KFRI Research Report No. 332

Water use by *Eucalyptus grandis* plantations in comparison with grasslands located in the downhill areas of Mannavan Shola in the Western Ghats of Kerala

(Project sponsored by Kerala Forest Development Fund)

(2004-2008)

Jose Kallarackal

Kerala Forest Research Institute
(An Institution of the Kerala State Council for Science, Technology and Environment)
Peechi 680653, Thrissur, Kerala, India

January 2010

CONTENTS

ACKNOWLEDGEMENTS

The Kerala Forest Development Fund administered by the Kerala Forest Department sponsored this project. I thank the PCCF and the CCF (Research) for the cooperation they have extended to me throughout this project work. I thank Dr J.K. Sharma, Dr R. Gnanaharan and Dr K.V. Sankaran, Directors of KFRI, who gave me the support and encouragement to complete this project. Thanks are due to the Superior, Sacred Heart Monastery, Kanthalloor for allowing me to set up an experimental plot in their eucalypt plantation at Kanthalloor, providing the facilities to install an automated weather station in their monastery and also providing the necessary history of the eucalypt growing area in the locality. I am thankful to Shajeesh Jan, Deepak Jolly George and V.J. Aneesh for providing me help with the fieldwork. I am grateful to Dr Ross Edwards, Edwards Industries, Otaki, New Zealand for giving the necessary technical advice on the use of the heat pulse sensors, especially when some bottlenecks arose during the experimental stage. He also provided a good discussion on the way to approach the problem. I thank Dr S. Sankar, Dr Thomas P. Thomas, and Dr K.V. Bhat for giving editorial comments on this report.

Project Proposal (in brief)

Project title:

Water use by *Eucalyptus grandis* plantations in comparison with rice fields and grasslands located in the downhill areas of Mannavan Shola in the Western Ghats of Kerala.

Background information:

During a recent visit to the drought-affected areas of Kerala, the Hon'ble Chief Minister was told by the residents of Kanthalloor and Pius Nagar in the Marayoor Forest Range belonging to the Munnar Forest Division, that the main cause for water shortage in their locality was the conversion of large areas of land for the cultivation of *E. grandis* trees. These locations were previously grasslands or cultivated with rice or vegetables.

The Kerala Forest Research Institute was asked to look into this location and submit a report on the scientific truth in the above allegation. A preliminary study conducted at the above sites, when evaluated against some of the previous studies made on *E. grandis* at other sites in Kerala reported that the allegations raised by the residents of Kanthalloor and Pius Nagar should be taken seriously and a detailed study should be conducted.

Objectives:

1. To ascertain if the water consumption by *Eucalyptus grandis* trees planted in the downhill areas of Mannavan shola is excessive in comparison with other traditional crops or grasslands.

Investigator: Dr. Jose Kallarackal, Programme Coordinator, Sustainable Forest Management Division, Kerala Forest Research Institute, Peechi.

Period of study: Three years

Methodology

The water use by transpiration in eucalypts in the area will be measured based on the heat-pulse velocity method using the sap flow gauge.

The water use by rice and grasslands round the year will be measured using the lysimeter method.

Expected outputs:

The study when completed is expected to give the following outputs:

1. Water loss of eucalypts by transpiration, canopy interception and ground evaporation – thereby the total evapotranspiration on a seasonal basis.
2. Water loss by rice crop during the seasons when they are in cultivation and at other times from the bare ground if not utilized for other purposes.
3. Water loss from the grassland, which is a major component in the natural vegetation of the area.

Research Assistant: Mr. V.J. Aneesh

Abstract

Eucalypts have been alleged to be consuming excessive amount of water, sometimes their roots even reaching the ground water table in several parts of the world. However, there are several reports mentioning the merits of this tree species in afforestation work. In 2004, based on a complaint from the residents of Marayoor and Pius Nagar in Idukki District of Kerala, the Chief Minister of Kerala ordered a thorough study on the problem of eucalypt plantations raised in the uphill areas of Marayoor causing drought situations in the downhill areas.

Relatively large areas in Kanthalloor, which form the uphill areas of Marayoor have been converted into plantations of *Eucalyptus grandis.* A eucalypt plantation and a grassland in this area were chosen for experimental work. This involved the measurement of transpiration in the eucalypt trees using sap flow method. Besides, other ecophysiological parameters such as leaf area index and leaf water potential were measured in the plantation. Along with the water use measurements in eucalypts, the evapotranspiration from an adjacent grassland was also measured for comparative purposes. Evapotranspiration from rice fields originally envisaged in this project could not be measured, as rice cultivation was not available in the uphill locations. Simultaneous with the above measurements, hourly weather data from the above location was monitored using an automated weather station. The stream flow of the river was also monitored at six strategic locations during different seasons to see the changes in the flow of the river as it passed through the different land use systems in this large catchment.

The results from the study showed that eucalypts show transpiration values very similar (1.32) to studies made elsewhere in the world, during the post monsoon season when the soil is saturated with water. However, during the dry period (pre monsoon), the transpiration values were much higher than the usually reported values (7.70 mm). The roots of the tree were found to reach more than 10 meters deep in the soil, indicating extraction of water from deep layers. The evapotranspiration from the grassland was much less than eucalypt plantation. When the stream flow was analysed, it was found that the stream flowing through the area had its main source in an underground spring, starting at much higher elevation. The stream flow was not considerably reduced as it passed down the eucalypt plantations in question.

The above results lead us to a conclusion that the drought-like situation in Marayoor is not due to the presence of eucalypt plantation because the water flow in the river does not seem to be seriously affected by the eucalypt transpiration. In spite of this, we recommend that the eucalypt plantation should not be expanded to the existing grasslands, as

grasslands are very good water conservation areas, especially in a geographical area where the rainfall is very seasonal.

Introduction

To understand the links between trees and water resources, a basic knowledge of hydrology and plant physiology, and a good understanding of various environmental processes including climatic data of the location are required. The large number of hydrological studies around the world suggest that the contribution of plantations to water regimes varies from different regions of the world and from one site to another. Specific studies on eucalypts have shown that topography, soil type, local climate and species involved and a variety of other factors will exert their own particular influence (Poore and Fries 1985).

Eucalypts have been alleged to be consuming excessive amount of water, sometimes even by reaching the ground water table in several parts of the world. Although this has been shown to be true in a few places, the excessive water consumption by all species of eucalypts cannot be generalized. Poore and Fries (1985) in their report published by FAO, after making a thorough study of this problem around the world, have recommended investigative studies in problem locations, and management decisions to be taken according to the requirement of the area.

During a recent visit to the drought-affected areas of Kerala, the Hon'ble Chief Minister was told by the residents of Marayoor and Pius Nagar, in the Marayoor Forest Range belonging to the Munnar Forest Division, that the main cause for water shortage in their locality was conversion of large areas of land for the cultivation of *Eucalyptus grandis* trees. These locations were previously grasslands or cultivated with rice or vegetables.

The Kerala Forest Research Institute was asked to look into this issue and submit a report on the scientific truth in the above allegation. A preliminary study conducted at the above sites, when evaluated against some of the previous studies made on *E. grandis* at other sites in Kerala reported that the allegations raised by the residents of Kanthalloor and Pius Nagar should be taken seriously because of the following reasons:

1. The locations in question are situated downhill of Mannavan shola, the largest and the least disturbed shola forest in Kerala, which probably sustains a very good stream flow round the year and acts as a watershed feeding the Pambar river and its basins.
2. There are evidences from elsewhere in the world, where, if eucalypts are provided with a rich source of water, they can consume excessive water and dry the soil.
3. Eucalypt roots were found to reach more than 10 m deep in the above location indicating water absorption by the trees from deeper layers of the soil.

Although the preliminary findings indicate excessive consumption of water by eucalypts, direct measurements on the water use by eucalypts in the above locations are required before the Government can take alternative management decisions. This research study proposal is intended to make direct measurements of the water consumption by eucalypts in comparison to the grassland in the Kanthalloor area. Besides the study also envisages gauging the stream that flows through this area to know the variations in stream flow.

STUDY LOCATIONS AND THE METHODOLOGY

Site details

Kanthalloor, a very small town (10º 12.903'N, 77º 11.915'E), nearly 19 km from Marayoor town is at an elevation of 1520 m above m.s.l. There is a road leading from here to Mannavan Shola, the largest shola forest of Kerala, through a small settlement called Perumala. The elevation of Perumala is approximately 1700 m above m.s.l. Uphill from Perumala is the Mannavan Shola which goes to much higher elevations. The area gets a rainfall in the range of 2000-3000 mm annually and enjoys a very cool weather round the year.

The eucalypt plantations are located in and around Perumala and Kanthalloor. On enquiry with the local Village Officer, it was noted that 60 per cent of Kanthalloor village is covered by *E. grandis* plantations and they are invariably private. Almost all of these plantations have been raised in the 1990s and the owners of these plantations are non-residents, mostly from other towns and cities in Kerala. The wood from the eucalypts is harvested every six or seven years and sold as pulpwood to Hindustan Newsprint Ltd. (HNL), a public sector undertaking having a pulp processing factory near Kottayam. There is also a relatively large (approximately 600 ha) plantation of *E. grandis* above the shola area, planted by HNL. The local people also expressed the fear that some part of the Mannavan Shola, already planted with *Acacia mearnsii* by the Kerala Forest Department, is going to be given to HNL for planting *E. grandis*.

