded 600 mmol m^{-2} s^{-2}. The premonsoon values were extremely low in *E. urophylla*. This indicates the sensitivity of the stomata to either vapour pressure deficit (VPD) of the atmosphere or the lower water availability in the soil. It has been found in a previous study that both the above factors are responsible for stornatal closure in *E. tereticornis* and *E. grandis* (Kallarackal and Somen 1997a, 1997b). In *E. urophylla*, it appears from the present observations shown in Fig.11 that stornatal closure during the premonsoon period is not dependant on the atmospheric VPD. Even at lower VPD values, the g_S, is almost the same as those at higher VPD values. However, the postmonsoon values show a tendency towards stornatal closure at higher VPD values. From these observations, it becomes apparent that in *E. urophylla*, soil water stress can cause good stornatal responses than compared to atmospheric water stress. It should be noted that the minimum water potentials during the premonsoon were between -1.0 and -1.5 MPa. The capacity of *E. urophylla* to reduce the g_S considerably at the above values of water potentials should be regarded as an extremely efficient water conserving feature for a eucalypt species. This would make this species suitable for locations where water conservation is also critical along with plantation production.

Since the present study has been carried out on 12 year old trees, the probable inability of *E. urophylla* to penetrate deeper into the soil is also indicated. It should be pointed out here that hardly any study has been conducted in India about the possibility of using this species in plantations, nor its physiological characteristics.

In *E. camaldulensis*, like in *E. urophylla*, the g_S during the premonsoon period is independent of the atmospheric VPD. However, the g_s values are much higher than that of *E. urophylla*. The postmonsoon g_S values, however, show a negative correlation with increasing VPD. The high $1g_S$ values even at VPD≈5.0 kPa indicates that *E. camaldulensis* is a drought tolerant species. The water potential in this species did not come down to less than -2.0 MPa during any part of the year. This would indicate that these trees have deep penetrating root system. These features make *E. camaldulensis* suitable for planting in drought-prone areas. However, the ecophysiological characteristics of this species show that it is a relatively high water consumer and may not be suitable for an area where water conservation is also desirable.

In *E. brassiana*, the g_S in relation to atmospheric VPD shows that, the reduction in g_s during the premonsoon period is not dependant on the VPD. Since the water potential values are lower during the premonsoon period, it is possible that the g_s is regulated more by the leaf water potential than by the atmospheric VPD. During the postmonsoon period, there seems to be more regulation of stomatal opening by the atmospheric VPD. Although partial stomatal closure occurs in this species during the postmonsoon period, the g_S values are relatively high. The possibility of this species extracting water from the deeper soil layers cannot be ruled out.

The relationship between g_s and VPD in *E. pellita* shows that the g_S values during the premonsoon period are less than those of the postmonsoon period. However, unlike the other species already discussed, the g_S during the premonsoon period showed a tendency to be regulated by VPD. Thus it seems that g_S in *E. pellita* is dependant on both VPD and leaf water potentials. Since the water potentials do not reach very low values during the premonsoon period, the indirect indication is that this species also may have deep penetrating root system. Because this species maintains relatively high g_S during the premonsoon period, it is suitable for dry locations where water conservation is not all that important.

In *E. degluptu*, it is seen that partial to complete stomatal closure occurs beyond a VPD value of 3.0 kPa. Unlike in the species already discussed, there is no difference in the magnitude of g_S values of premonsoon and postmonsoon periods. This means that the g_s is mostly regulated by the atmospheric VPD and not the leaf water potentials. It should be noted that the leaf water potential in this species did not fall to values less than -1.5 MPa. This means that the stomatal closure mechanism, which is very much regulated by atmospheric VPD is probably helping to maintain a relatively high leaf water potential in this species. This way *E. degluptu* has some similarities to *E. urophylla*. However, the g_S values in *E. degluptu* are much higher than those of *E. urophylla*.

The relationship between g_s and VPD in *E. tereticornis* was more or less similar to that of *E. deglupta*. The premonsoon and postmonsoon values did not show any separation as in the other species. Partial stornatal closure was observed in response to increase in VPD. From observations it appears that VPD is regulating the stomatal responses more than leaf water potentials. The leaf water potentials did not fall below -1.8 MPa. From a previous study on *E. tereticornis* it was observed that the leaf water potentials did not fall below the above value (Kallarackal and Somen 1997). In this project also the excavation of the root system in *E. tereticornis* showed that its roots were penetrating to a depth of 9.3 m which is the depth of the water table in the study location. This could be the reason for this species maintaining a relatively high water potential. As observed in previous studies the stornatal closure was never complete even at high VPD. The g_s values remained at $\approx$200 mmol m^{-2} s^{-1}.

Colquhoun *et al*. (1984) have conducted detailed investigations on the relation between g_s and VPD in six widely occurring eucalypt species in Western Australia. They found that in *E. marginata* and *E. calophyla*, there was no correlation between g_s and VPD. Three other species, namely, *E. maculata*, *E. resinifera* and *E. saligna* showed some stomatal regulation based on VPD. *E. wandoo* showed stomatal control and also developed lower xylem pressure potentials. In *E. globulus* studied in Portugal, Pereira et al. (1986, 1987) have found correlation between g_s and VPD, however, the correlation depended on the leaf water potential variations also. Thus from the above studies including this report, it seems that the stomatal conductance in eucalypt varies much in different species depending on the variations in VPD as well as leaf water potential. What is most important in water use studies of eucalypts is to look for the behaviour of a particular species in a given environment.

Photosynthesis

In all the six species studied, the diurnal variations showed that photosynthesis was similar in magnitude during both premonsoon and postmonsoon periods. However, in *E. deglupta* there was a tendency towards reduced photosynthesis during the premonsoon period.

The plotting of P_n against PFD helps to understand the A_{max} as well as the light requirement for maximum photosynthesis. The A_{max} was highest in *E. camaldulensis* crossing 20 µmolm^{-2} s^{-1}. Although the g_s was lower in *E. urophylla* when compared to other species, it did not seem to affect the P_n in this species. The A_{max} in this species was $\approx$15 mmol m^{-2} s^{-1}. In all the species studied, the A_{max} was obtained at PFD between 800 and 1000 µmol m^{-2} s^{-1}.

The relation between net photosynthesis and g_s helps to understand the water use efficiency (WUE) of the species (Hall and Schulze, 1980; Schulze and Hall, 1982). The slope of the curve can give a comparative idea on WUE of the different species (Schulze and Hall 1982). From the figures which show the relation between P_n and g_s, it is apparent that there exists a linear correlation between these two parameters. A little scatter of points seen in the figures can be due to the measurements taken under field conditions. It is also interesting to note that in four out of six species, the premonsoon and postmonsoon values separate out clearly. The premonsoon values present a steeper slope than the post monsoon values. As suggested by Schulze and Hall (1982), this would indicate that in *E. urophylla, E. camaldulensis, E. brassiana* and *E. pellita* the water use efficiency during the premonsoon period is much higher compared to postmonsoon period. The slope is probably steepest in *E. urophylla,* indicating the highest water use efficiency compared to the other species mentioned above. It is interesting to note that the premonsoon and postmonsoon values in *E. deglupta* and *E. tereticornis* occur intermingled in a plot of P_n versus g_s. This means that the WUE is not different during these two periods. To get an absolute value for the intrinsic WUE in the above species, it may be necessary to do measurements at controlled conditions.

The higher water use efficiency during the premonsoon period in four out of six species presents an interesting point for discussion. If water use efficiency is defined as assimilated carbon per unit of transpired water, then according to theory, this value is inversely proportional to VPD (Bierhuizen and Slayter 1965). Thus lower VPD gives higher WUE (Baldocchi *et al.* 1987; Bassman and Zwier, 1991; Cienciala and Lindroth, 1995). This would mean that we should expect lower WUE during the premonsoon period instead of the higher WUE found in the present study. However, it may be noted that in these four species, VPD exerts no stomatal regulation (Figs. 11 and 12). The stomatal regulation in these species is probably exerted by the leaf water potentials. In the other two species, *E. deglupta* and *E. tereticornis* the stomatal opening is regulated by VPD (Fig.13). In these latter two species it may be seen that the WUE is not different in the premonsoon season.

The downward penetration of tree roots is commonly limited by mechanical impedance, by annoxia, by dry subsoils, or in cold regions, by very low soil temperatures or permafrost. An exhaustive account of the maximum vertical and radialextents of the roots were tabulated for various woody species by Stone and Kalisz (1991). The data are available for 49 families, 96 genera and 211 species. In this list 17 species of eucalypts are reported indicating the maximum depth and radius of roots. In one of the *Eucalyptus* species, Jennings (1971) has reported the maximum depth to be 60.0 m. But the method of study is reported as casual observation. Very few excavation studies have been done on eucalypt species. The maximum depth reported by excavation study in a eucalypt species is in a 235 year old *E. regnans* where Ashton (1975) has reported a rooting depth of 7.1 m. By core sampling Carbon et al. (1980) have reported a rooting depth of 19.0 m in *E. marginata* and a depth of 40.0 m in the same species by Dell *et al.* (1983). Dye (personal communication) has reported live roots of *E. grandis* 38 m below the surface in South Africa. When compared to the above reports, the rooting depth in the present study which is 9.3 m is certainly lower. It is probably the maximum depth reported using excavation method.

Another interesting aspect of the present work is that the root length density and root biomass have been determined for every 30 cm depth. The higher length and higher biomass of roots in the top layers of the soil indicate that there are more roots at the top layers for absorption of nutrients and water. The higher biomass in the top layers is also due to the higher quantity of large- diameter roots, which are lateral roots serving as structural roots. The main tap root did not extend beyond 1.5 m. The deeper penetrating roots probably originated from other sinker roots by branching. These roots travelled to a depth of 9.3 m which would be mainly for extracting form the water table. Studies in Australia have shown that these root systems were deeper and denser at high tree densities, although total length and mass of roots produced per tree decreased with increasing tree density (Eastham and Rose 1990). This gives the indication that the trees in eucalypt plantations should be spaced wider if water conservation is also intended. A spacing of 3 x 3 m has been already recommended by Kallarackal and Somen (1997) and a spacing of 3.75 x 3 m is recommended by Adlard (1992). Trials conducted at ITC, Badrachalam, A.P have also shown that a 3 x 3 m spacing gives same yield of usable biomass as a 2 x 2 m spaced plantation (Kulkarni, personal communication).

A knowledge of the depth of rooting is helpful in estimating the water requirements of the tree as well as the extent of stress experienced by a tree. From the data already available from our studies, the water requirements for *E. tereticornis* in sandy loam soils can be estimated as:

Available water in the soil	= 130 mm/m
Rooting depth	= 9.3m
Available water to the roots	= 130 x 9.3
	= 1235 mm

Only 50% of this available water can be extracted by most trees. After that stage stress can occur. This means that in the present instance, only 620 mm is available for normal tree growth, say by end of November if the monsoon season is normal. The measured transpiration in the location where the root excavation was done is 738 mm from December to March, when there is no rainfall (Kallarackal 1993). This would mean a deficit of 118 mm (738-620) for the trees if no other water source is available for the root system. By penetrating the soil up to 9.3 m, which is the water table depth, the eucalypts at the study site are assuring that no water stress is experienced for almost the whole of the dry period which extends from December to April. Only by the end of March the trees start experiencing water stress. This stress is usually broken by summer showers which occur during the end of March and beginning of April in this locality. This could be the reason for *E. tereticornis* showing relatively high water potential even during the dry period. The same could be true with other eucalypt species investigated in this project. The possibility for their root system going very deep cannot be ruled out. However, in species like *E. urophylla* and *E. deglupta* where the stomatal regulation of transpiration is high, the water consumption would be drastically reduced. This leads us to a reasonable assumption that in the above two species the root system need not penetrate to deep seated water resources to sustain the transpirational loss. Hence these two species could be recommended for locations where water conservation is equally important as softwood production provided these two species are acceptable to the pulpwood industry.

5. Conclusions

The following conclusions have been drawn from this study:

5.1. Water potential measurements in the six eucalypt species indicate that the water stress is minimal in all the species as manifested by the relatively higher predawn leaf water potentials. The diurnal leaf water potentials were always lower during the premonsoon period in all the six species, indicating some degree of stress during the dry period. This difference was least in *E. pellita* and most apparent in *E. camaldulensis.*

5.2. The stornatal conductance values showed variations in magnitude in the different species. The lowest values were found in *E. urophylla* and the highest values in *E. camaldulensis.* Only *E. deglupta* showed a tendency for midday closure of stomata. The premonsoon values of stornatal conductance were only half of that shown by the postmonsoon period.

5.3. The stomatal closure during the premonsoon season was regulated mostly by the atmospheric VPD, leaf water potential or both. In *E. tereticornis* and *E. deglupta,* atmospheric VPD had the maximum effect. In *E. brassiana* and *E. pellita,* the regulation by VPD was only slightly apparent and in *E. urophylla* and *E. camaldulensis,* it was least apparent. However, in all the species, stomatal regulation by atmospheric VPD was apparent during the post monsoon period.

5.4. Although the stornatal conductance showed significant variations between postmonsoon and premonsoon values, this was not manifested in their net photosynthesis values except in *E. urophylla* and *E. camaldulensis.* The net photosynthesis was higher during the forenoon in all the six species. A second peak was shown in the afternoon only in *E. deglupta.* The maximum value for net photosynthesis (25 μ mol $m^{-2}s^{-1}$) was shown by *E. camaldulensis.*

5.5. The relation between net photosynthesis and stornatal conductance was almost linear. In *E. urophylla, E. camaldulensis, E. brassiana* and *E. pellita,* the premonsoon values for net photosynthesis was higher at lower stornatal conductance. This is a good indication for the better water use efficiency compared to the other two species.

5.6. Root excavation studies in *E. tereticornis* show that the root system of a 20 year old tree extends to 9.3 m deep in the soil. AT depths lower than 2 m, only roots with a diameter less than 5.0 mm were found. The root length density and root weight density were maximum in the upper 2 m depth of soil.

5.7. Examination of the water table in the wells dug for domestic purposes showed that the water table at the excavation study location occurred between 9.0 and 12.0 m depth. This indicates that the root system of *E. tereticornis* was extracting water from the phreatic aquifer.

6. Recommendations

Based on the above conclusions, the following recommendations are given:

6.1 All the six eucalypt species *(E. urophylla, E. camaldulensis, E. brassiana, E. pellita, E. deglupta* and *E. tereticornis)* are drought tolerant to some degree. However, the most drought tolerant is *E. camaldulensis* from leaf water potential observations. Hence this species is recommended for relatively dry locations.

6.2 The closure of stomata in response to atmospheric VPD and leaf water potential gives much indications for the water conservation characteristics. The much lower stornatal conductance in general, the lower stornatal conductance during premonsoon period in particular gives *E. urophylla* the status of a good water conserver and hence recommended for locations where water conservation and plantation productivity are equally important. However, more silvicultural research is recommended in this species as it can turn out to be a promising species in India.

6.3 From the photosynthesis data, there is a reason to believe that *E. camaldulensis* will give better productivity compared to other species. But this species has less developed water conserving features.

6.4 The root excavation study confirms the fear that *tereticornis* extracts the water from the water table. This need not be true for other species. However, this reaffirms the need for wider spacing (3x3 m) in eucalypt plantation already recommended in a previous report submitted to the Ministry of Environment and Forests (Kallarackal, 1993).

CONTENTS

		Page	File
	Symbols and Abbreviations	i	r.136.2
	Abstract	iii	r.136.3
1	Introduction	1	r.136.4
2	Materials and Methods	3	r.136.5
3	Results	6	r.136.6
4	Discussion	10	r.136.7
5	Conclusion	16	r.136.8
6	Recommendations	17	r.136.9
7	References	18	r.136.10

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			E. tereticornis (25/30)	*E. tereticornis* (21/30)	*E. tereticornis* (1/30)
E .brassiana (22/30)	*E. tereticornis* (25/30)	*E .tereticornis* (19/30)	*E. tereticornis* (23/30)	*E. tessellaris* (15/30)	*E. pellita* (15/30)
E .cloeziana (0/30)	*E. brassiana* (24/30)	*E. brassiana* (23/30)	*E. brassiana* (25/30)	*E. brassiana* (26/30)	*E. brassiana* (29/30)
E .cloeziana (0/18)	*E.pellita* (17/30)	*E.pellita* (19/30)	*E. resinifera* (0/30)	*E. saligna* (0/30)	*saligna* (0/30)
E. camaldulensis (12/30)	*E. camaldulensis* (27/30)	*E. deglupta* (5//30)	*E. resinifera* (0/30)	*E. pilularis* (1/29)	*E. microcorys* (0/30)
E.deglupta. (0/20)	*E.grandis* (0/30)	*E.grandis* (0/30)	*E.urophylla* (18/30)	*E.urophylla* (10/29)	*E.urophylla* (18/26)
E.propinqua (0/25)	*E.grandis* (0/30)	*E.grandis* (0/30)	*E.grandis* (0/30)	*E.grandis* (0/30)	*E.grandis* (0/30)

Fig. 1. Plot design of Eucalyptus Arboretum, Nilambur, Kerala showing the number of plants in each species planted on 7-9-1983 and the survival as on 24-11-1996. The denominator represents the number of species planted and the numerator represents the number of surviving trees.