Most of the local residents are small farmers cultivating rice and vegetable crops for the last few years. They complained that, with the arrival of eucalypts, the area under cultivation of these crops is getting reduced because of water scarcity. Hence it is affecting the income of the local people.

It is interesting to note that this location is suitable for cultivation of many high value temperate vegetables such as cabbage, cauliflower, carrot, potato, turnips etc., and also some temperate orchard trees such as apple, pear, plum and cherries. Although some of the progressive farmers have taken up their cultivation relatively on a small scale, the area under these high value crops is very limited.

Weather data

The weather data of the locality was measured on an hourly basis using an automated weather station (Skye Instruments, UK) located very near to the experimental plot. The parameters measured

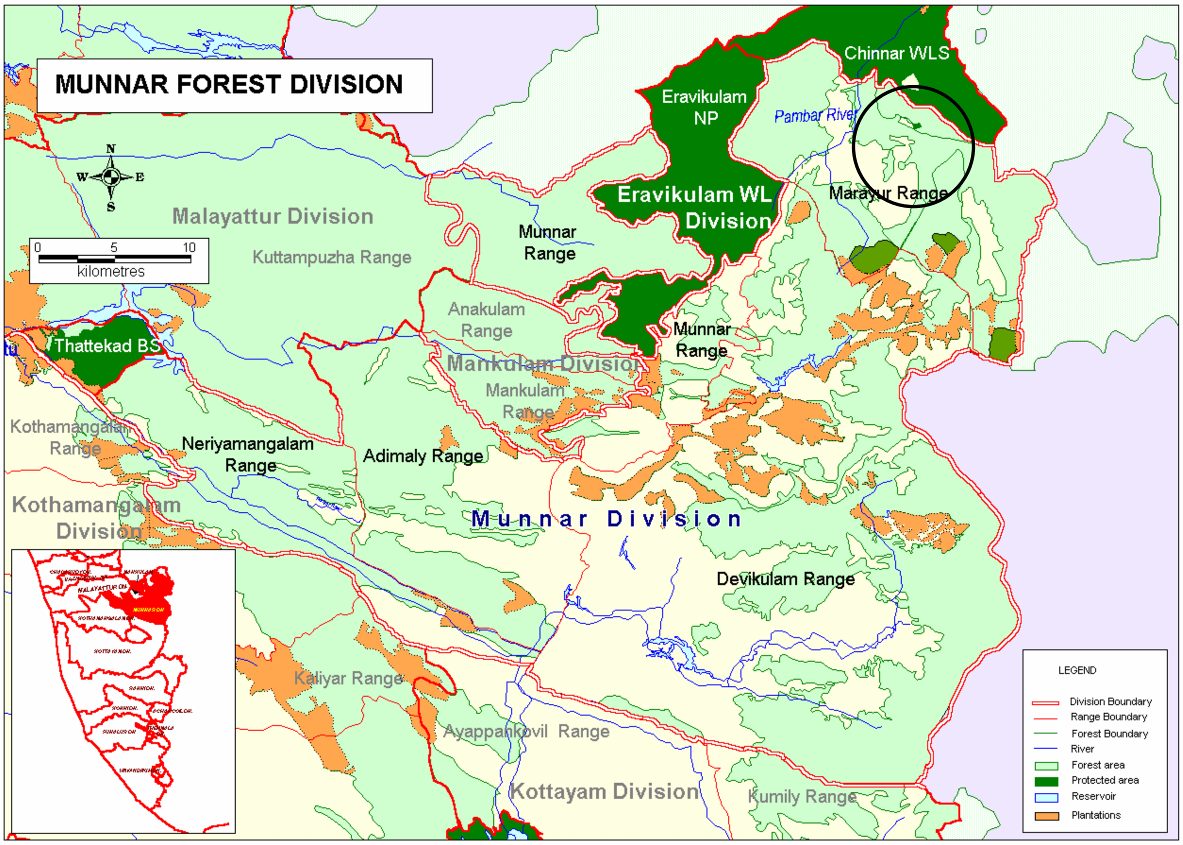


Fig. 1. Map of Munnar Forest Division showing the study area encircled.

included atmospheric temperature, relative humidity, rainfall, solar radiation, and wind velocity and direction.

Physical and physiological parameters of the trees

A eucalypt plantation in Kanthalloor owned by the Sacred Heart Monastery, which also runs a Higher Secondary School in Kanthalloor was chosen for the experimental studies. The following physical and physiological parameters of the eucalypt trees were measured in the plantation.

1. The DBH of the trees.
2. The leaf area index (LAI) of the plantation.
3. Summer season leaf water potentials at predawn.

4. Sap flow through sample tree trunks during two seasons of the year.

The DBH of the trees in the experimental plot was measured by dividing the plot into 5 blocks each with 100x50 m dimension. In each block the girth at breast height (gbh) was measured using a measuring tape. These measurements were later converted to diameter at breast height (DBH) using appropriate formula.

The LAI of the plantation was determined using the Canopy Analyser (LA-2000, Li-Cor, Nebraska, USA), which uses the principle of light interception method. The instrument had been previously calibrated by destructive sampling method.

Predawn leaf water potentials (Ψ) were determined using a Scholander type pressure chamber (Soil Moisture Equipment Corporation, Ohio, USA). The leaves were first enclosed in plastic bags for a few minutes in the early morning, later severed from the plant and immediately subjected to pressure chamber measurements. The balancing pressure for the water drop to appear on the cut end of the petiole was noted, and this was taken as the leaf water potential for all practical purposes.

The sap flow through the tree trunk was measured to quantify the transpiration of individual eucalypt trees belonging to different DBH classes. Four trees were subjected to detailed measurements during two seasons. The same four trees were used for measurements during the two seasons. The details of the measurements are described below:

Sapflow method for measuring the water use by individual trees

In this project, the sapflow method, widely used nowadays in studies on water use by trees, has been employed for measurement of the water use by the eucalypt trees in Kanthalloor. Since the method is not familiar to many general readers, a brief account of the history and theory of this method is given below.

Principle and method of sapflow measurement

At appropriate time-scales (≥1 day) changes in tree water storage are low and water flux through the sapwood (water conducting tissue or xylem) equals tree canopy transpiration (cf. Schulze et al., 1985). Depending on the water conducting system of species and on forest structure, various approaches can be used to scale from individual measurements in trees to the stand. In most cases tree sapwood area, which is closest related to water transport in the tree, is used as a structural scaling factor.

From sapflow density (flow rate per sapwood area) of individual sensors and the related sapwood area *(A_s)*, canopy transpiration *(E_c)* is determined as follows:

E_c=J_{mean}*A_s^{-stand},
(0)
Where J_{mean} = mean sapflow density of sample trees (kg m^{-2} s^{-1}) and A_s^{-stand} = cumulative sapwood area per ground area (m^2 m^{-2}).

In homogenous stands, the coefficient of variation (CV) for estimates of J_{rnean} is usually less than 15% using approximately 10 sample trees (Köstner *et al.*, 1996b) but variation may increase in older less homogenous stands requiring a larger number of sample trees (Köstner et al., 1998a). Estimates of A_s^{-stand} can be derived with relatively high accuracy from regression curves between stem diameter at breast height (dbh) and sapwood area of a subsample of trees applied to all trees within the patch (cf. A1sheimer et al., 1998). In forest stands composed of different canopy layers or tree species, *Ec* is summed up from several equations of type (2) representing different subsamples E_{ci} *(i* = layers, species, etc.) of the patch. Scaled sapflow rates provide an independent estimate of tree canopy transpiration as compared to total water vapor flux above the forest (Granier et al., 1996a, Kostner et al., 1998b).

The total water vapor transfer conductance *(g_t)* accounting for conductances from height of the "average" stomata in the tree canopy to the height of measurement of vapor pressure deficit of the air *(D;* Thorn, 1972) can be estimated from *Ec* (Kostner et al., 1992):

$$g_t=E_c/D*P_w*G_v*T_K \quad (3)$$

where, *Ec* = canopy transpiration (mm s^{-1}); D = vapor pressure deficit of the air (kPa), *Pw* = density of water (998 kg m-3), *Gv* = gas constant of water vapor (0.462 m3 kPa kg-I K-I), T_K = air temperature (Kelvin).

The total conductance includes components of both stomatal *(g_c)* and aerodynamic conductance (leaf boundary layer and eddy diffusive conductance, *g_a).* Typically, g_a is more than an order of magnitude higher than g_c in rough forests, where g_t approximates g_c ($1/g_t = 1/g_c + 1/g_a$). Estimates of g_c derived from sapflow rates range within leaf-level estimates determined by porometer (Kostner et al., 1992) and are comparable to model-based estimates of g_c derived from canopy gas exchange (Kostner et al., 1998a).

Since all the water transpired by a tree must pass through the stem (tree trunk), this is a convenient site for measurement. There is no disruption to either the root or crown, and relatively minor perturbation to the stem.

Heat is a convenient marker, being non-destructive at the levels used, completely removed by the transpiration stream, has none of the environmental disadvantages of radio-isotopes, and is easily monitored.

Superficially a simple technique, quantification of heat pulse velocity to sap velocity, and in turn to total flow rates has required a fuller understanding of the physics involved in flow, and this has developed slowly in the literature.

As early as 1932, the German physiologist B. Huber used a heat pulse from a resistance wire, sensed by a single thermocouple downstream in the stem of a transpiring plant (Huber, 1932). Uncertainty in interpretation of the resulting rise and fall in temperature at the thermocouple led to development of the so-called `compensation method' (Huber and Schmidt, 1937), using thermocouples above and below the heat source. If the downstream distance to the thermocouple was larger than the upstream distance, this effectively separated the movement of the heat pulse into its component mechanisms of conduction and mass movement or convection.

Conduction caused the closer, upstream thermocouple to warm first. As the heat pulse was carried up the tree, however, a position midway between the thermocouples was obtained and then passed; at that point the temperature of the thermocouples was the same. Thus if the thermocouples were joined in series with a measurement device, the output became first of one sign, then passed through the balance point to the other sign. The time taken from initiating the pulse till the signal returned through the balance point, together with the distance travelled by the pulse from the point of initiation to the point midway between the sensors, gave the heat pulse velocity.

Difficulties in interpretation remained, since the apparent heat velocity was clearly less than the actual sap velocity in the vessels.

Marshall (1958) provided a better physical basis, by pointing out that the heat pulse moved as if the sap and woody matrix were a single medium, heat interchanging freely between sap and wood. An analogous situation exists with chromatography - the dye front moves more slowly than the solvent. Heat pulse velocity was shown to be a function not only of sap velocity, but also the ratios of

(i) lumen conducting area to total sapwood area
(ii) density of sap to that of wet wood
(iii) specific heat of sap to that of wet wood.

Subsequent work showed that sap velocity derived using Marshall's theory was still less than actual sap velocity, and most workers simply relied on direct calibration.

Swanson (1983) finally identified the probe implantation wound as a primary source of error. The wound caused a violation of Marshall's assumption of homogeneity within the stem, effectively adding more 'inert' or non-moving material to slow the heat pulse. Swanson and Whitfield (1981) conducted an elegant two-dimensions numerical solution to the problem, and provide tables for wound corrections based on particular probe spacing and construction.

Application of the method in eucalypts at Kanthalloor

In an experimental plot, four eucalypt trees with different DBH were chosen for the sap flow measurements. The sap flow system used in the present study (Heat Pulser, Edwards Industries, New Zealand) is based on all three of the major advances in this field: i.e., the compensation system of Huber to produce heat pulse velocities, Marshall's analysis to convert to sap velocities, and Swanson's analysis of the effect of wounding. Verification of this system has involved direct comparisons with excised stem sections using forced flow, the cut-off tree technique of J Roberts (1977), weighing lysimetry in both single tree and forest situations, and comparisons with micrometeorological estimates of transpiration using the Penman-Monteith equation.

Heat pulse velocities are measured using the compensation technique of Huber and Schmidt (1937) and Swanson (1974). Two thermistors, accurately placed 10 mm above and 5 mm below a 2 mm diameter tube heater are connected in a Wheatstone bridge configuration. To make a measurement, a short (typically 0.5 to 1 s) electrical pulse is applied to the heater. The heat pulse so produced is conducted onwards from the tube heater in all directions, reaching the lower (closer) thermistor first and throwing the bridge out of balance. As the sap flow carries the heat pulse upwards however, the bridge returns through the balance point at a time when the heat pulse is midway between the thermistors.

The heat pulse velocity is calculated from the time taken for the pulse to travel the distance of 2.5 mm, i.e., the distance between the heater and a point midway between the thermistors.

Implantation of the probes

Four trees of different girth classes standing within an area of 100 m^2 were selected at a time for measurement of the sap flow velocity. The stem should be regular and not flawed because of damage, also avoiding trees with prominent fluting. The rough outer bark was smoothened with a rasp so that a good over-bark measurement of circumference could be made. If the bark was very thick - say more than 5 mm - then consideration was given to reducing this thickness at the sites of implantation. This is because accurate assessment of probe/heater separations are essential, and implantation through massive bark layers make this difficult to attain. A ring of masking tape was applied around the smoothened portion of the bark for conveniently marking the implantation sites. First mark was made due north. Carefully measured the circumference, recording it on the form - decided the number of probes to be used, typically this will approximate one per 100 -150 mm of circumference, however, we invariably used four probe sets per tree. Each probe site was numbered consecutively. The depth of the probe was decided based on the depth of the sapwood, which was ascertained by core sampling. The shallowest was about 5 mm below the cambium. The deepest probe was up to 36 mm. Most trees sampled had sapwood depth not more than the above value. Intermediate depths were chosen based on the depth of the sapwood. The details of implantation and probe depth

Table 1. Implantation and heat pulse probe spacing record.

	Probe depth in wood (mm)				Probe spacing (mm)			
Channel #	Tree 1	Tree 2	Tree 3	Tree 4	Tree 1	Tree 2	Tree 3	Tree 4
Nov-Dec								
1,5,9,13	9	9	9	9	5.2	5.0	5.1	4.9
2,6,10,14	12	12	12	12	5.1	5.1	5.0	5.3
3,7,11,15	22	22	22	22	5.0	5.7	4.3	5.0
4,8,12,16	32	32	32	32	4.9	5.1	5.2	5.4
Feb-Mar								
1,5,9,13	16	16	16	16	5.25	4.85	4.65	4.35
2,6,10,14	21	21	21	21	4.75	4.90	4.90	5.30
3,7,11,15	26	26	26	26	4.65	5.55	5.05	4.35
4,8,12,16	36	36	36	36	4.85	5.60	5.20	4.90

and spacing are given in Table 1.

A jig was strapped firmly to the tree at the first site, ensuring it is oriented tangentially to the tree so that the drills will enter radially. Using a 1.80 mm long-series drill and portable electric drill three holes were drilled to a depth approximately 15 mm below the nominal probe depth. Thus the total drill depth below the surface of the jig will include the jig thickness (20mm) plus bark thickness plus nominal probe depth plus 15 mm. The drill bit was cleaned frequently to ensure that the drill could move freely in and out of the hole and no debris was allowed to get trapped in the hole. Three sets of holes were made for each probe set. The distance between the holes in a set was measured accurately using three stainless steel tubes of the same diameter as the hole. They were inserted gently into the set of holes. A card was gently placed against the tubes starting closest to the tree and rolling the card slightly so the tape makes contact without changing the orientation of the blank probes. Using a scalpel and fresh blade as a marker, both sides of each blank probe was traced so that the blade point is held gently against the probe. Six very thin lines will be formed, easily distinguished under the scaled magnifier using back-lighting. The scaled magnifier was used to make measurements between the three holes using a standard procedure.

The heater elements were now implanted. The heater and the sensors were greased for easy insertion into the hole. In extreme cases of difficulty in insertion, the hole was broached using a 1.85 drill. The temperature probes were temporarily marked to the required depth below the cambium plus the bark thickness. All leads were finally strapped to the trunk to avoid strain on the probes. The probes were now connected to its corresponding channel on the logger. Protection from direct solar radiation was given by wrapping the tree trunk gently with aluminium foil to form a large bulge, constrained top and bottom with tape. The entire set up was left in the field for 2-3 weeks depending on the field conditions. At the end of the specified period, the data from the data logger was downloaded in the field using a laptop computer and the raw data was subjected to analysis using the standard software provided by the manufacturer (see Plate I and II for photographs of the set up).

Evapotranspiration measurements in the grassland

Evapotranspiration from an adjacent grassland, located in the same slope as the eucalypt plantation mentioned above was measured using a small weighing lysimeter of the type described by Kelliher et al. (1990) (see Plate II for the set up). Several such lysimeters were fixed in the grassland and the weight was determined at 2 hour intervals for 3 days each during the post monsoon and premonsoon period. The evapotranspiration was calculated from the lysimeter weight differences recorded.

Stream flow gauging

Stream flow measurements were made at six points in Chengalar from near its origin down to locations where it joins the Chinnar river at Marayoor. Specific locations were gauged so that it is possible to know the reduction in flow of the river as it passes through the entire catchment. The velocity of flow was determined using a small float dropped at the surface of the stream. The cross sectional area of the stream at that point was determined from depth and width measurements.