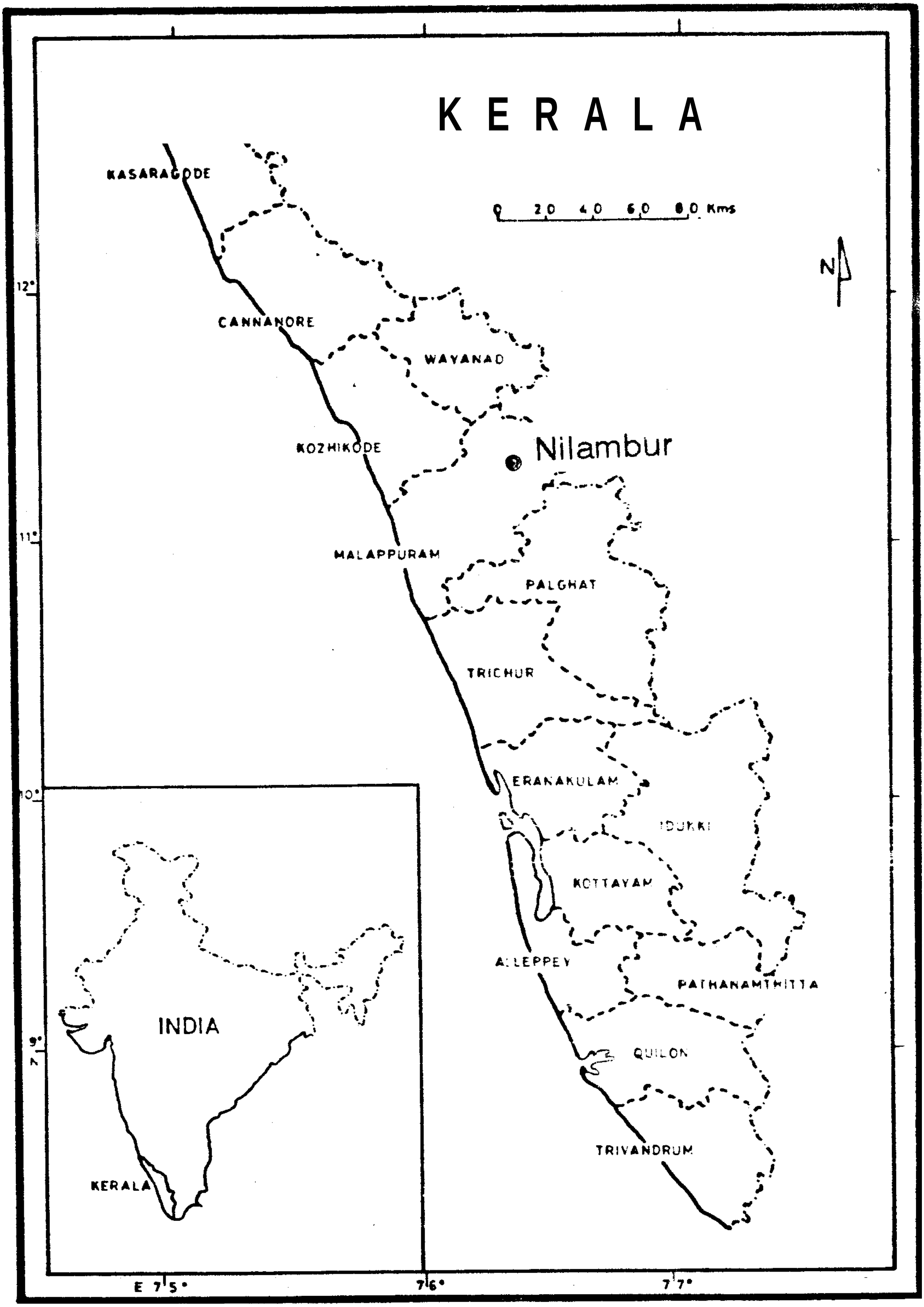


Fig. 2. Outline map of Kerala State showing the study location, Nilambur.

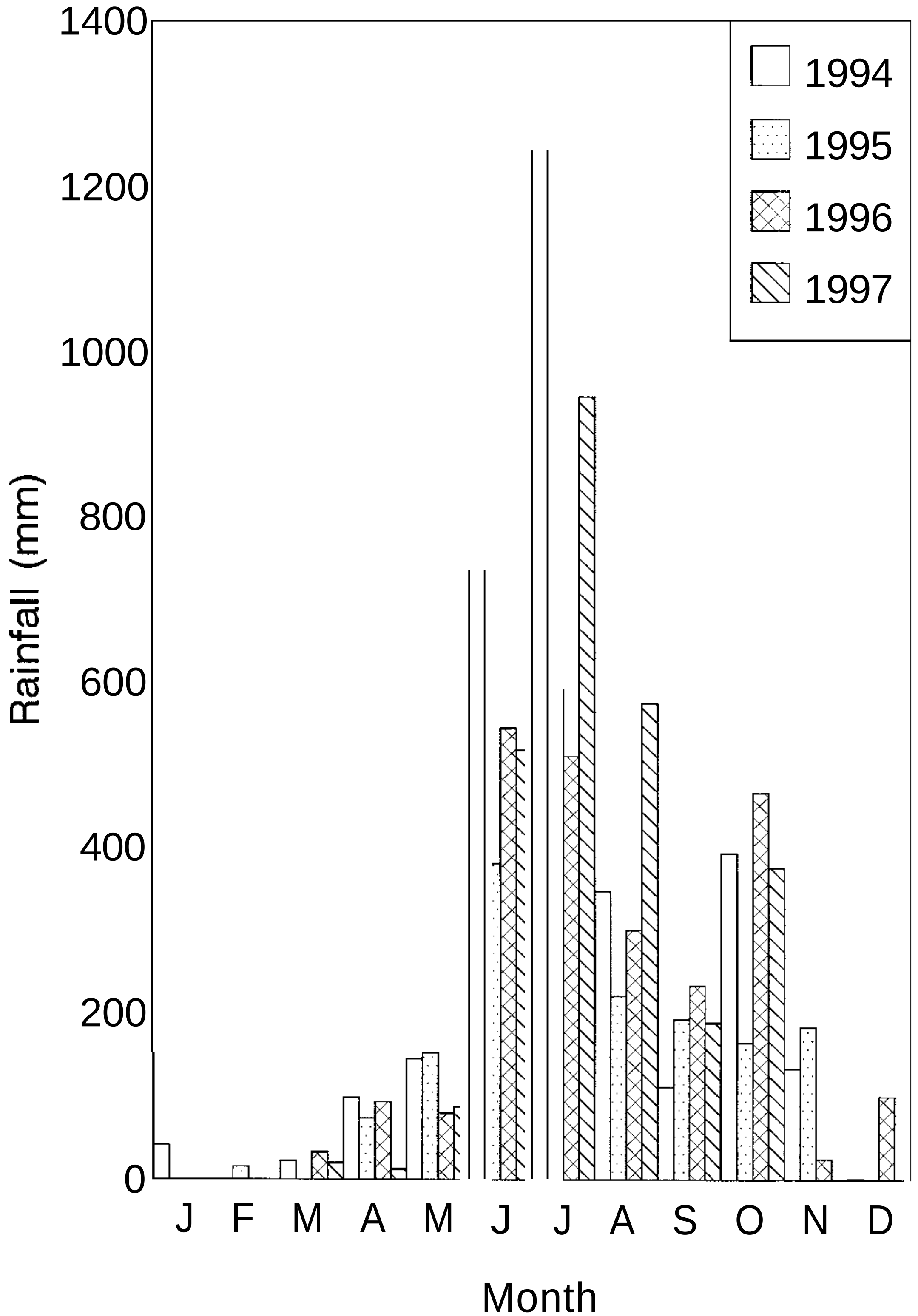


Fig. 3. Rainfall data measured during 1994-97 at the study location. The higher rainfall during June to November is due to the operation of two monsoons.

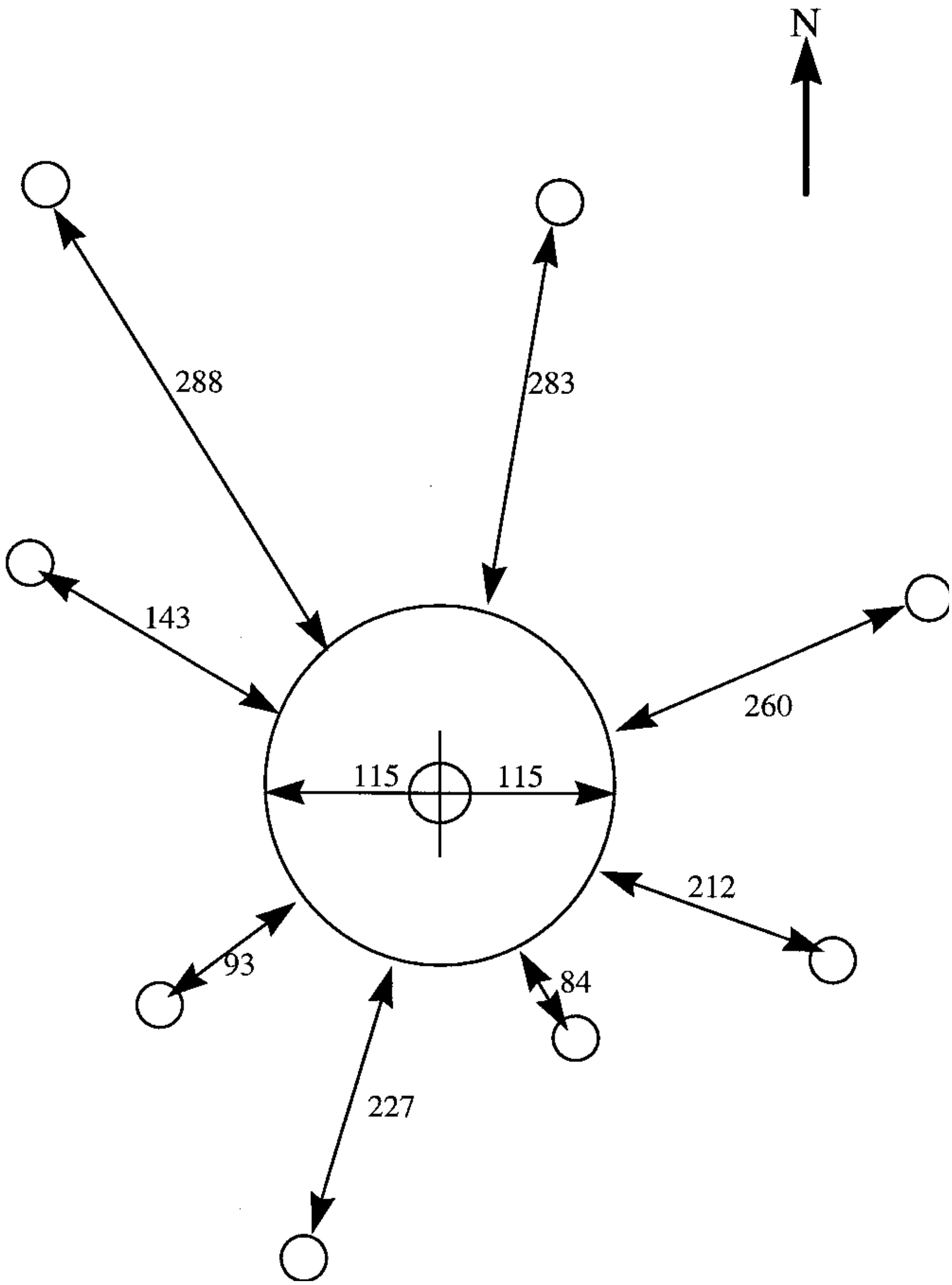


Fig. 4a. A plot map showing the location of the first excavation for root studies. The large circle represents the pit and the small circles represent the tree stems. The numbers shown are measurement in cm.

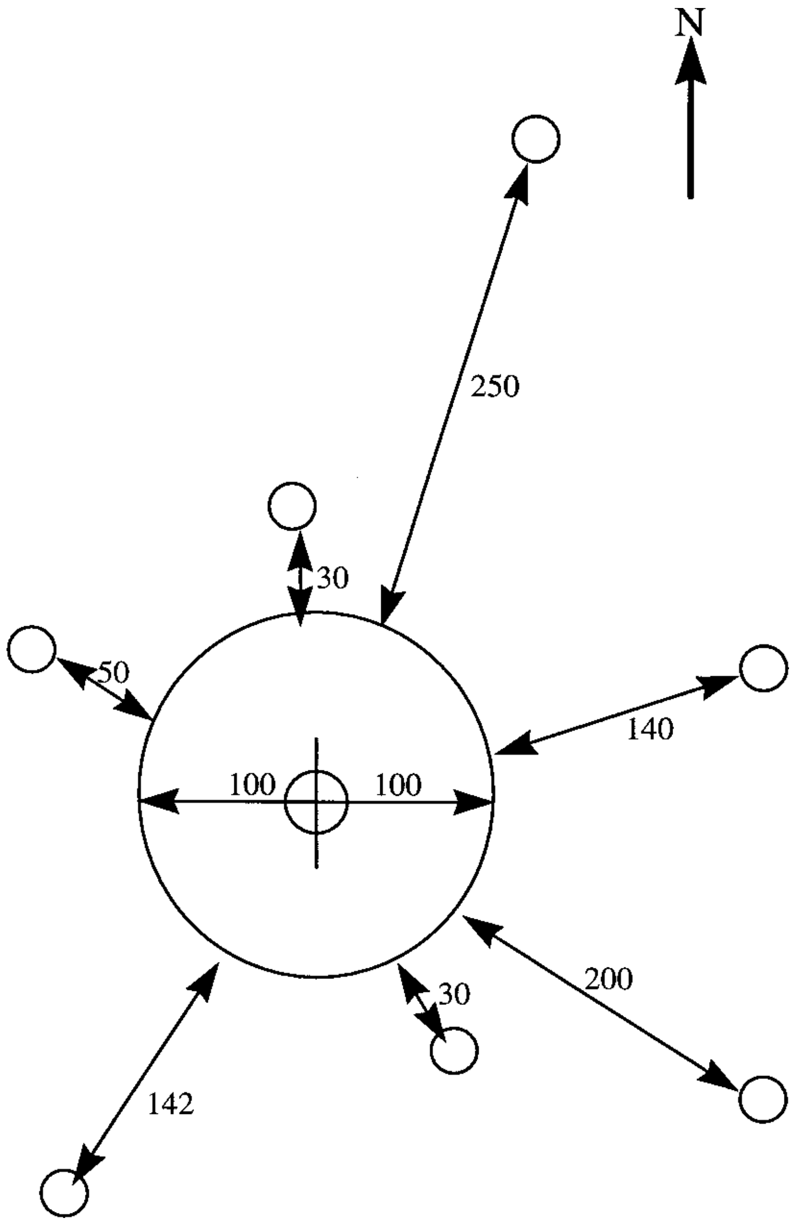
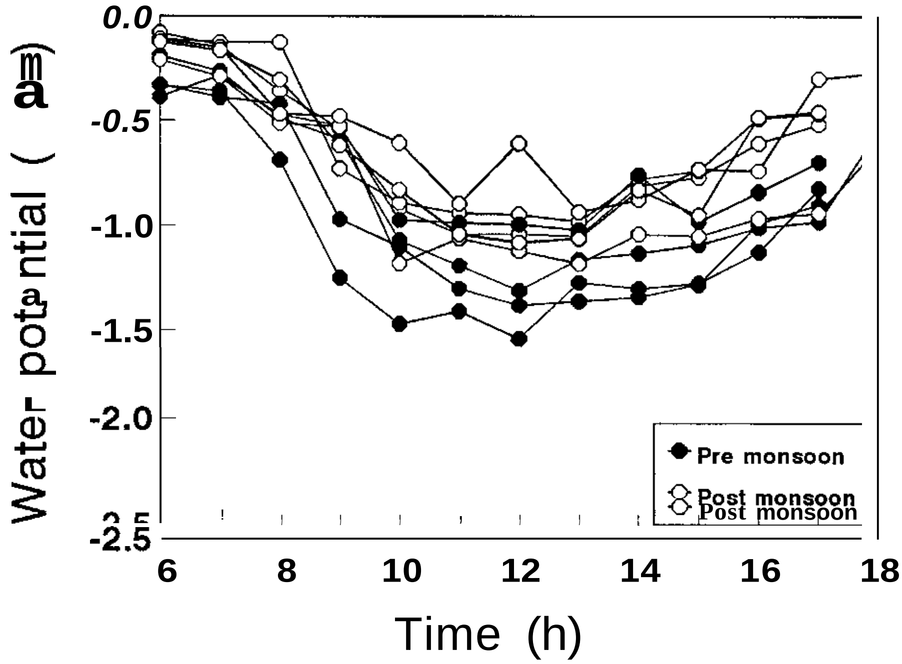


Fig. 4b. A plot map showing the location of the second excavation for the root studies. The large circle represents the pits and the small circles represent the tree stems. The numbers shown are measurement in cm.

1. *Eucalyptus urophylla*



2. *Eucalyptus camaldulensis*

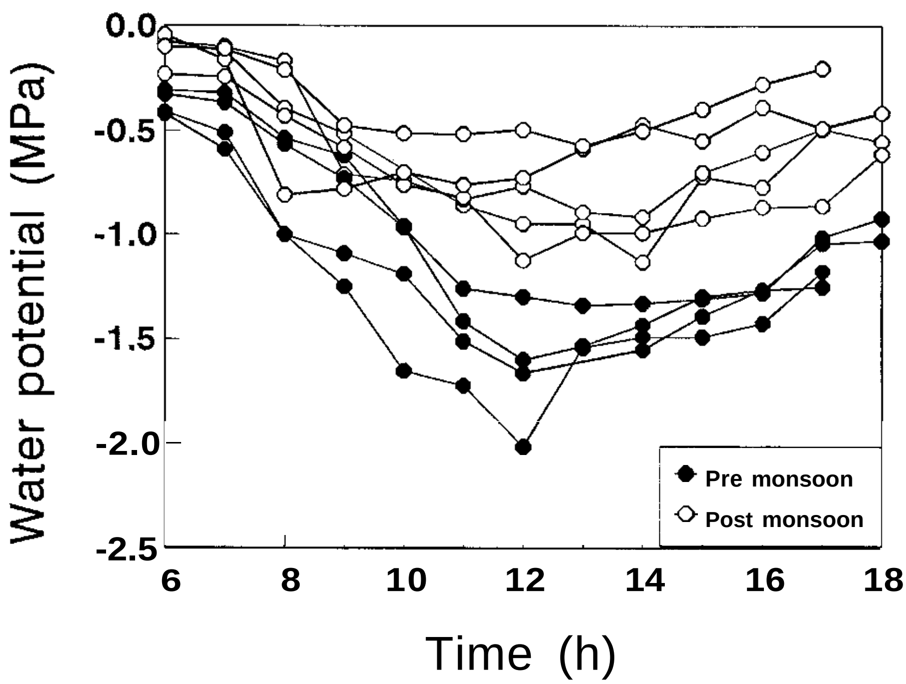
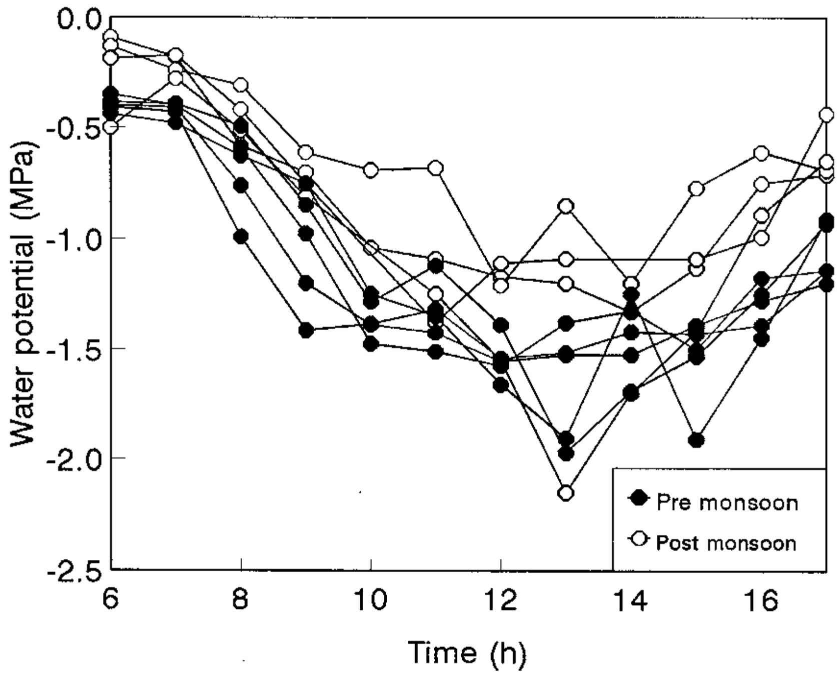


Fig. 5. Diurnal variations of leaf water potential in *E. urophylla* and *E. camaldulensis.* Each point represents the mean of at least 5 measurements using pressure chamber.

1. *Eucalyptus brassiana*



2. *Eucalyptus pellita*

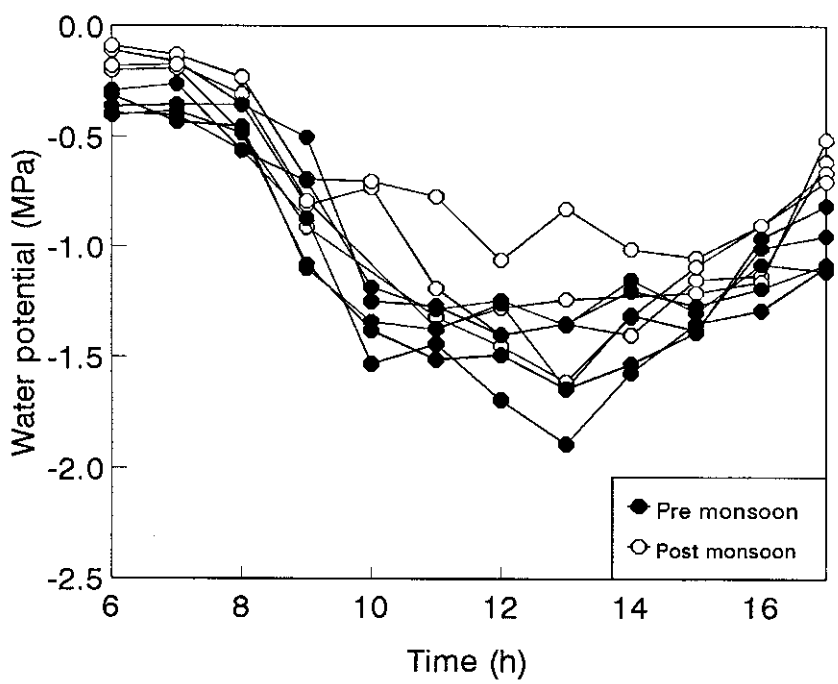


Fig. 6. Diurnal variations of leaf water potential in *E. brassiana* and *E. pellita*. Each point represents the mean of at least 5 measurements.

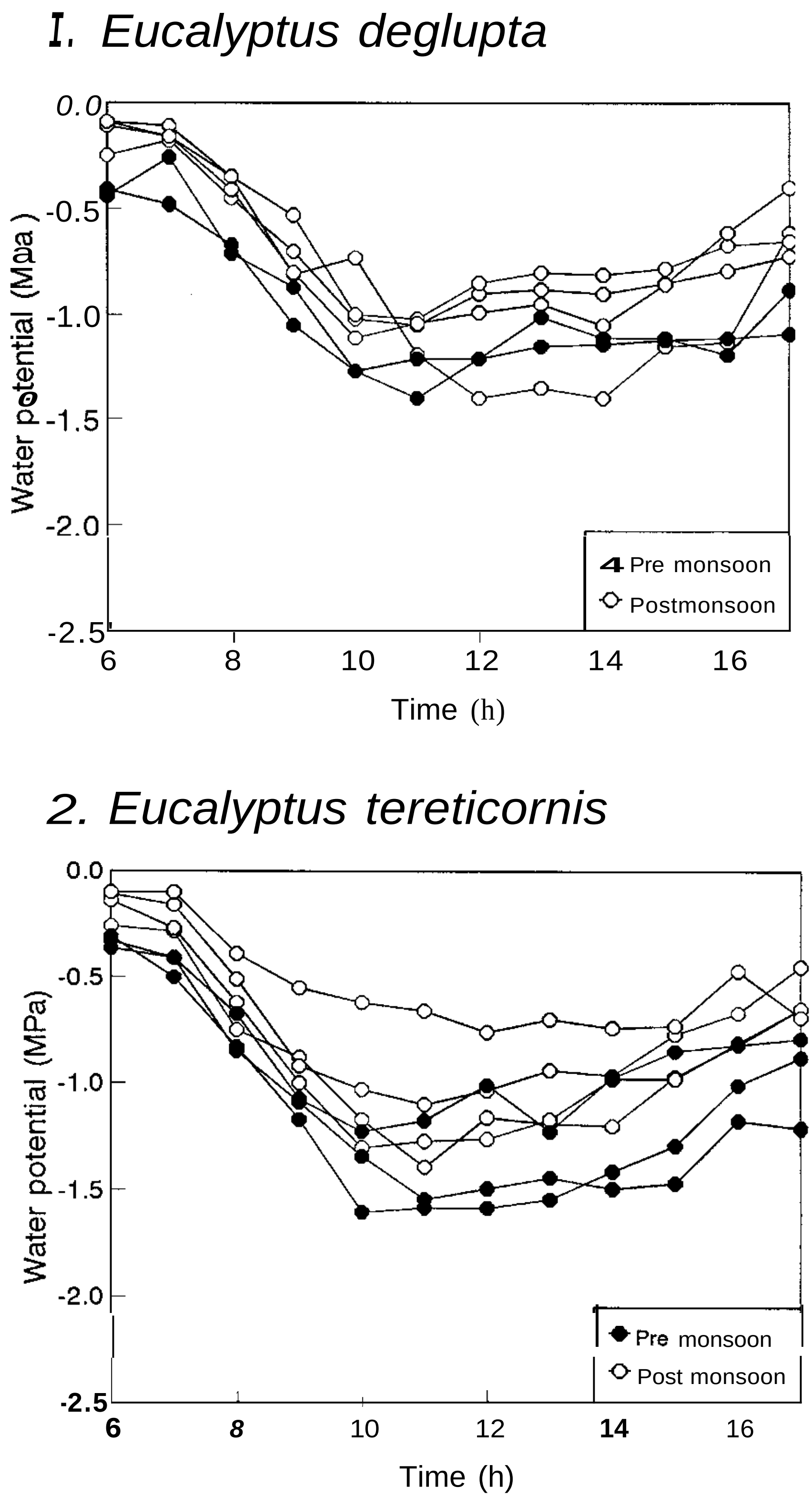
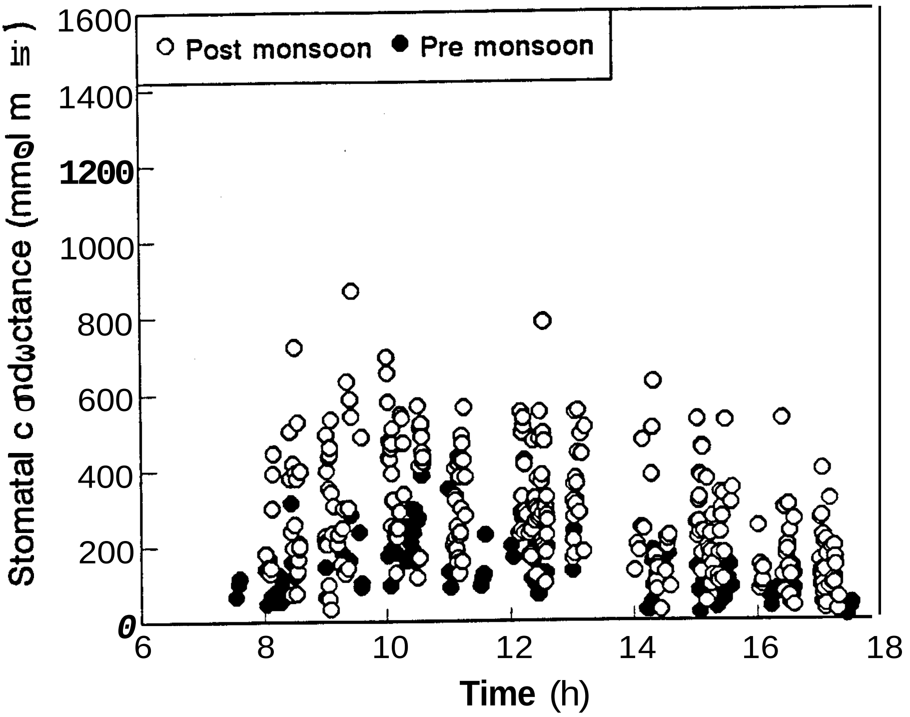


Fig. 7. Diurnal variations of leaf water potential in *E. deglupta* and *E. tereticornis*. Each point represents the mean of at least 5 measurements.

1, Eucalyptus urophylla



2. Eucalyptus camaldulensis

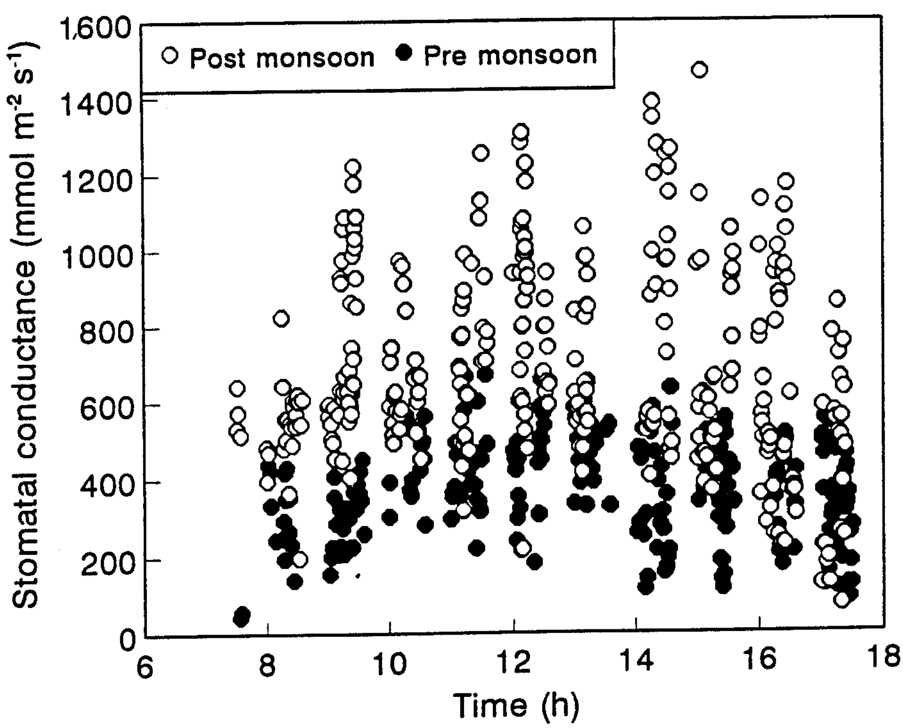
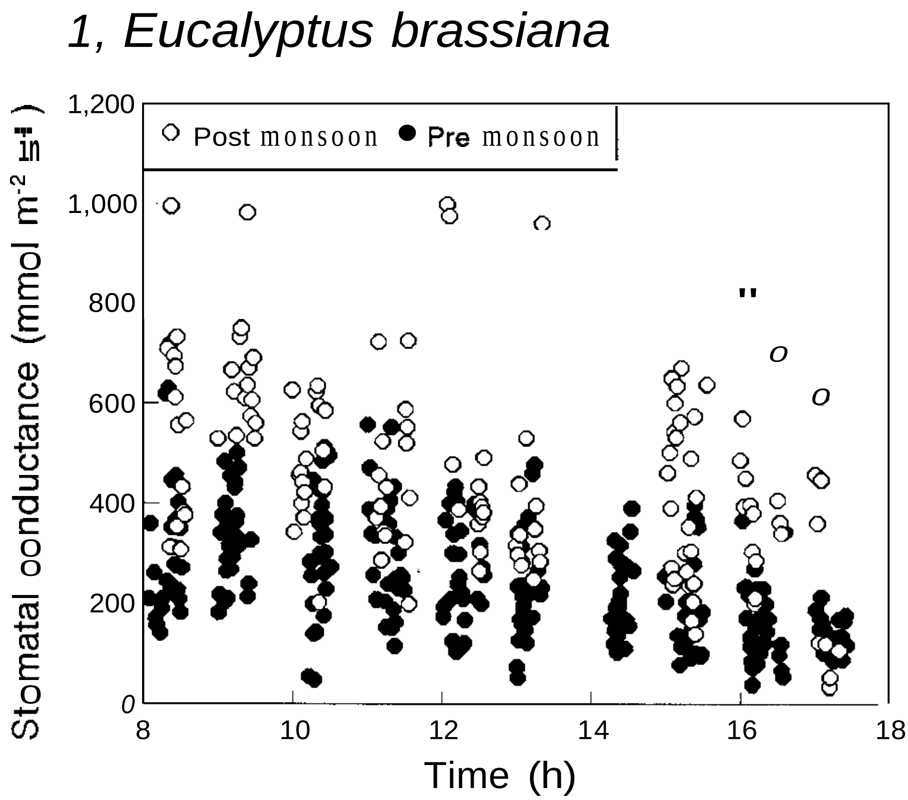


Fig. 8. Stomatal conductance in *E. urophylla* and *E. camaldulensis*. Each point is the result of measurement on individual leaves belonging to 4 different trees made with Portable Photosynthesis System.