Results

Hydrology of the location:

Mannavan Shola, located above Kanthalloor is probably one of the best-protected forests in Kerala, retaining its virginity and ecosystem functioning. It is possible to notice very good stream flow within this shola even during the dry season. Naturally, it is forming the watershed for nourishing the villages around that locality and also the Pambar river. The Mannavan Shola drains into Chengalar, which is the main stream flowing through the eucalypt plantations located in and around Kanthalloor (Fig. 2). This stream further flows down to join at Dindikombu another major stream named Tirthalar, which drains from the Tirthamala Reserve Forest. During the course of the Chengalar, water is diverted for domestic use and irrigation purposes at several locations

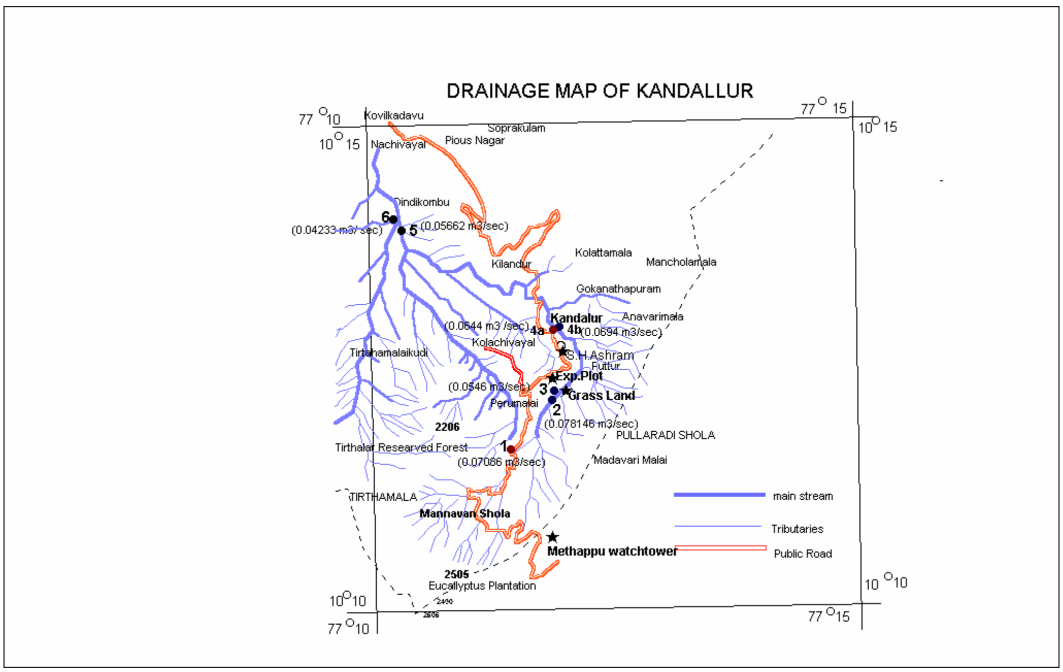


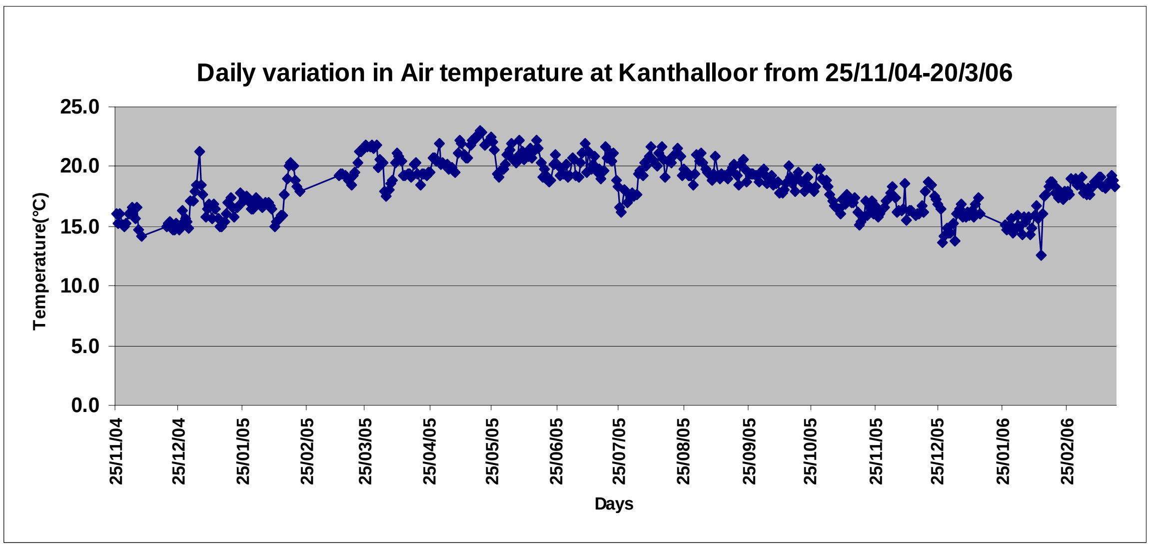
Fig. 2. Drainage map of Kanthalloor and surrounding areas.

using water hoses and irrigation canals. At Dindikombu, both these streams join together and flow down to join the Pambar river at Kovilkadavu near Marayoor.

Both in Kanthalloor and Perumala, one fails to notice any open well or bore well. People are depending on the stream flow in Chengalar from the shola above, which is led through canals and plastic hoses to their residences and premises. The locals explain that wells are not giving ‘good water’ and they were not interested in digging wells even during the harsh drought of 2004.

Weather data

The weather data of Kanthalloor from November 2004 to March 2006, as measured continuously using an automated weather station located very close to the eucalypt plantations is given in graphic form (Figs. 3-4). The daily temperature shows that the variation was between 12°C and 23°C during the project period. The relative humidity was relatively high with the RH remaining above 60 per cent throughout the year. Very rarely the RH reached 40 per cent level (Fig. 3). The solar radiation measured using the pyranometer showed that the maximum solar radiation remained at around 20 MJ m^{-2} d^{-1} (Fig. 4). The wind velocity at this location was relatively high, with the velocity reaching 6 km h^{-1}. The locality received both the monsoons. However, the rainfall received during the north-east



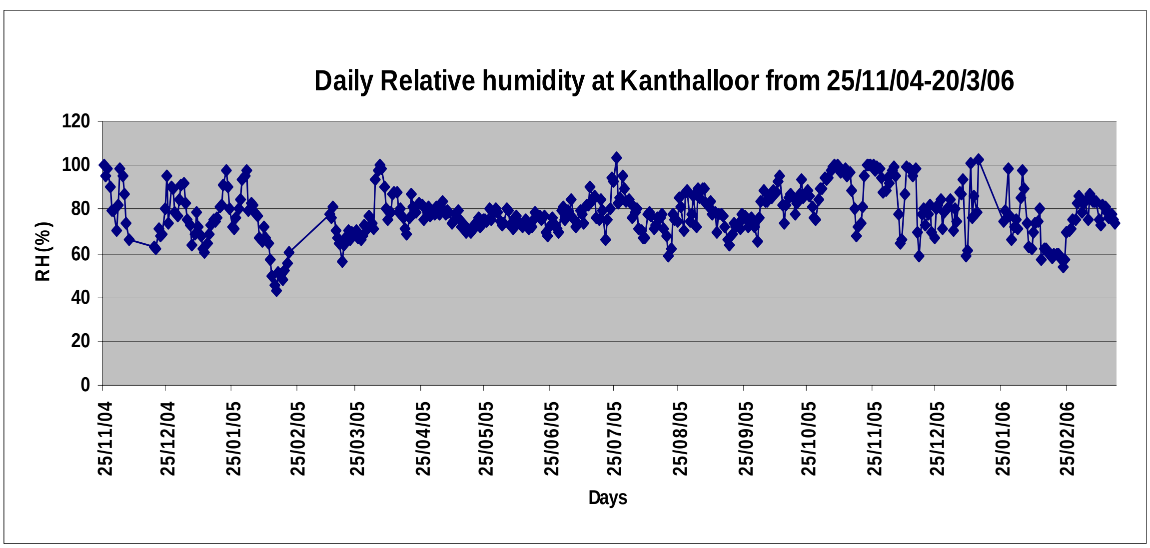


Fig. 3.Daily variations in temperature and relative humidity at Kanthalloor recorded using an automated weather station located very near the experimental plot.

monsoon was much higher compared to the south-west monsoon unlike most other locations in Kerala. The annual rainfall was only 1430 mm during the 2004-05-measurement period. Sometimes, the rainfall was very heavy reaching more than 150 mm during a day.