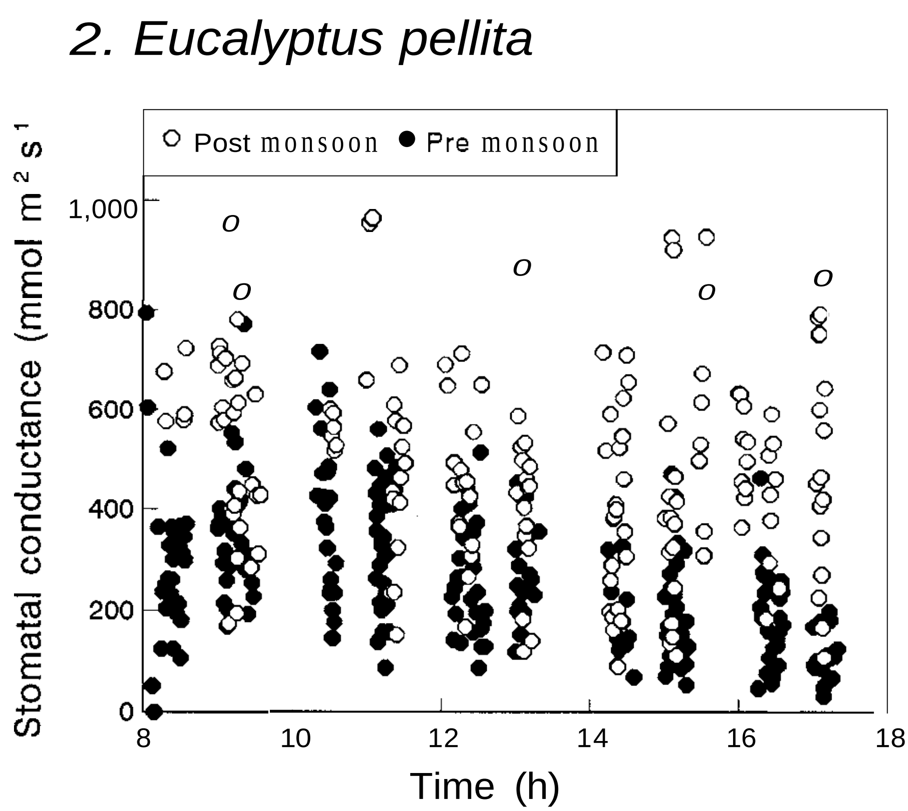
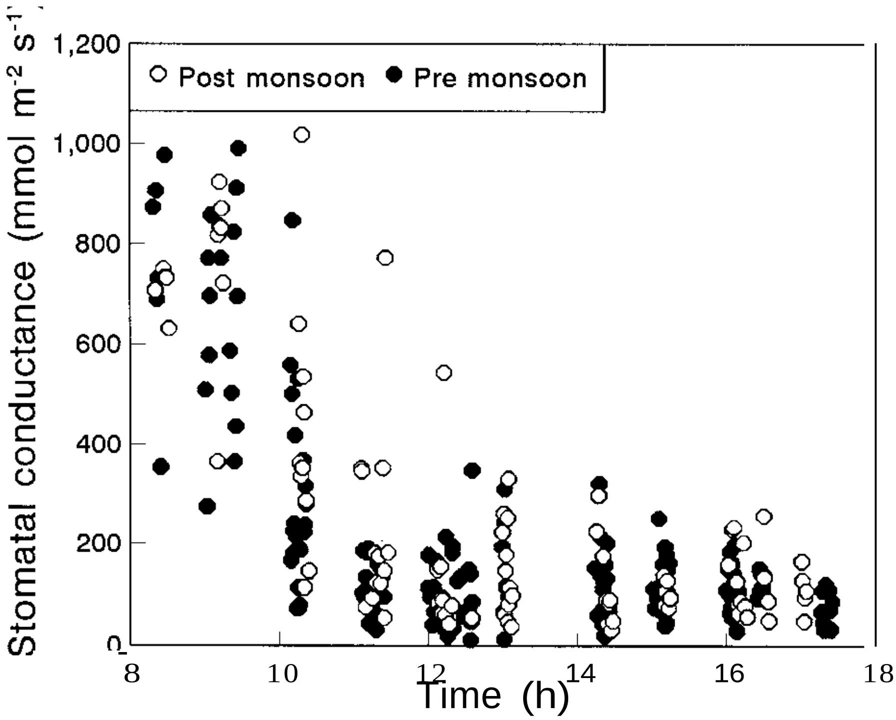


Fig. 9. Stomatal conductance in *E. brassiana* and *E. pellita*. Each point is the result of measurement on individual leaves belonging to 4 different trees made with Portable Photosynthesis System.

1. Eucalyptus deglupta



2. Eucalyptus tereticornis

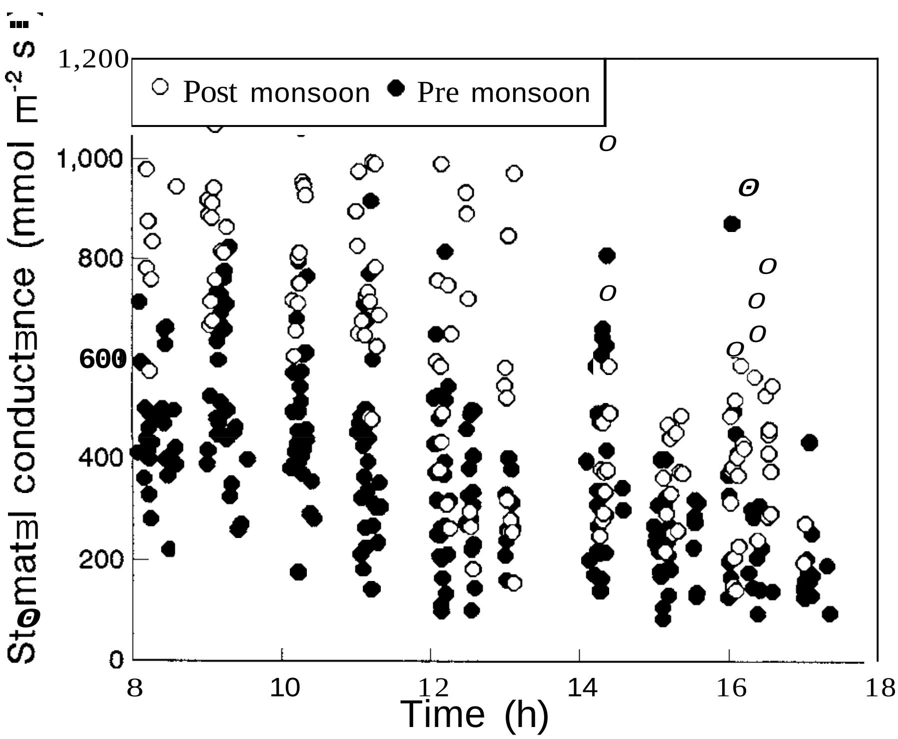
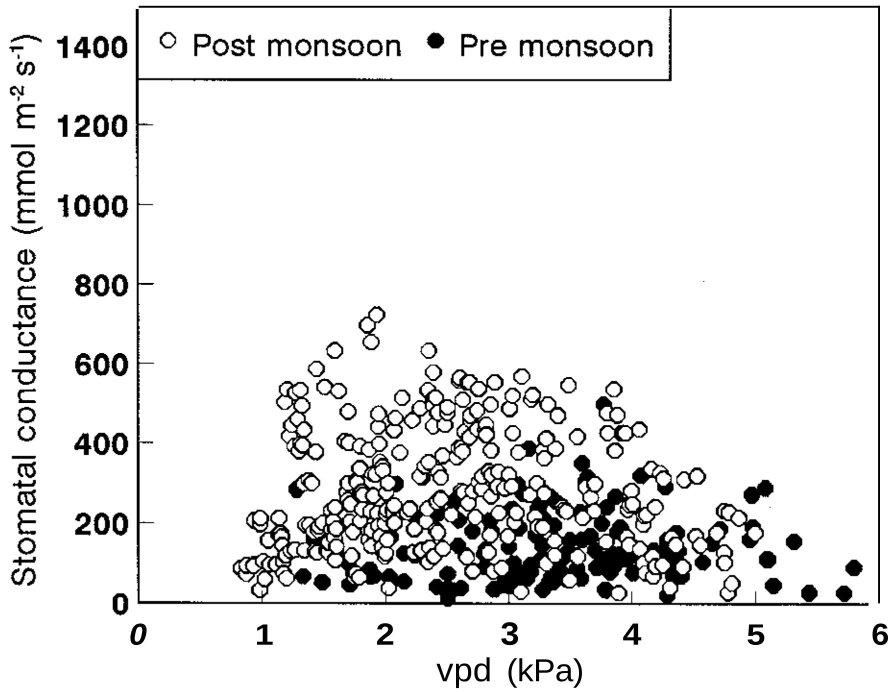


Fig. 10. Stomatal conductance in *E. deglupta* and *E. tereticornis*. Each point is the result of measurement on individual leaves belonging to 4 different trees made with Portable Photosynthesis System.

1. *Eucalyptus urophylla*



2. *Eucalyptus camaldulensis*

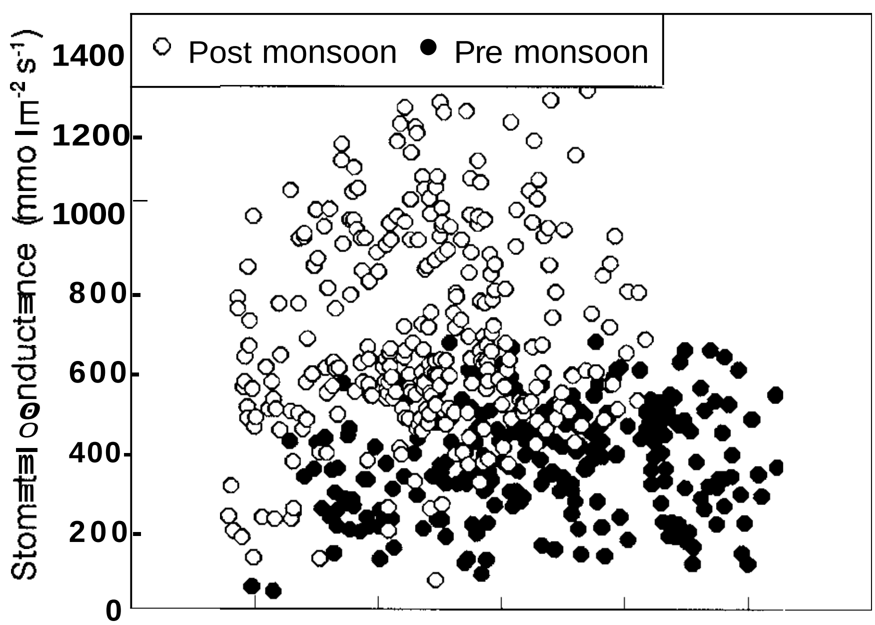
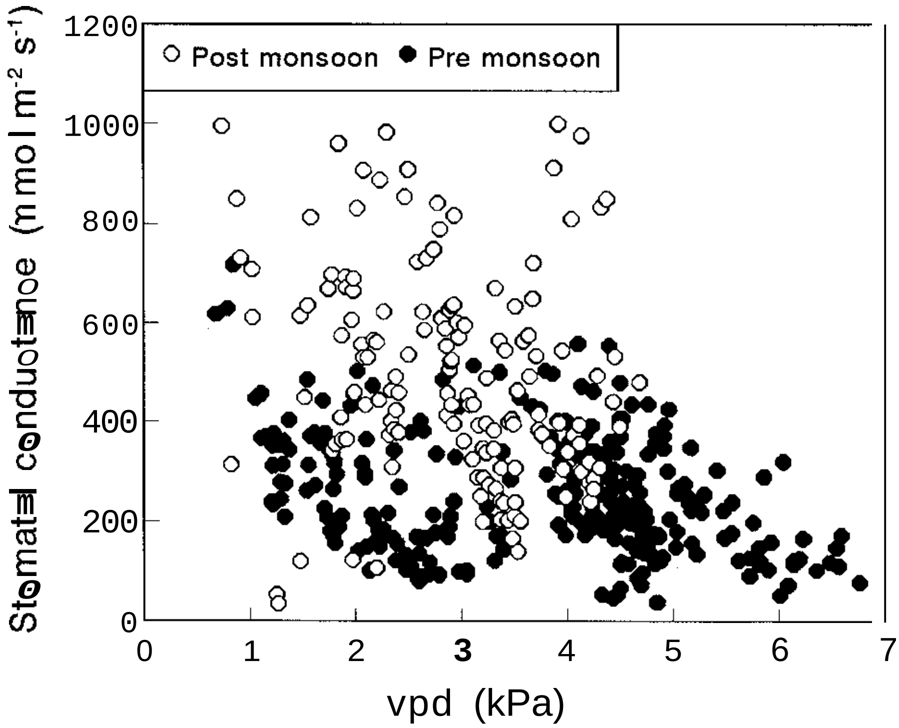


Fig. 11. Relation between stomatal conductance and atmospheric vapour pressure deficit in *E. urophylla* and *E. camaldulensis.* Note the lower conductance during the premonsoon period.

I. *Eucalyptus brassiana*



2. *Eucalyptus pellita*

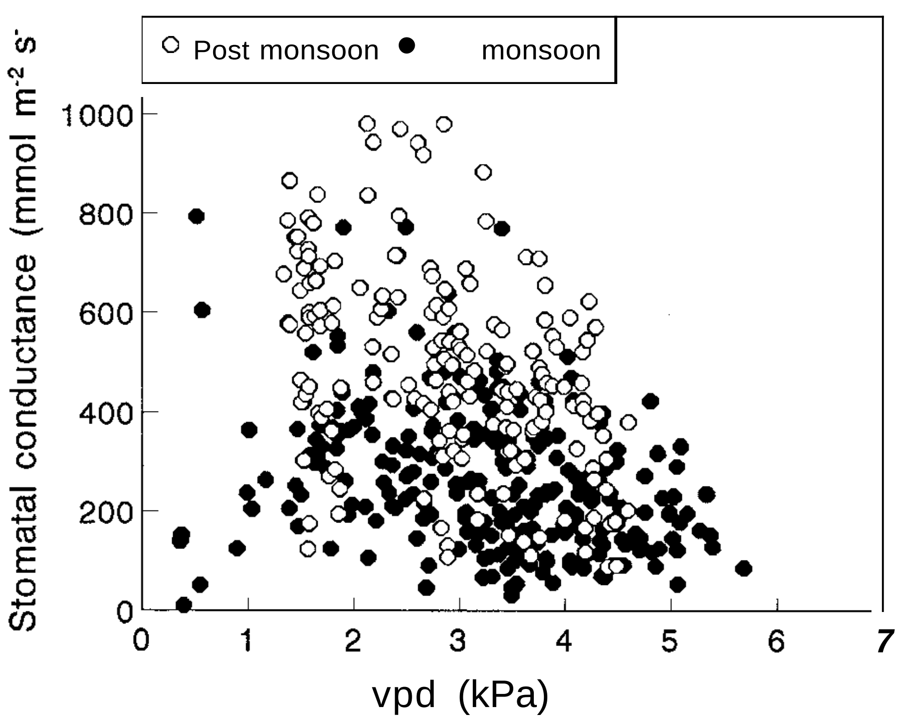
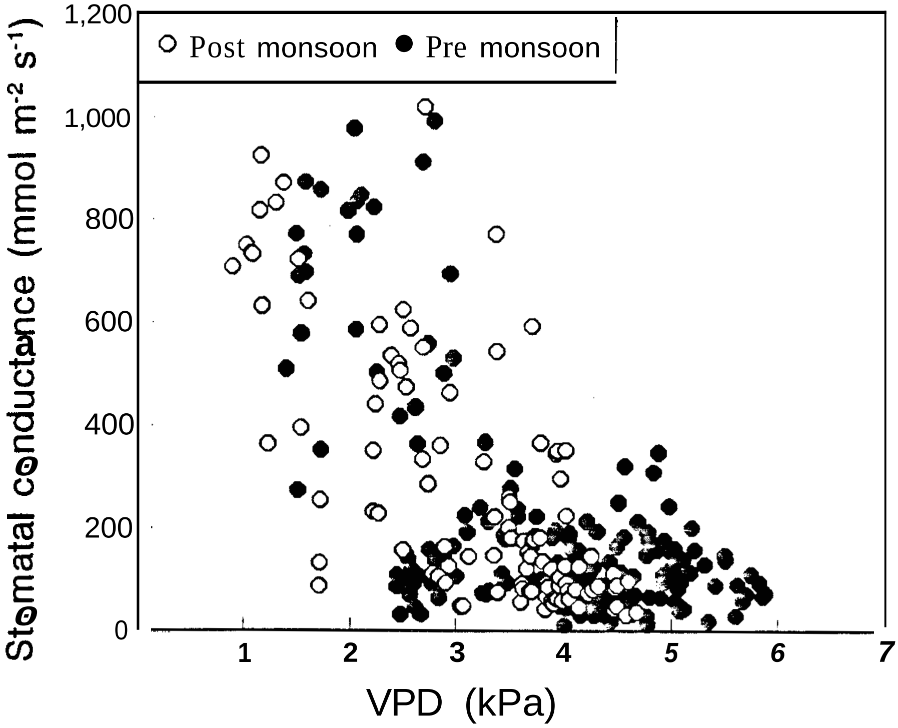


Fig. 12. Relation between stomatal conductance and atmospheric vapour pressure deficit in *E. brassiana* and *E. pellita*. Note the lower conductance during the premonsoon period.

1.Eucalyptus deglupta



2. Eucalyptus tereticornis

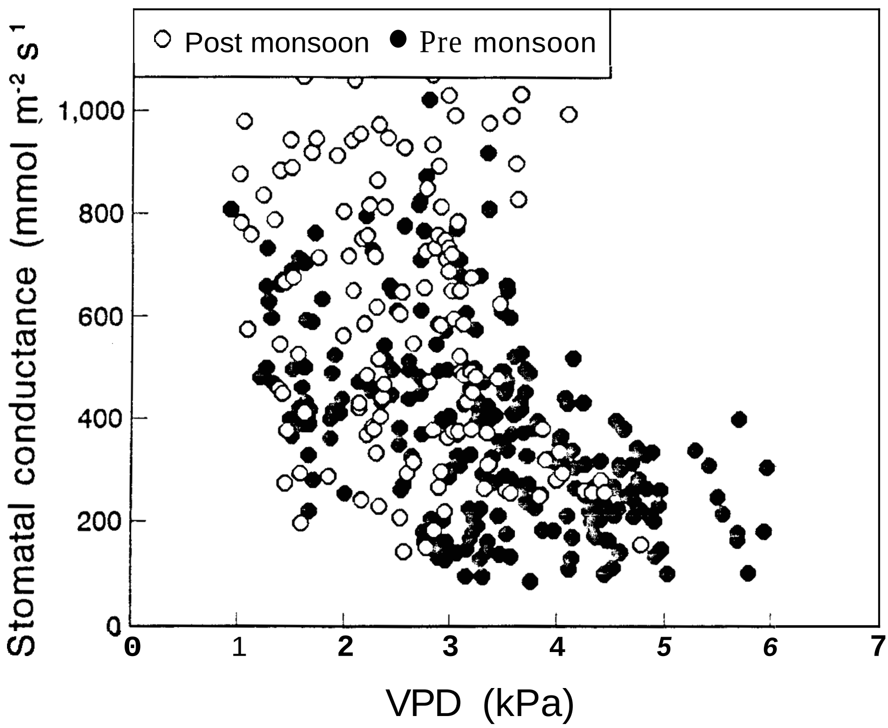


Fig. 13. Relation between stomata1 conductance and atmospheric vapour pressure deficit in *E. deglupta* and *E. tereticornis*. Unlike in other four species the magnitude of premonsoon and postmonsoon values are nearly same.

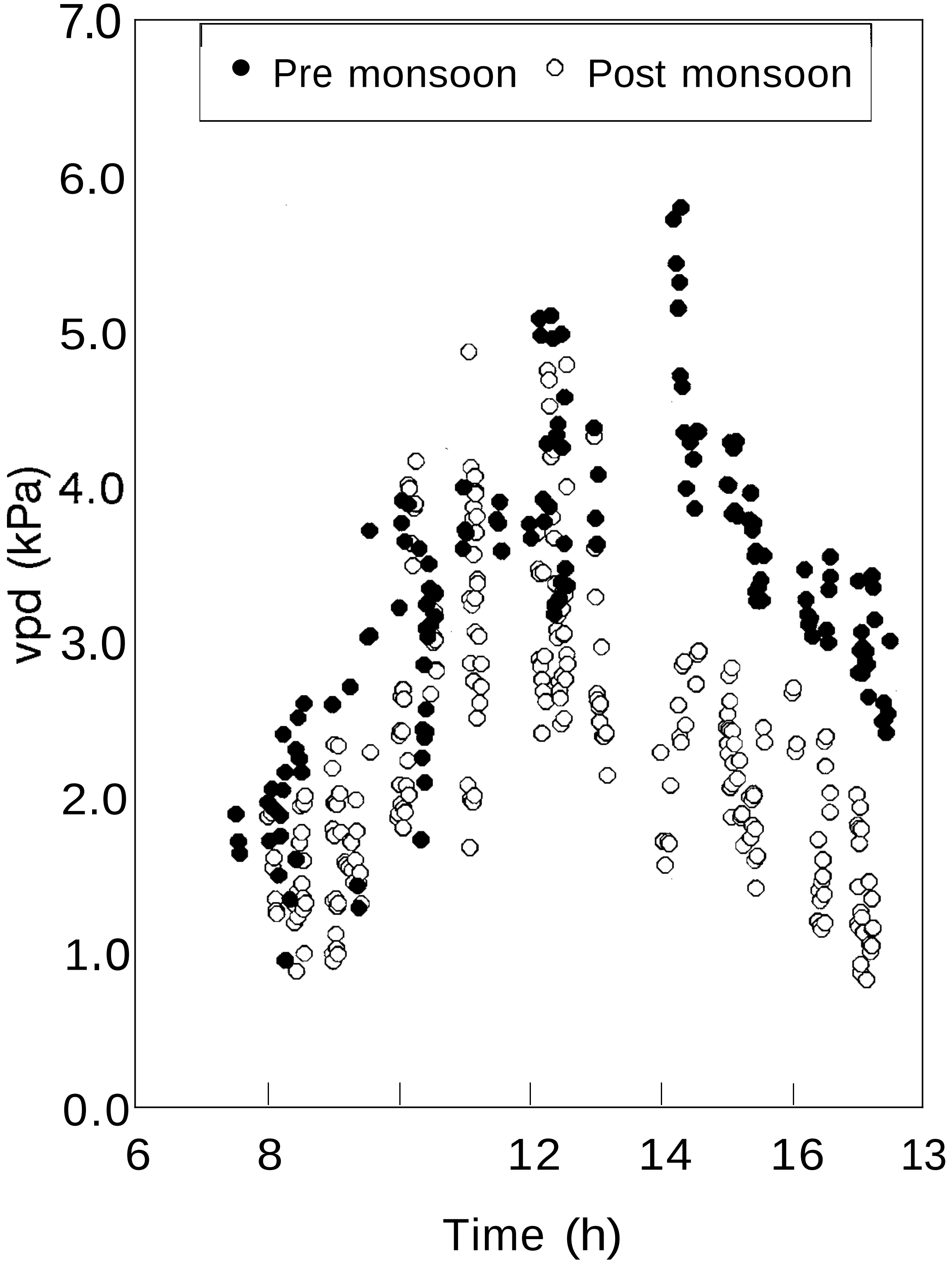
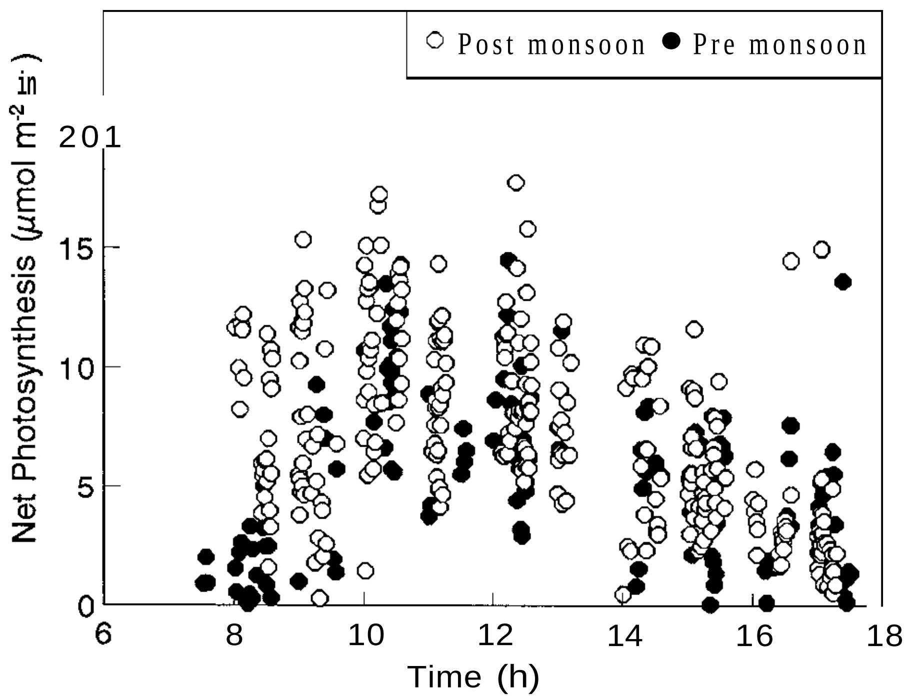


Fig. 14. Atmospheric vapour pressure deficit measured diurnally in the study location. The instantaneous measurements were made using the temperature and humidity sensors of the Portable Photosynthesis System.

1. Eucalyptus urophylla



2. Eucalyptus camaldulensis

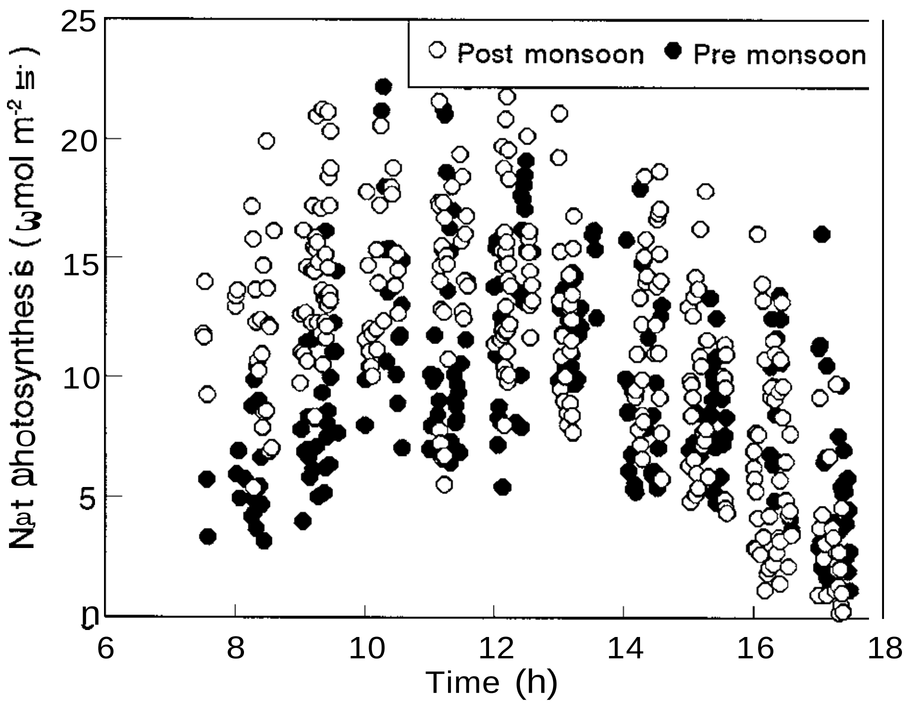
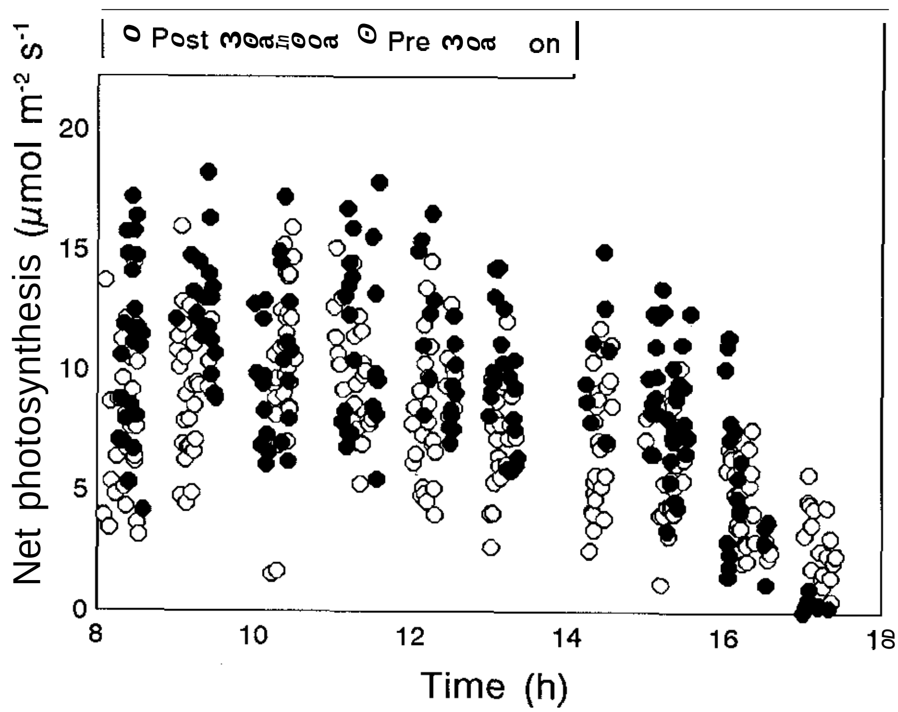


Fig. 15. Diurnal values of net photosynthesis in *E. urophylla* and *E. camaldulensis*. The difference between post and premonsoon values are negligible. Note the peak values during the forenoon in both the species.