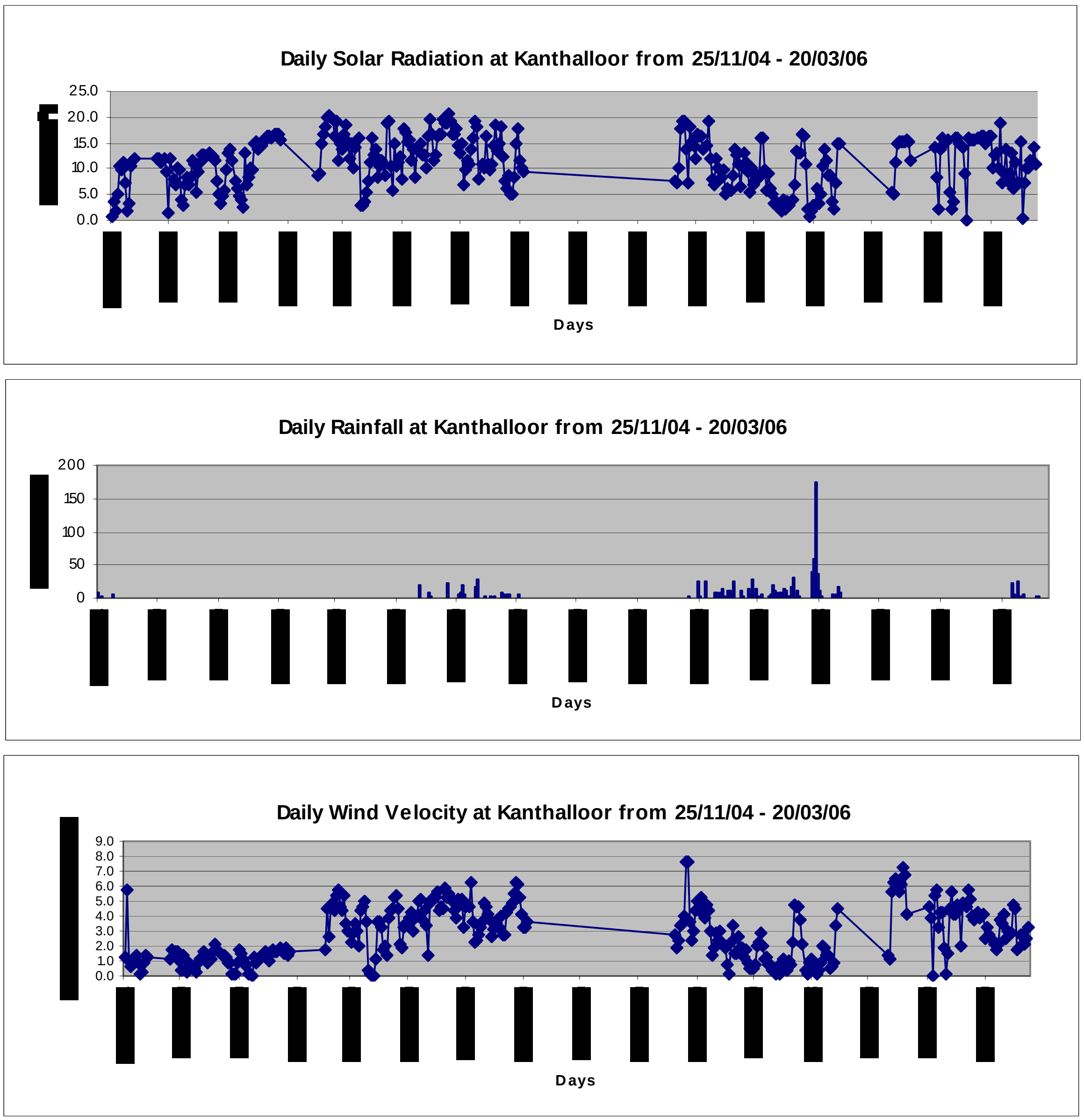


Fig. 4. Daily measurements of solar radiation, rainfall and wind velocity recorded using an automated weather station located near the eucalypt experimental plot at Kathalloor.

The experimental eucalypt plantation and its silvicultural and ecophysiological details

For detailed measurements on the consumption of water by the eucalypt trees, an experimental plot was selected in a plantation located on the way from Kanthalloor to Perumala. This was a 20 ha eucalypt plantation (N 10^{o} 12.385'; E 77^{o} 11.840') belonging to the Sacred Heart Ashram, at Kanthalloor. An upstream part of the Chengalar was flowing near to this plantation.

Measurements of DBH were made after dividing the experimental plot into five blocks, each with 50 trees. The details of the measurement are shown in Table 2.

Table 2. D.B.H of *Eucalyptus grandis* in different blocks at Kanthalloor

BLOCK / Tree No.	NO. 1	NO.2	NO.3	NO.4	NO.5
	D.B.H in cm	D.B.H in cm	D.B.H in cm	D.B.H in cm	D.B.H in cm
1	12.7	35.4	28.1	23.2	22.6
2	9.3	6.5	9.1	13.6	10.7
3	12.3	15.4	26	26.8	15.5
4	11.0	15.5	8.3	11.0	17.5
5	8.4	9.0	28.7	16.7	22.3
6	19.3	29.4	10.1	14.4	6.0
7	11.1	10.7	11.8	12.2	21.2
8	9.5	13.7	7.7	14.1	17.5
9	9.4	22.4	13.3	26.1	5.1
10	12.2	13.2	10.0	34.1	7.7
11	12.2	22.0	15.6	27.7	8.5
12	16.7	12.6	22.9	33.2	13.3
13	10.4	10.0	12.9	14.7	15.2
14	7.5	9.0	15.3	8.1	13.7
15	14.4	28.3	43.5	7.0	12.2
16	12.2	13.1	11.0	10.5	7.5
17	13.2	13.7	18.2	13.7	7.7
18	9.9	20.2	8.2	8.7	17.8
19	9.8	8.1	20.1	8.5	9.1
20	15.7	42.4	11.7	8.3	6.3
21	13.3	18.2	10.3	7.4	11.1
22	12.8	13.4	19.5	9.5	9.8
23	14.4	9.1	7.3	4.6	7.2
24	13.9	21.5	32.7	8.0	9.0
25	10.3	11.1	26.7	6.0	8.5
26	19.7	17.6	5.1	10.2	13.7
27	15.3	16.4	16.1	8.4	11.5
28	26.5	11.2	7.0	14.6	4.5
29	10.0	10.2	6.2	8.0	7.0
30	17.5	14.5	8.1	10.7	8.2
31	13.0	8.5	15.2	14.5	8.0

32	10.9	12.2	28.7	11.7	12.3
33	10.4	19.5	11.3	21.4	19.5
34	10.1	18.2	13.1	11.5	11.8
35	22.6	37.3	19.3	14.2	9.0
36	9.1	13.3	11.0	19.1	13.0
37	10.1	7.1	7.1	7.5	6.0
38	16.1	16.4	5.1	8.6	7.2
39	13.2	8.5	9.5	12.6	19.4
40	21.3	10.5	15.6	20.1	14.8
41	19.0	8.5	9.2	12.2	6.4
42	17.0	8.0	31.1	15.5	10.2
43	9.1	17.7	6.0	11.7	13.5
44	10.3	16.1	31.2	27.1	10.5
45	12.0	8.4	13.1	18.0	12.6
46	14.3	8.1	11.7	16.1	11.6
47	13.5	17.6	22.2	28.8	9.5
48	16.6	14.2	12.5	14.0	11.4
49	9.3	14.8	12.5	11.7	7.2
50	17.1	6.5	26.6	38.0	8.1
Mean	**13.3**	**15.3**	**15.6**	**15.0**	**11.3**

Note:
Location Kanthalloor
Date of Observation - 25/11/04
Plot dimension- 100X50 m^2
Total no. of trees – 1315 trees/ha

The leaf area index (LAI) of the plantation as measured using the light interception method is given in Table 3.

Table 3. Leaf area index (LAI) of the experimental plantations during the two seasons. (± s.e. is indicated).

Month & Year	December 2004	March 2005
Leaf area index	1.40 ± 0.09	1.32 ± 0.04

The summer season predawn leaf water potential (*Ψ*) of the eucalypt trees in the plot measured using a pressure chamber is given in Table 4. It may be noticed that the values are relatively high (very near zero) indicating very little water stress for the trees during the summer period. It also indicates that the roots of the trees are probably in contact with a good source of water.

Table 4. Predawn water potentials measured in the eucalypt plantations at Kanthalloor during the two seasons.

Sample No.	November 2004	March 2005
	Ψ (MPa)	Ψ (MPa)
1	-0.02	-0.2
2	-0.01	-0.14
3	-0.05	-0.13
4	-0.04	-0.14
5	-0.07	-0.13
Mean	**- 0.038**	**- 0.15**

Sap flow in eucalypt trees:

Four trees for sap flow measurements were chosen based on the general DBH measurements done in the plantation. Trees with DBH in the range of 10 to 25 cm was chosen for implantation of the sap flow probes.

Sapwood characteristics

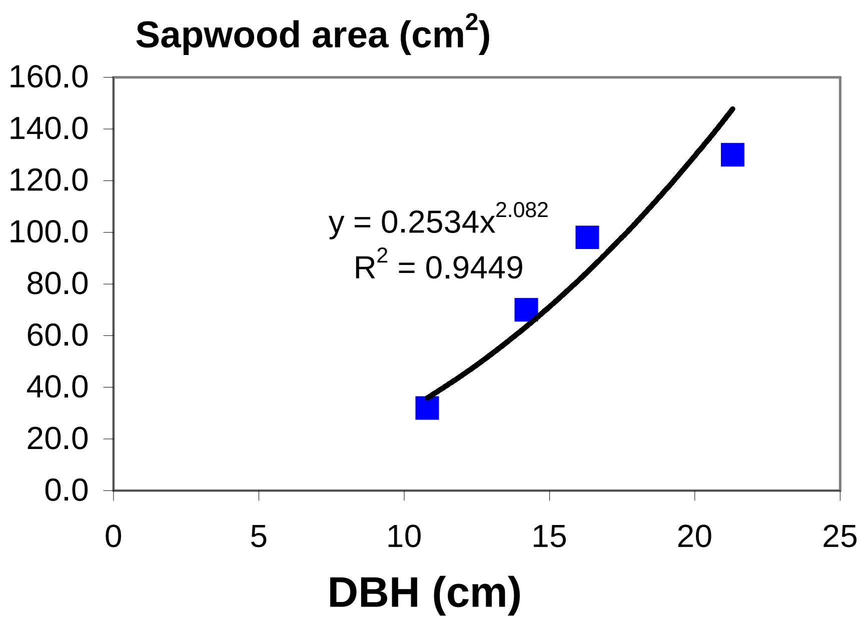


Fig. 5. Relation between sapwood area and DBH of *E. grandis* trees subjected to sap flow measurements at Kanthalloor for the trees subjected to sap flow measurements.