1. *Eucalyptus brassiana*



2. *Eucalyptus pellita*

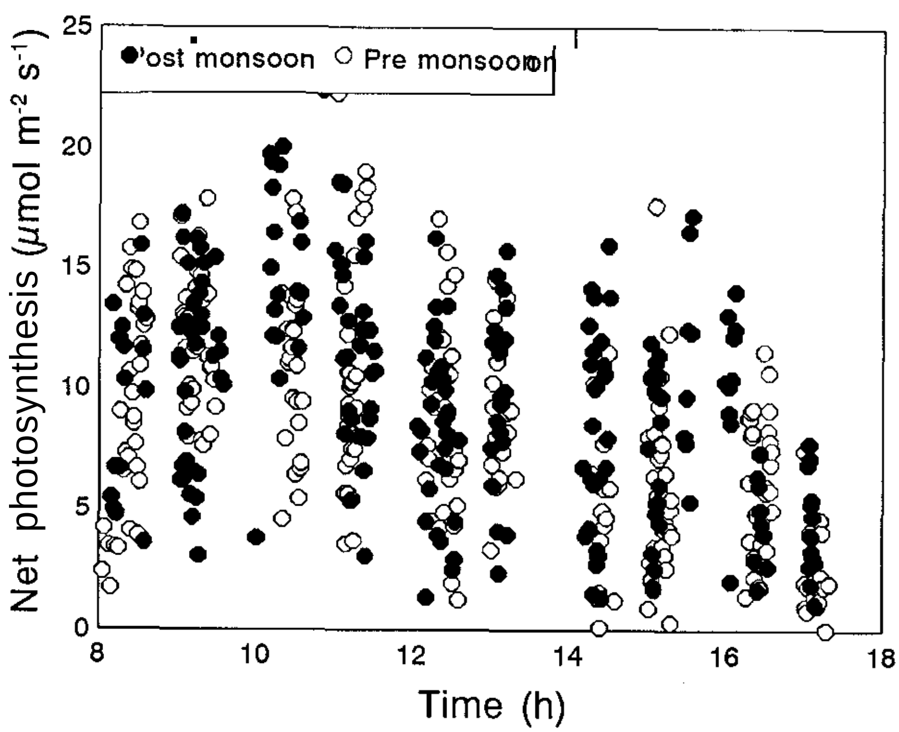
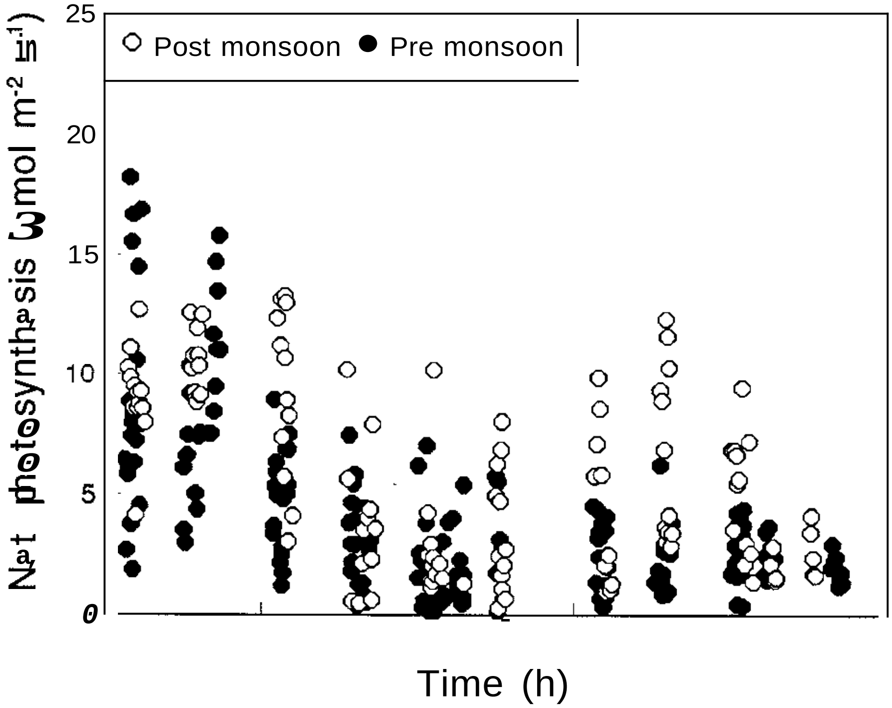


Fig. 16. Diurnal values of net photosynthesis in *E. brassiana* and *E. pellita*. The difference between post and premonsoon values are negligible. Note the peak values during the forenoon in both the species.

1. *Eucalyptus deglupta*



2. *Eucalyptus tereticornis*

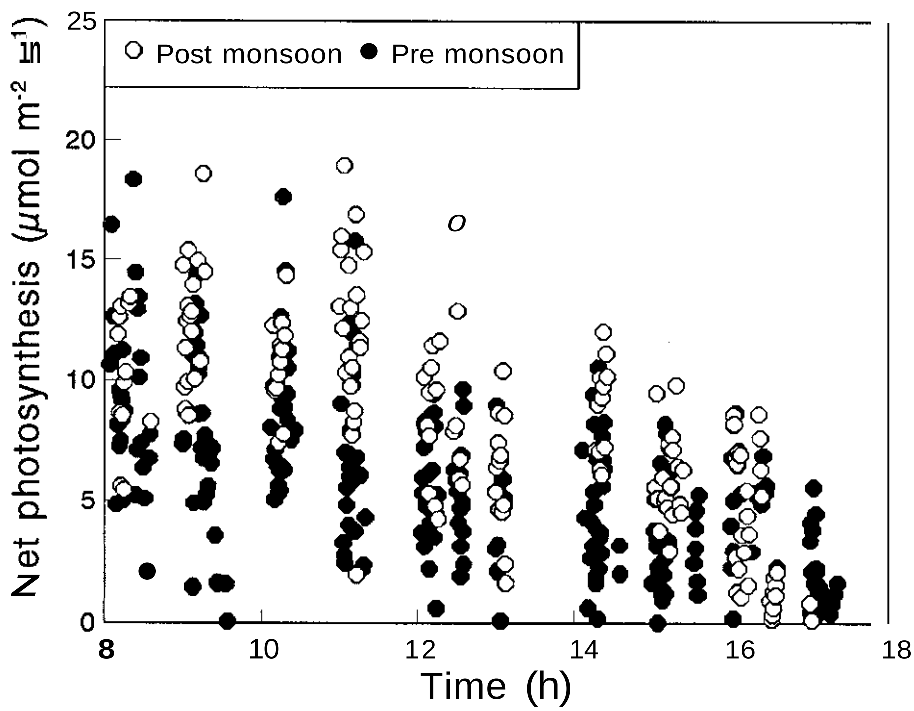
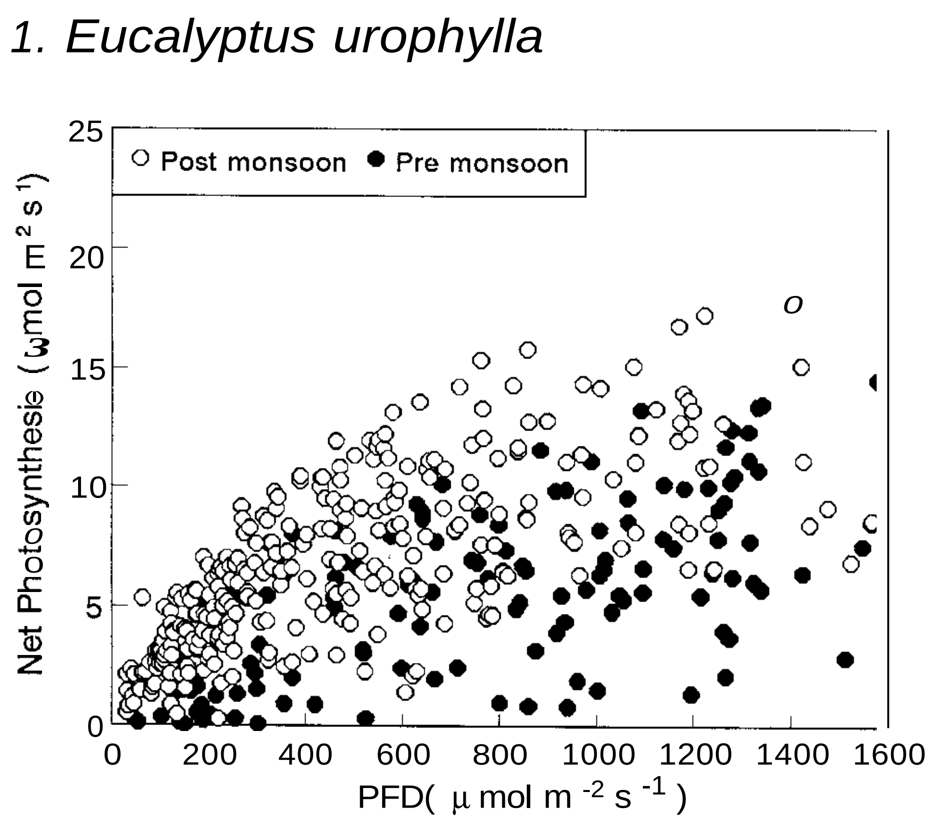


Fig. 17. Diurnal values of net photosynthesis in *E. deglupta* and *E. tereticornis*. There is tendency for lower values during the premonsoon period. Note the presence of two peaks in *E. deglupta*.



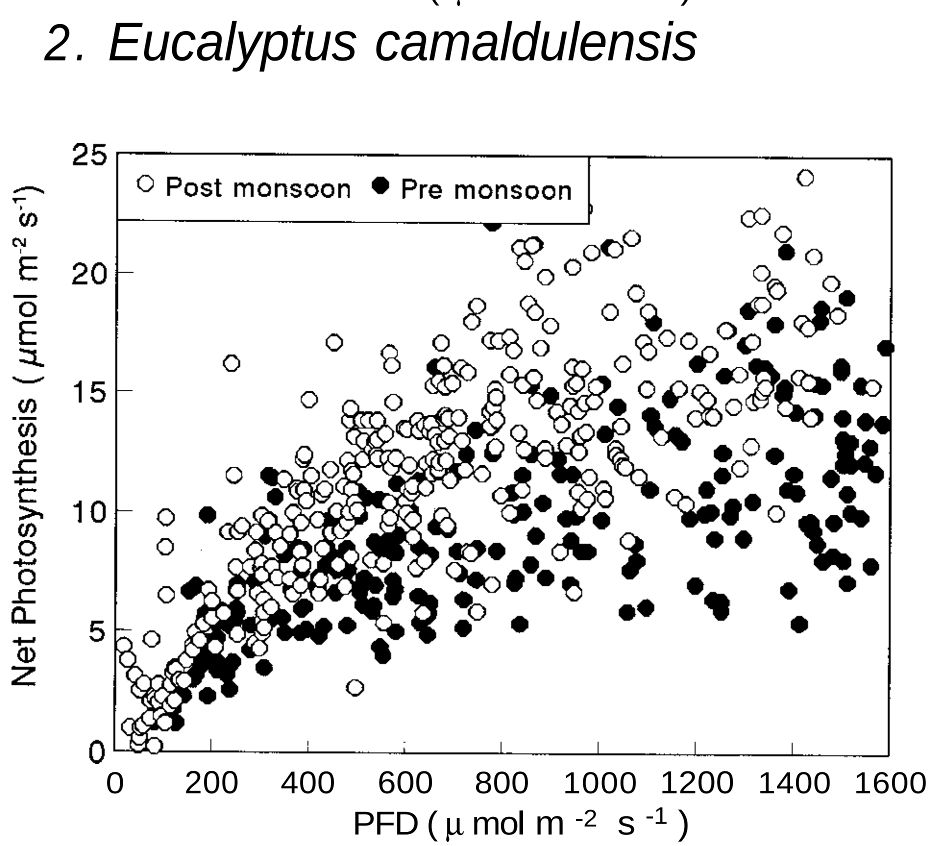
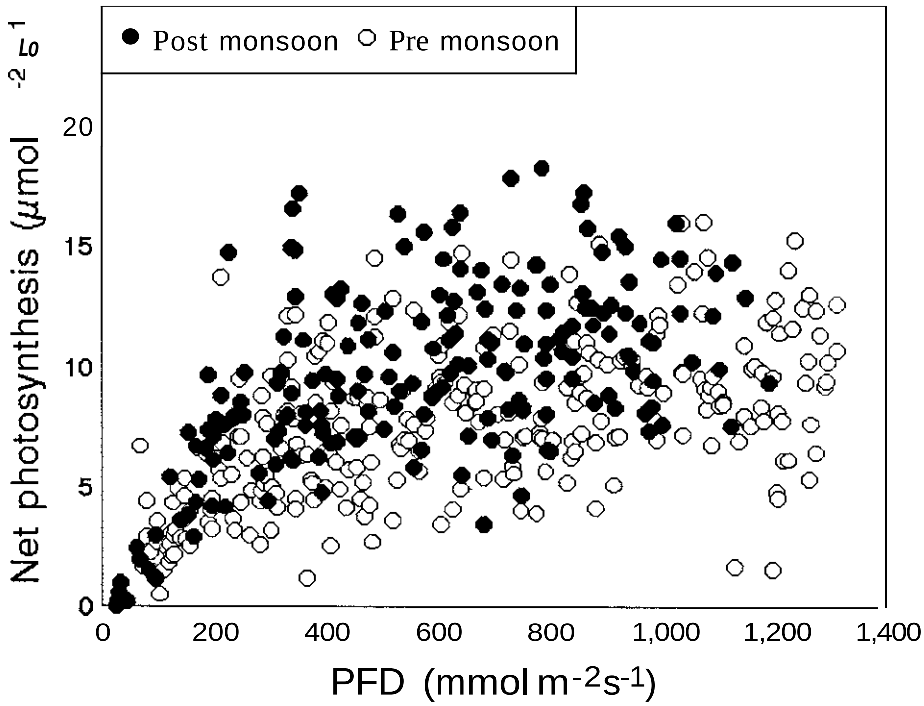


Fig. 18. Net photosynthesis values plotted against Photon Flux Density in *E. urophylla* and *E. camaldulensis.* All the measurements were taken in natural daylight during several days in the year. The light at which maximum photosynthesis is obtained may be noted.

1. Eucalyptus brassiana



2. Eucalyptus pellita

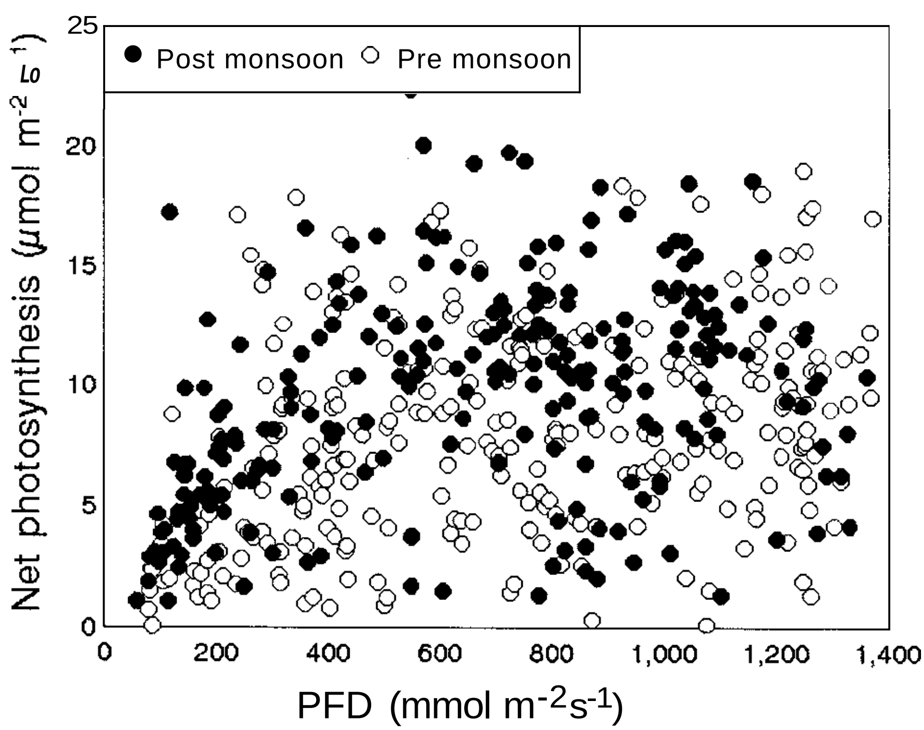


Fig. 19. Net photosynthesis values plotted against Photon Flux Density in *E. brassiana* and *E. pellita*. All the measurements were taken in natural daylight during several days in the year. The light at which maximum photosynthesis is obtained may be noted.