A linear relationship predicting stem sapwood area (A_s) from DBH was highly significant ($P < 0.001$) for *E. grandis* trees. Sapwood area was determined from increment core samples stained with 0.1% methyl orange to identify the sapwood-heartwood boundary. This was later confirmed using the sap flow sensor by noticing the flow rates at different depths. A_s and DBH for the measured trees and was plotted to find the regression between them. It was found that 94% of the variation in sapwood area was explained by DBH (Fig. 5).

The volume fractions of wood (V_w) and water (V_h) determined by gravimetric method gave a value of 0.38 and 0.54 respectively.

Sap velocity and sap flow density

The diurnal variations in sap flow in four eucalypt trees were followed during the post-monsoon (soil and atmosphere relatively wet) and the pre-monsoon (soil and atmosphere relatively dry) period during the years 2004 and 2005. The results obtained during post monsoon (November – December), when the soil was almost saturated with water and in pre monsoon (February – March) when maximum dryness of the soil was found are depicted in the Figs. 6-10.

Fig. 6 shows the velocity of sap flow measured simultaneously during the post monsoon period in four eucalypt trees showing variations in DBH. The velocity of sap flow in sensors inserted at different depths in the sapwood is depicted. In general, the outermost layer of sapwood shows the maximum velocity in the trees examined, with the velocity decreasing towards the inside. The maximum velocity was approximately 40 cm h^{-1} although tree No.2 showed just half that value. Invariably sap flow was strongly related to the VPD as noticed in the diurnal values of VPD shown along with the Fig. 6.

Similar to the above measurements, the velocity measured during the pre monsoon period is depicted in Fig. 7. The major difference from the post monsoon measurement is the magnitude of the velocity. The maximum velocity recorded during the pre monsoon period was approximately 30 cm h^{-1}, showing a 25 per cent reduction compared to the post monsoon values. The pattern of sap flow was almost the same, with the outermost ring of sapwood showing the maximum velocity compared to the inner rings of sapwood. The sap flow was very much related to the VPD, which showed a nearly three times increase during the pre monsoon period compared to the post monsoon. Probably this promoted more steady transpiration during the day time compared to the post monsoon sap flow as seen from the figures.

The sap flow rate (kg h^{-1} $tree^{-1}$) was calculated; it was found that the pre monsoon sap flow was nearly twice that of the post monsoon values (Fig. 8). This could be due to the more steady sap flow noticed in the pre monsoon season compared to the post monsoon period in spite of the slightly higher velocity noticed during the post monsoon period. The post monsoon values ranged between 2 and 4 kg h^{-1} $tree^{-1}$ compared to the 6 and 8 kg h^{-1} $tree^{-1}$ noticed in the pre monsoon period.

The daily values of sap flow density (SFD) (kg cm^{-2} d^{-1}), which is the kilogram of water transpired per unit area of sapwood calculated from the above data is presented in Table 5. The mean SFD was 0.09 kg cm^{-2} d^{-1} for the post monsoon period and 0.44 kg cm^{-2} d^{-1} for the pre monsoon period. This shows that the daily values of SFD are five times higher during the pre monsoon period compared to the post monsoon measurements.

Although the daily values of sap flow showed much seasonal variations, they showed good correlation with the sapwood area of the tree (Fig.10). As can be seen from Fig.10, the sapwood area explained 97 per cent of the variations in sap flow during the post monsoon period when the same explained 90 per cent of the variations during the pre monsoon.

Table 4. Sapflow density (kg cm^{-2} d^{-1}) calculated in *E. grandis* plantation at Kanthalloor.

Date	**Tree 1**	**Tree 2**	**Tree 3**	**Tree 4**	**Mean ± s.e.**
Nov.-Dec.	0.0583	0.0653	0.1079	0.1193	0.0877 ± 0.0284
Feb.- Mar.	0.6836	0.4561	0.4086	0.2428	0.4478 ± 0.0960

The daily sap flow (kg d^{-1}) obtained by cumulating the half-hourly data shows that the sap flow is positively correlated to the DBH of the trees (Fig 6). The tree with the maximum DBH (Tree No.4) transpired nearly 60 kg d^{-1} of water during the post monsoon period, and nearly 90 kg d^{-1} of water during the pre monsoon. The difference was much more pronounced in the smallest tree out of the four examined, showing a value of 10 kg d^{-1} and 75 kg d^{-1} for the post monsoon and pre monsoon periods respectively.

Fig. 6. Sap velocity (post monsoon) of the four *E. grandis* trees at Kanthalloor measured using the sap flow sensors. The VPD measured simultaneously is also depicted.

Fig. 7. Sap velocity (pre monsoon) of the four *E. grandis* trees at Kanthalloor measured using the sap flow sensors. The VPD measured simultaneously is also depicted.

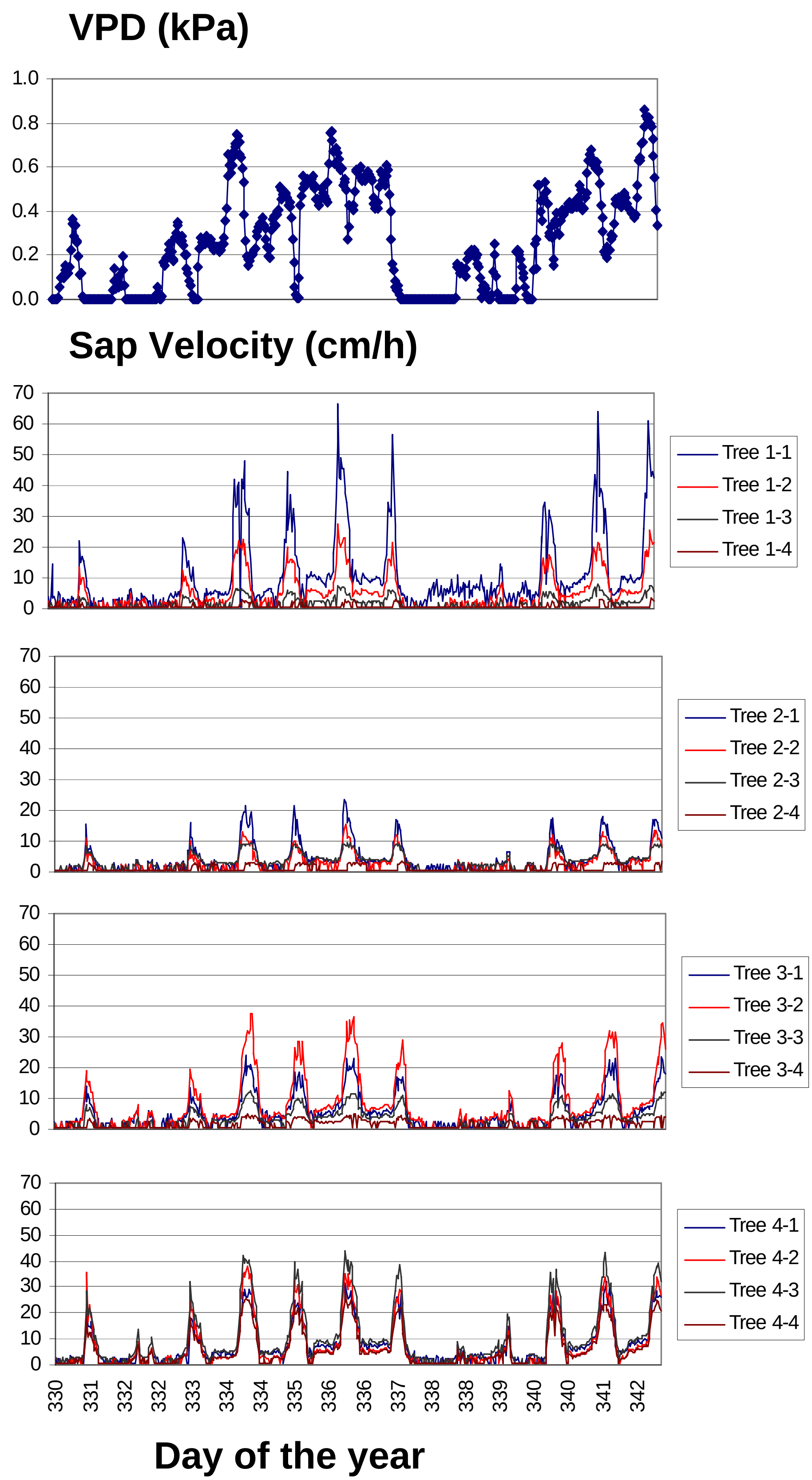
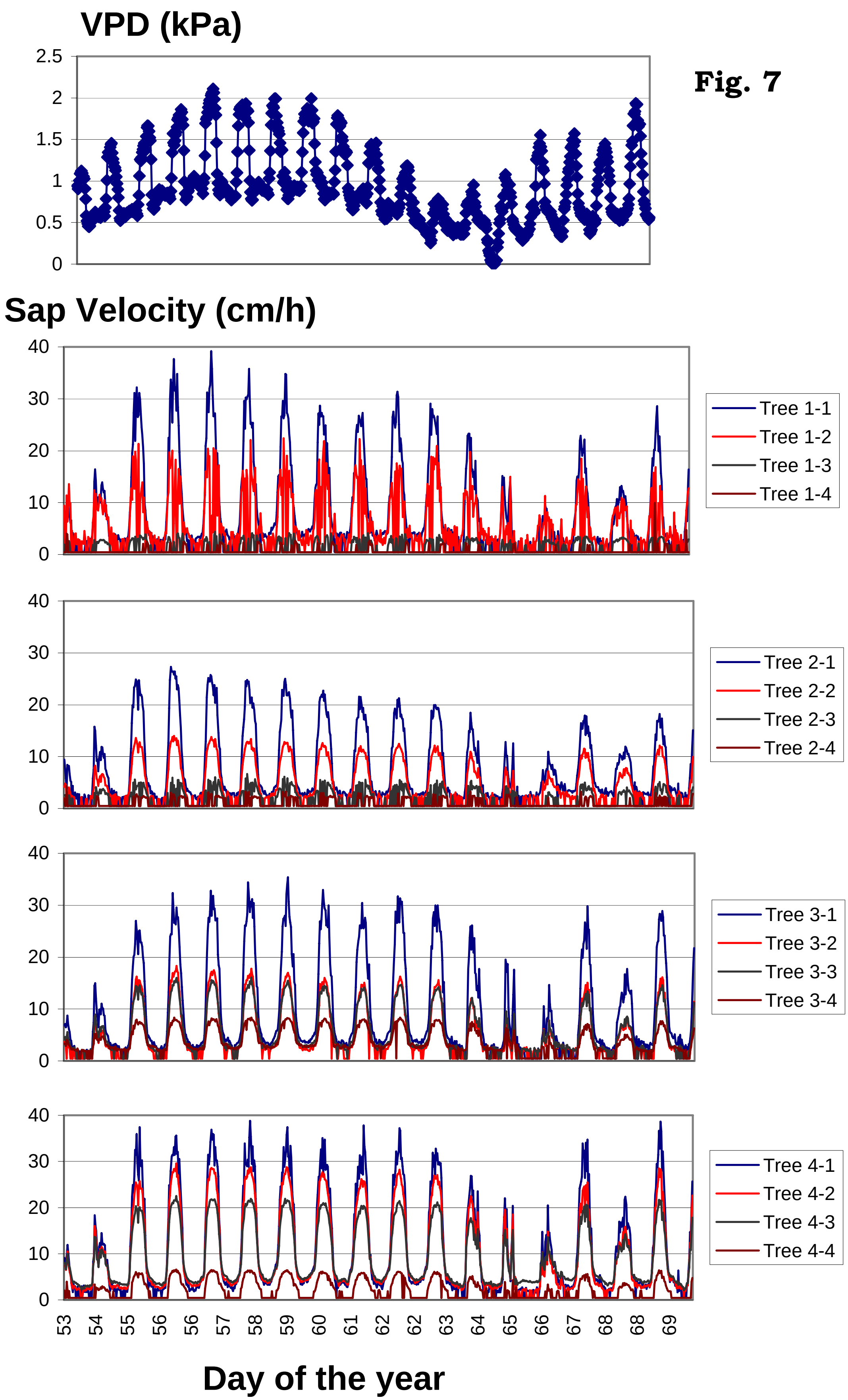