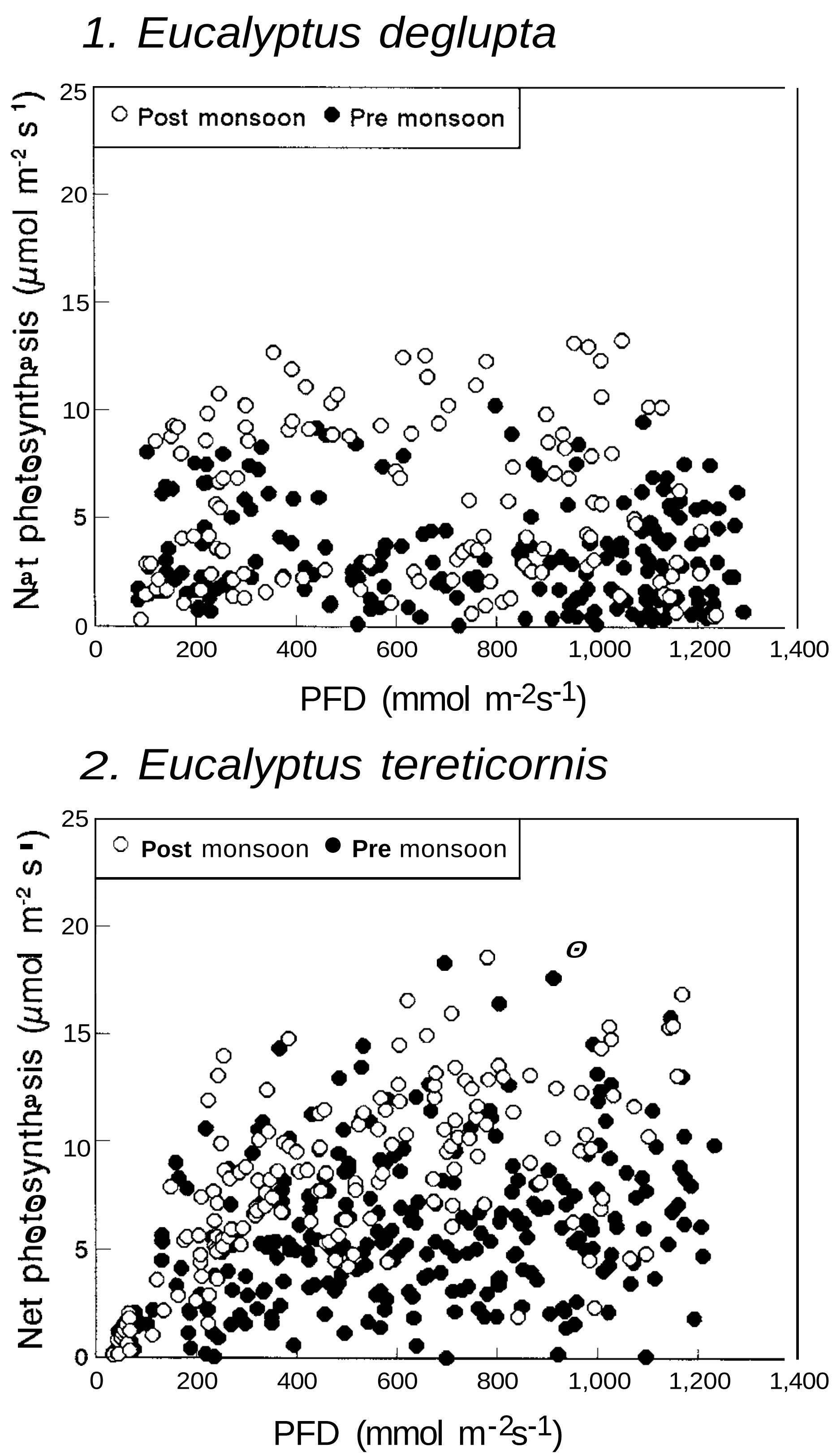
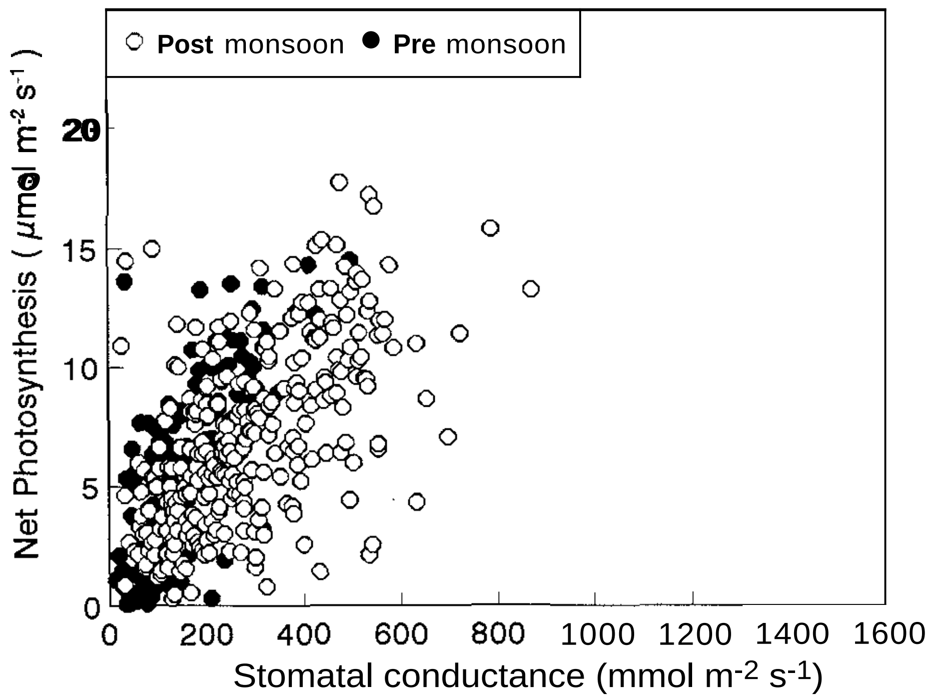


Fig. 20. Net photosynthesis values plotted against Photon Flux Density in *E. deglupta* and *E. tereticornis*. The unusual scatter seen in *E. deglupta* may be due to the interference of some other factors apart from light in this species.

1. *Eucalyptus urophylla*



2. *Eucalyptus camaldulensis*

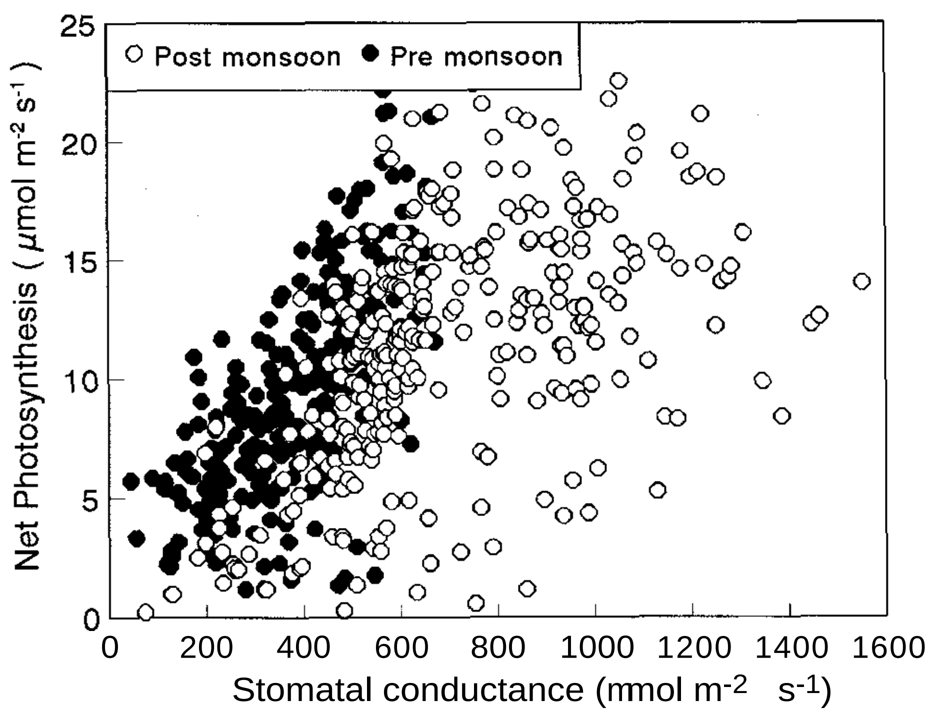
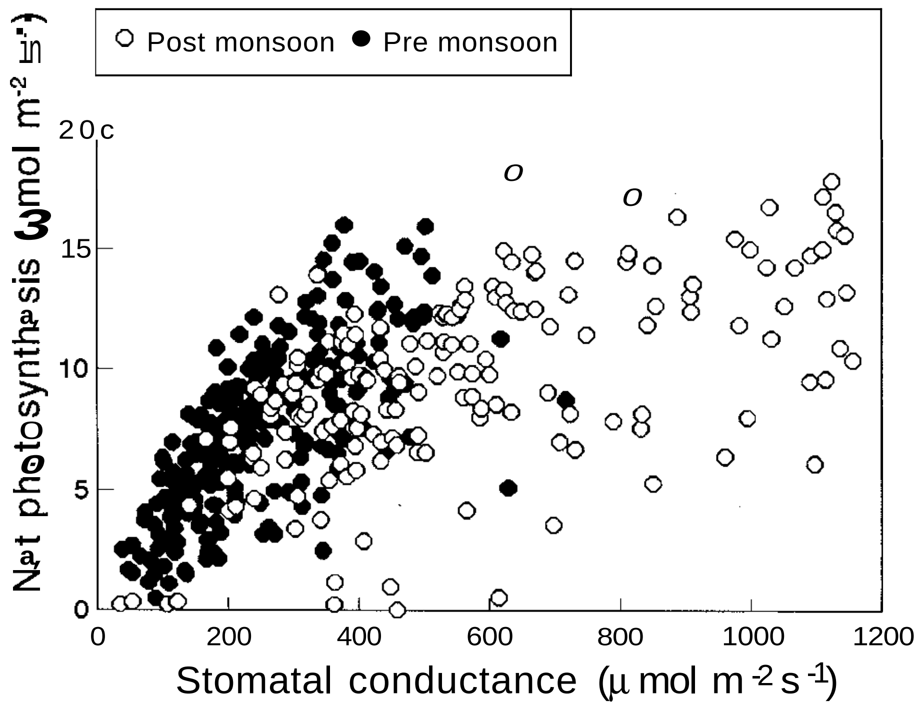


Fig. 21. The relationship between net photosynthesis and stornatal conductance in *E. urophylla* and *E. camaldulensis*. The trend for same photosynthesis at lower stornatal conductance is apparent in both the species.

1. *Eucalyptus brassiana*



2. *Eucalyptus pellita*

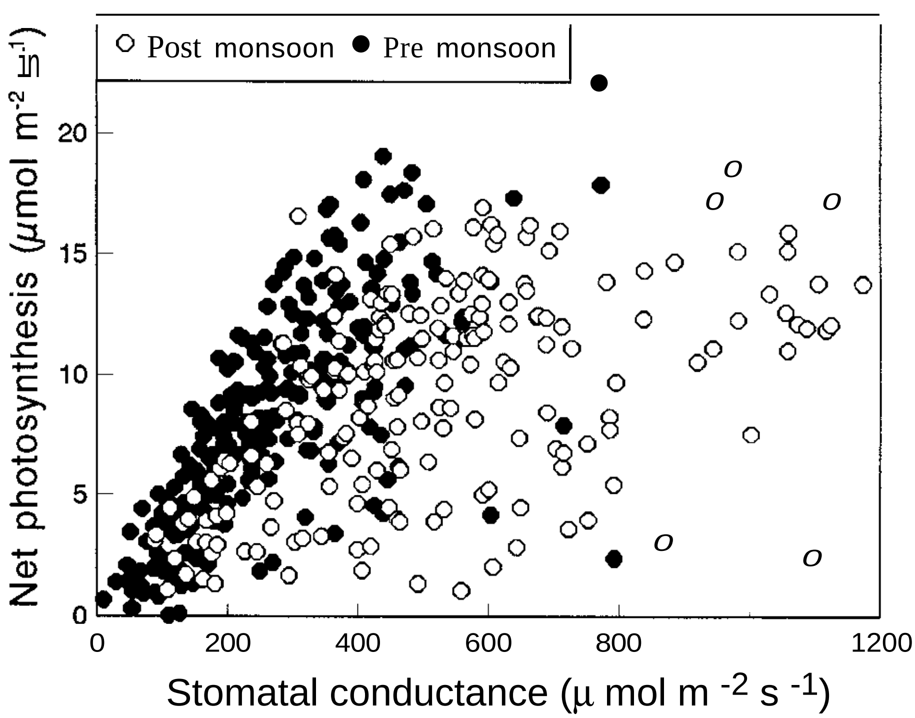
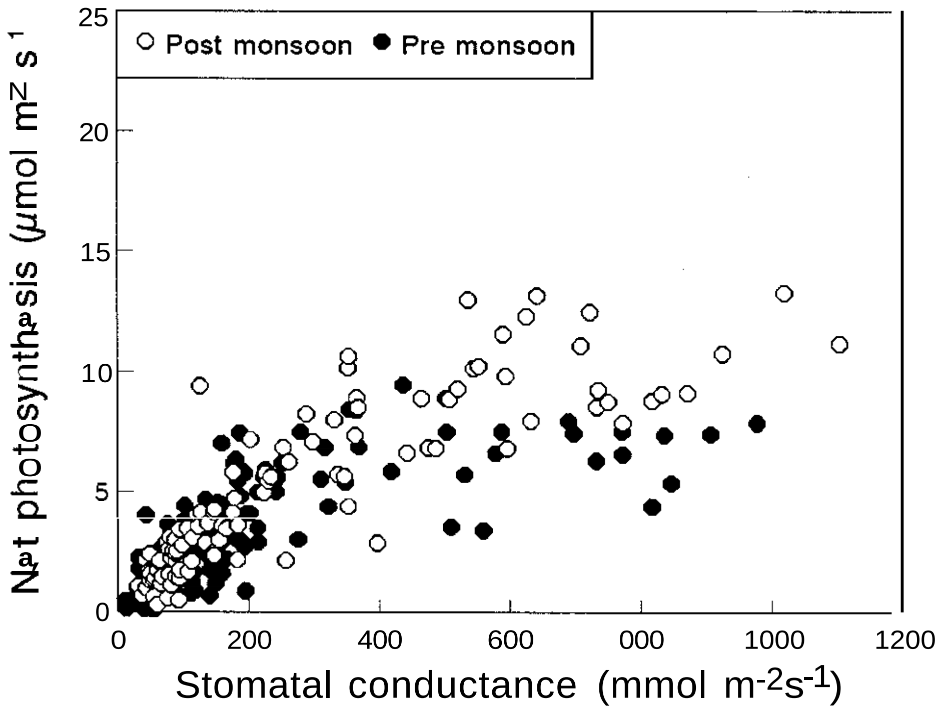


Fig. 22. The relationship between net photosynthesis and stomatal conductance in *E. brussiana* and *E. pellita*. The trend for same photosynthesis at lower stomatal conductance is apparent in both the species.

1. Eucalyptus deglupta



2. Eucalyptus tereticornis

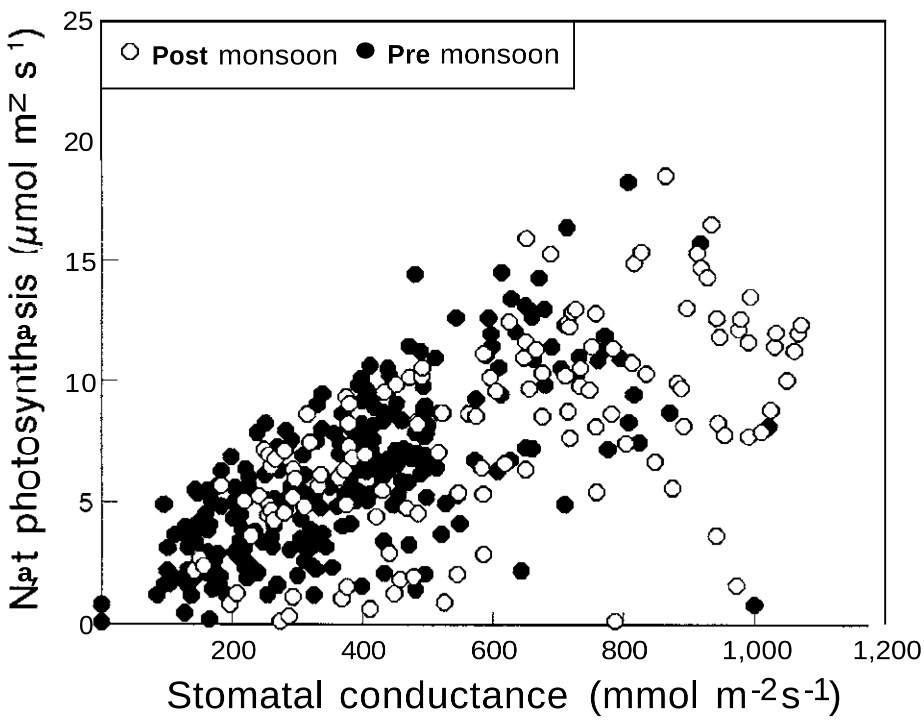


Fig. 23. The relationship between net photosynthesis and stomatal conductance in *E. deglupta* and *E. tereticornis*. Unlike in other four species there is not much difference in the pre- and postmonsoon values in relation to stomatal conductance.