VPD (kPa)
Sap Velocity (cm/h)
Tree 1-1
Tree 1-2
Tree 1-3
Tree 1-4
Tree 2-1
Tree 2-2
Tree 2-3
Tree 2-4
Tree 3-1
Tree 3-2
Tree 3-3
Tree 3-4
Tree 4-1
Tree 4-2
Tree 4-3
Tree 4-4
Day of the year

Fig. 6



VPD (kPa)
2.5
2
1.5
1
0.5
0
Sap Velocity (cm/h)
40
30
20
10
0
Tree 1-1
Tree 1-2
Tree 1-3
Tree 1-4
Tree 2-1
Tree 2-2
Tree 2-3
Tree 2-4
Tree 3-1
Tree 3-2
Tree 3-3
Tree 3-4
Tree 4-1
Tree 4-2
Tree 4-3
Tree 4-4
53
54
55
56
56
57
58
59
60
61
62
62
63
64
65
66
67
68
68
69
Day of the year

Fig. 7

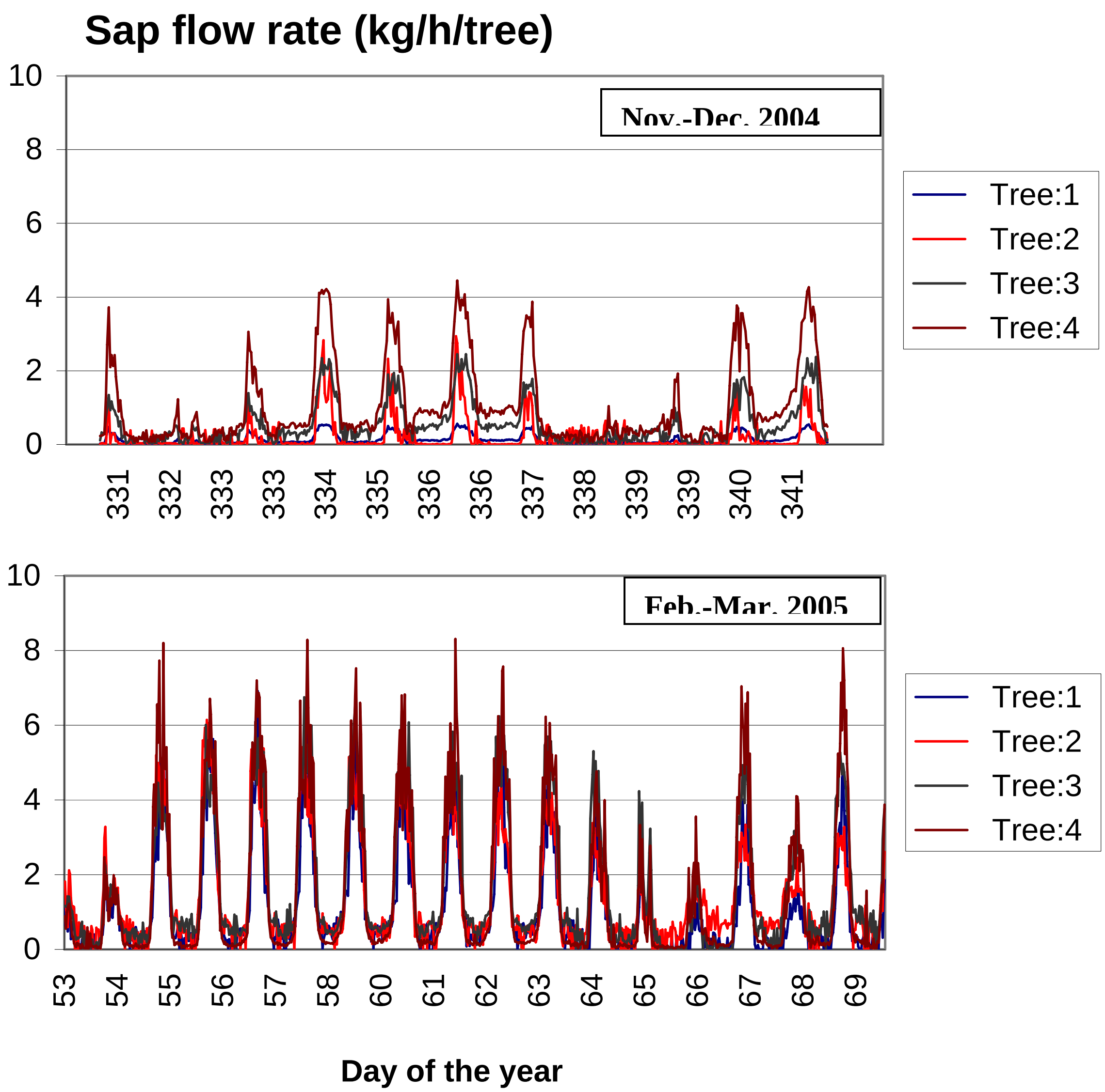


Fig. 8. Sap flow rate of *E. grandis* trees at Kanthalloor measured using the sap flow sensors. Note the much higher rate of flow during the pre monsoon period compared to the post monsoon period in all the four trees measured.