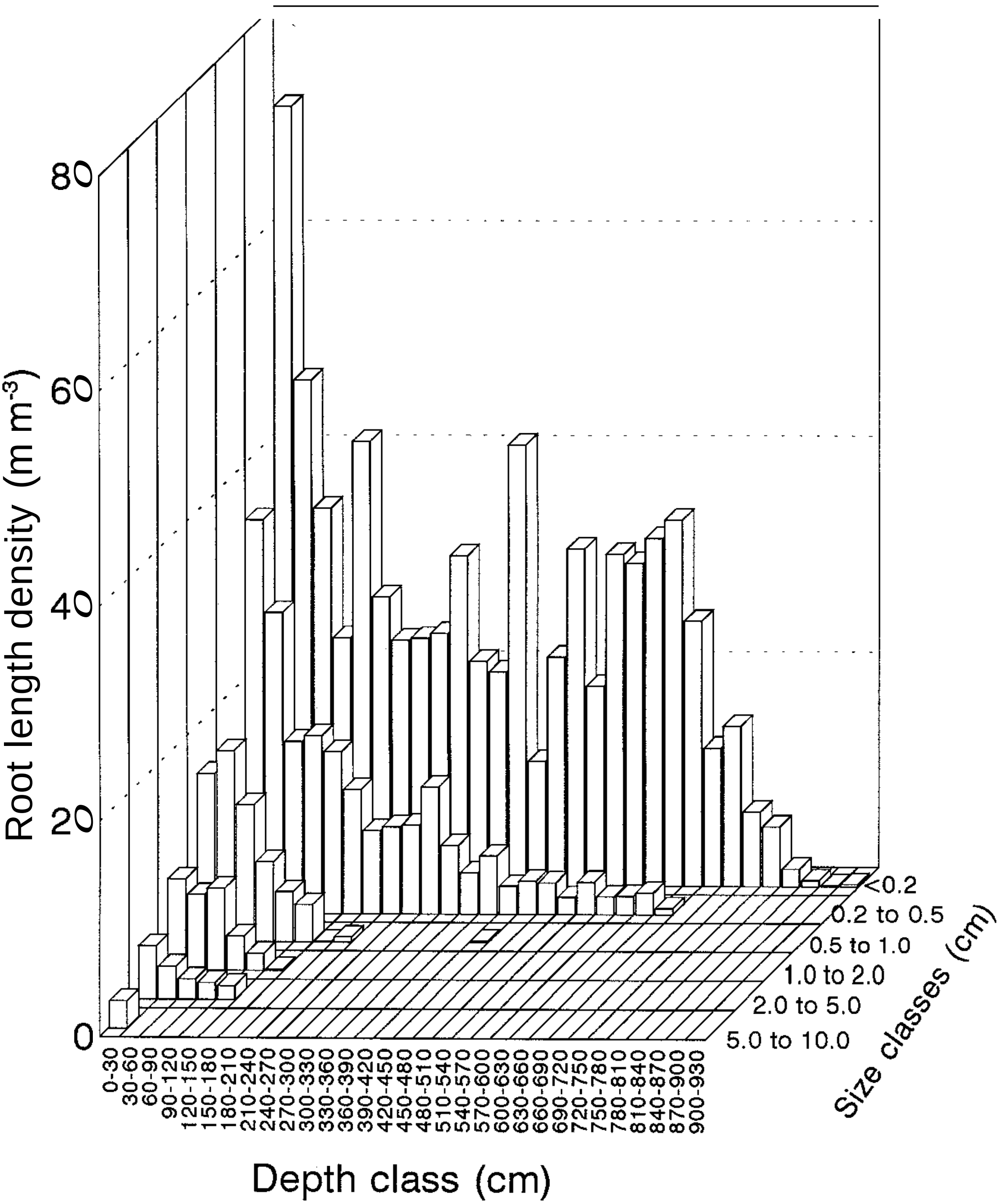


Fig. 24. Root length density in *E. tereticornis*. The length of roots according to various size classes is depicted against their depth in the soil. This data is obtained from measurements in the pit where the root stump was in the centre of the pit.

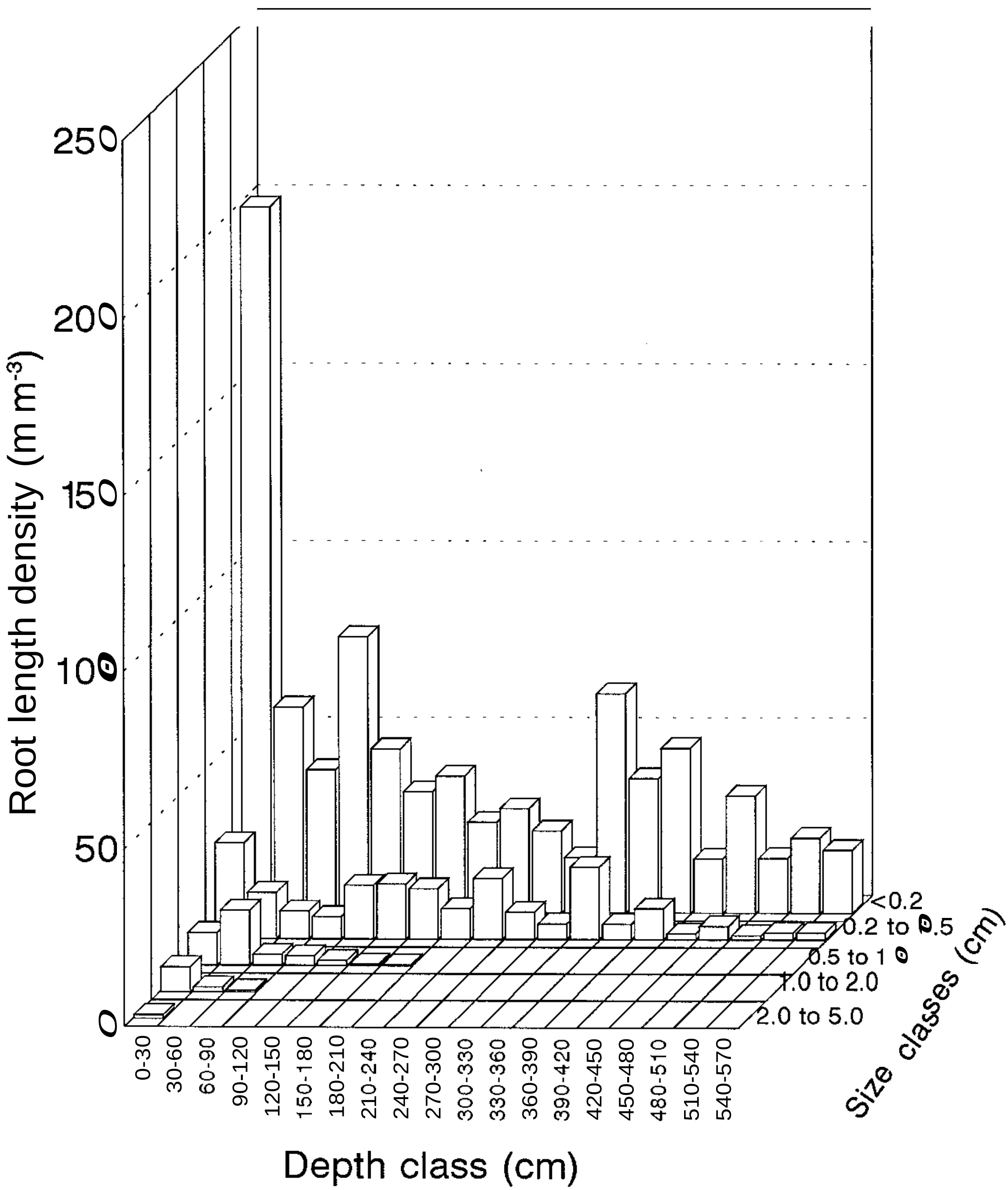


Fig. 25. Root length density in *E. tereticornis*. This data is obtained from measurements in the pit which was in between the trees.

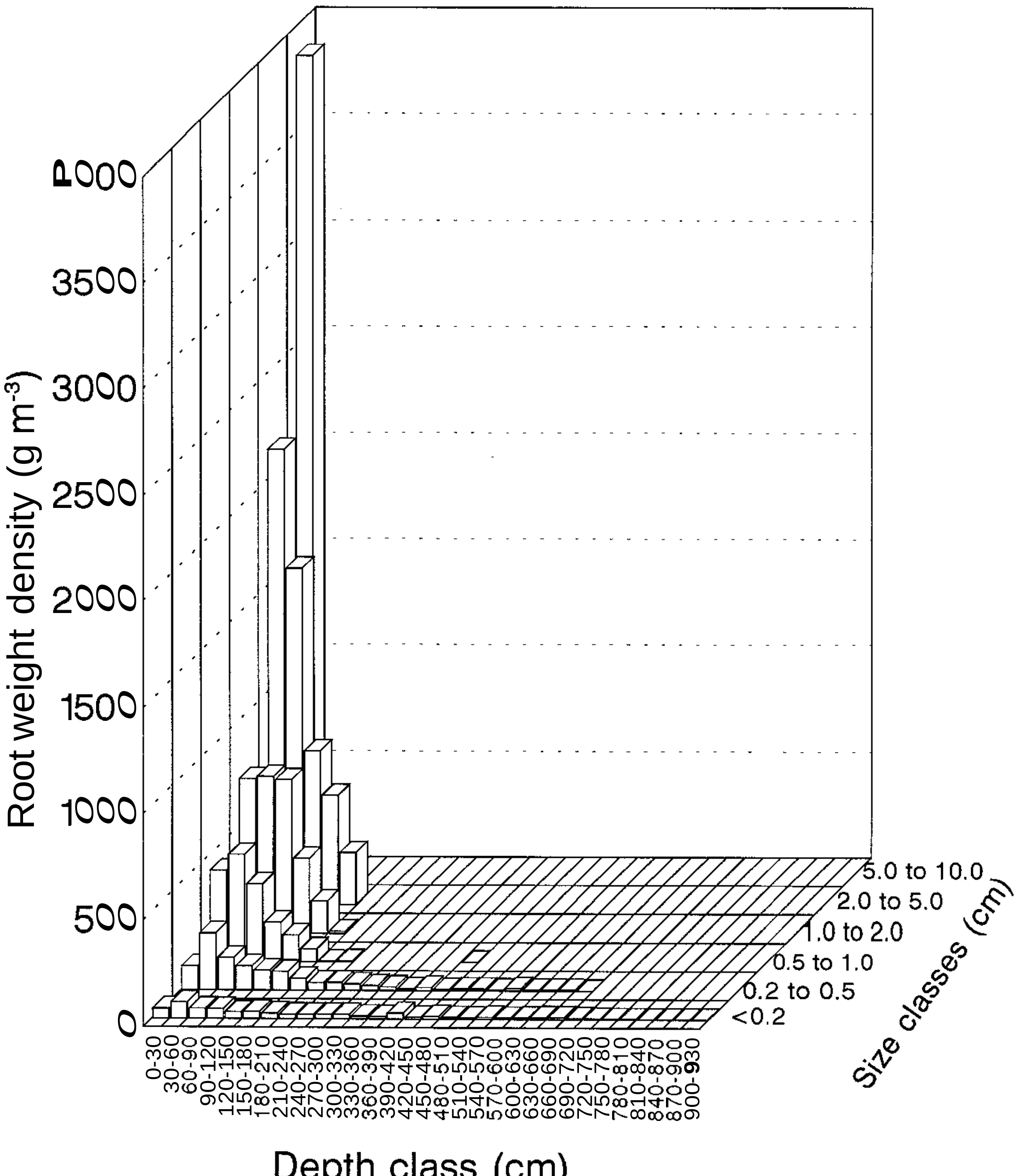


Fig. 26. Root weight density in *E. tereticornis*. The weight of roots according to various size classes is depicted against their depth in the soil. This data is obtained from measurements in the pit where the root stump was in the centre of the pit.

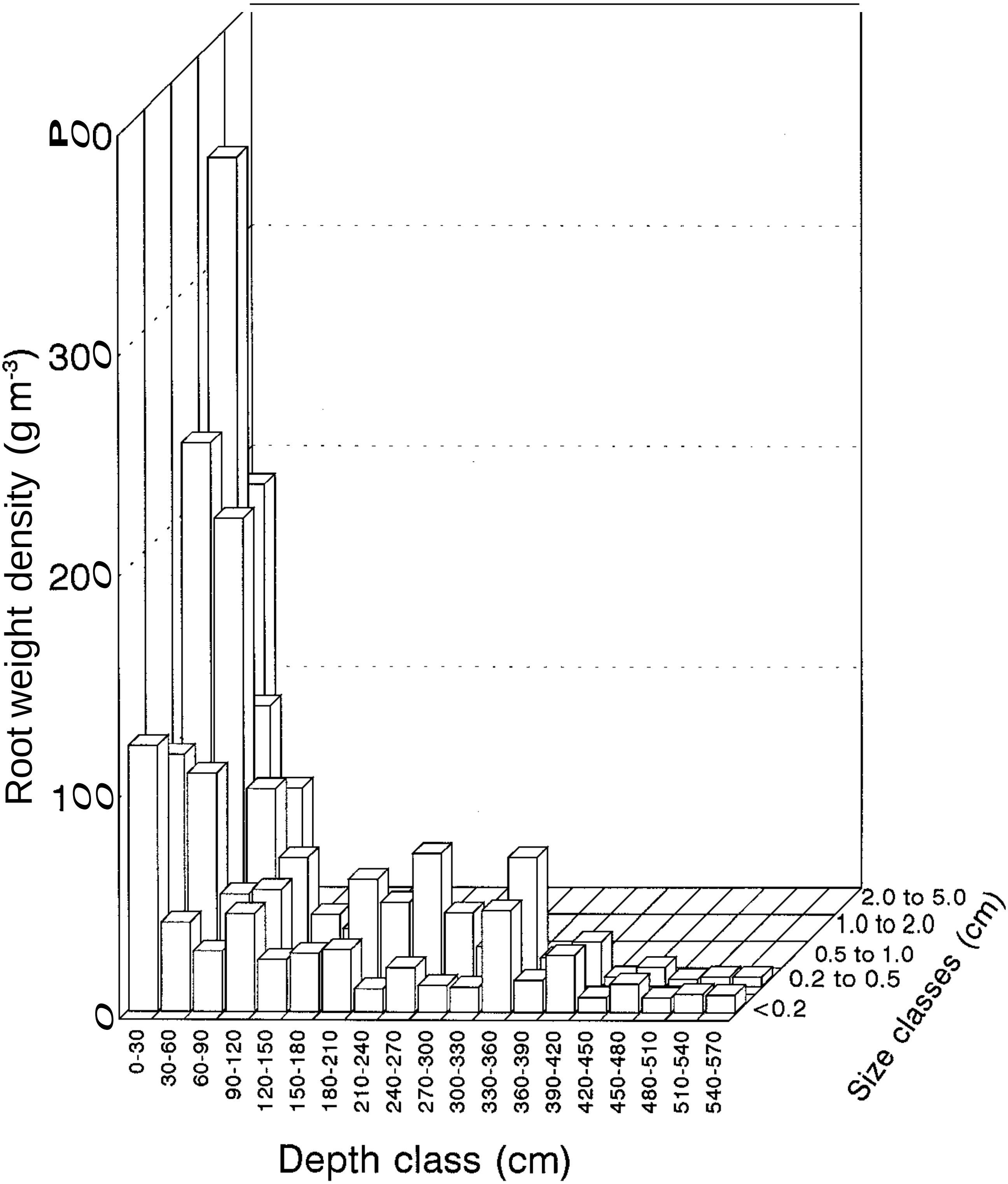


Fig. 27. Root weight density in *E. tereticornis*. This data is obtained a[3] measurements in the pit which was in between the trees.