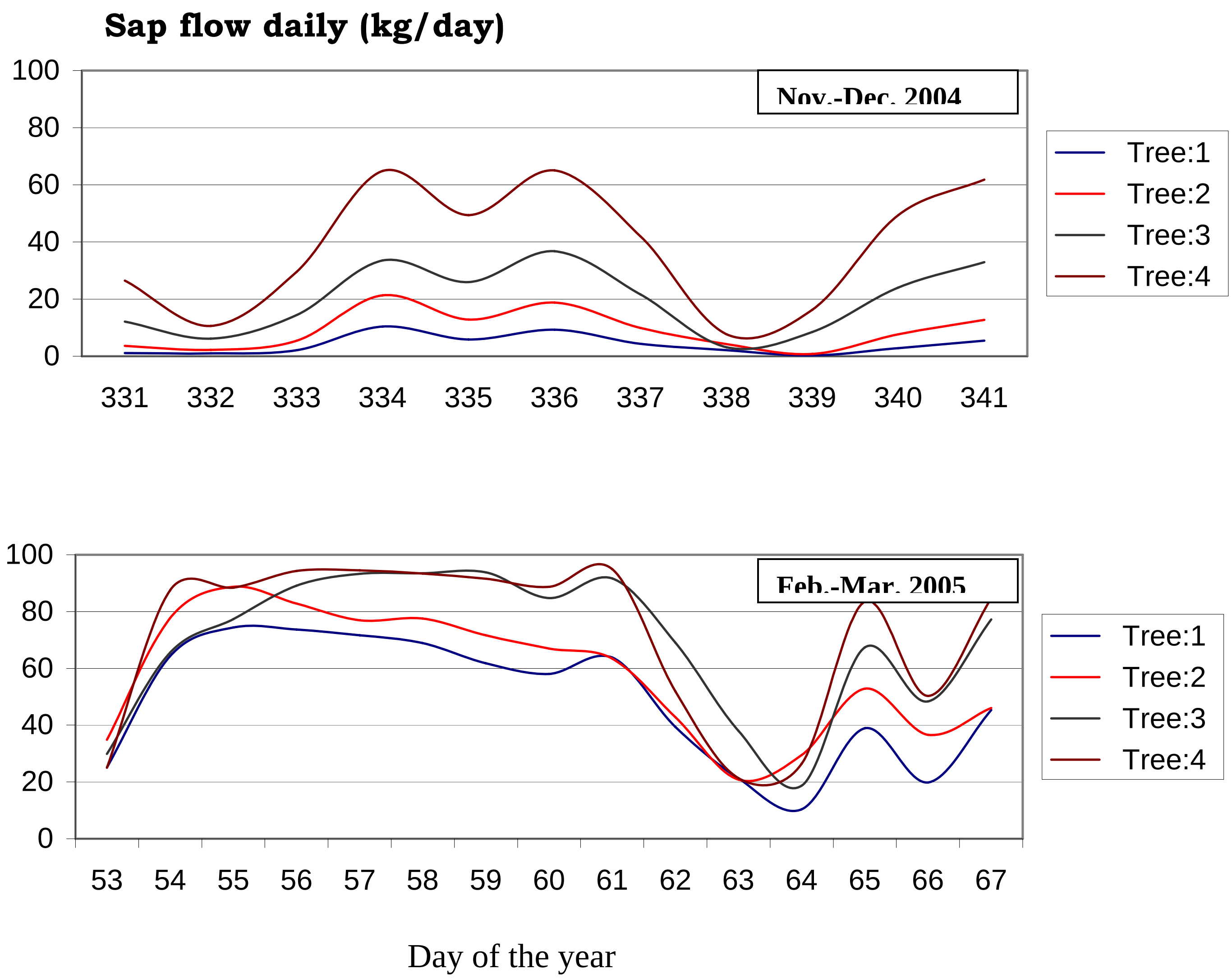


Fig. 9. Daily sap flow in the four *E. grandis* trees at Kanthalloor.

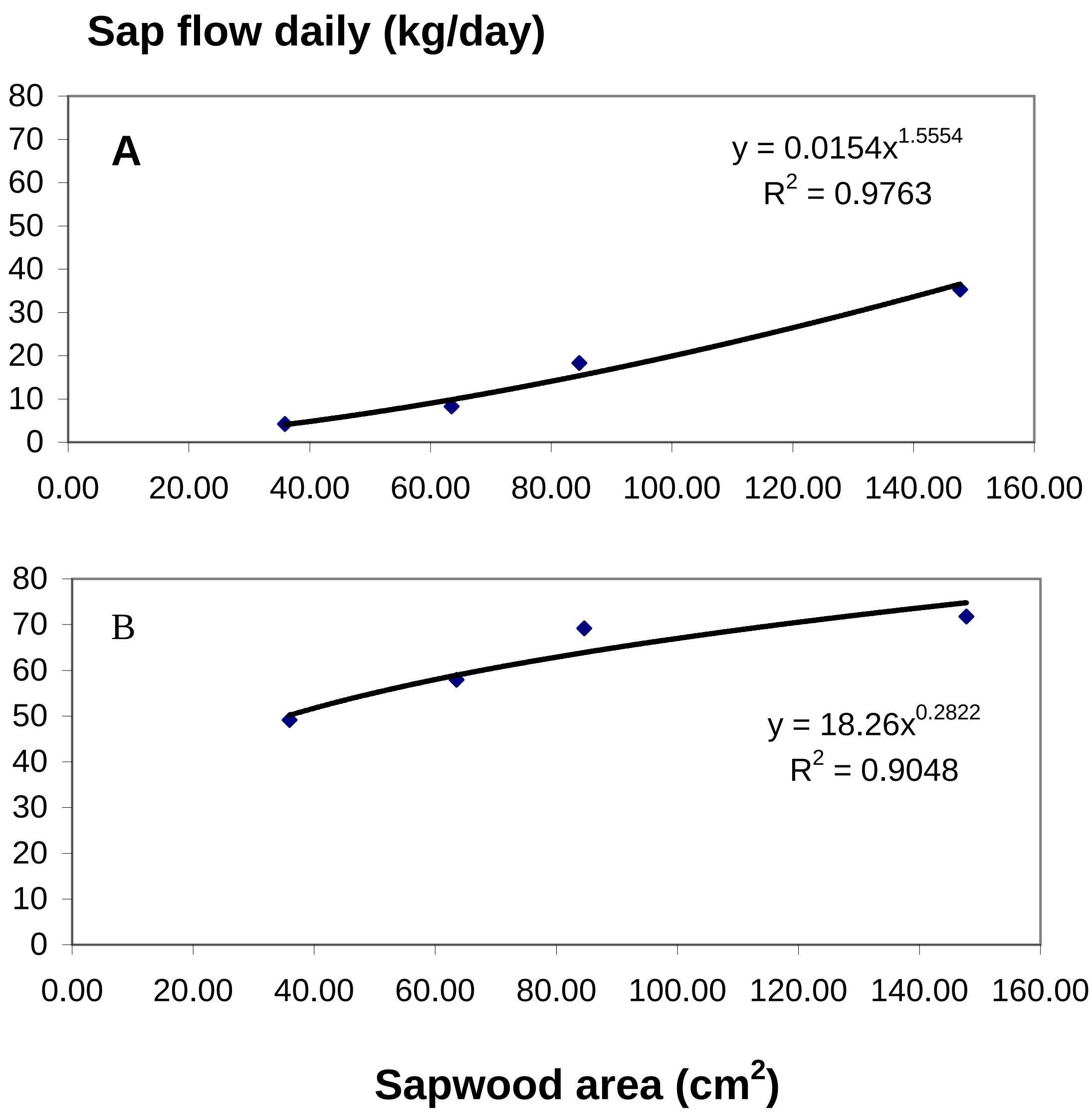


Fig. 10. The relation between daily sap flow and sapwood area in the *E. grandis* trees measured at Kanthalloor.

Transpiration from the plantation

Table 5. Sap flow calculated from the DBH measurement in the plantation using equations generated from the Fig. 10 for post and pre monsoon period.

Mean DBH of blocks (cm)	Calculated Sapwood area (cm^2)	Sap flow (kg $d^{-1}tree^{-1}$) during post monsoon	Sap flow (kg $d^{-1}tree^{-1}$) during pre monsoon
13.3	55.4	7.9	56.7
15.3	74.2	12.5	61.6
15.6	77.2	13.3	62.3
15.0	71.2	11.7	60.8
11.3	39.5	4.7	51.5
Mean	63.5	10.0	58.6

The sap flow data collected during the post monsoon and pre monsoon periods from the four trees with varying DBH was used to extrapolate the transpiration from the plantation (Table 5 & 6).

Table 6. Transpiration calculated for the two seasons at Kanthalloor.

	Post monsoon	Pre monsoon
Mean Sap flow calculated for 1318 trees ha^{-1}	13,184 kg ha^{-1} d^{-1} (1.32 mm)	77,031 kg ha^{-1} d^{-1} (7.70 mm)

It may be noted that during the post monsoon period, the water use by the plantation is 13,184 kg ha^{-1} day^{-1}, whereas it went up to 77,031 kg ha^{-1} day^{-1} during the pre monsoon period. On an area basis, the values were 1.3 mm and 7.7 mm respectively for the pre and post monsoon periods. Thus it may be noted that the summer transpiration is nearly 6 times higher compared to the post monsoon transpiration.

Evapotranspiration from Grasslands

The evapotranspiration from a grassland adjacent to the eucalypt plantation was measured using a small weighing lysimeter. The results are presented in Table 7.

Table 7. Evapotranspiration from a grassland adjacent to the eucalypt plantation at Kanthalloor.

Seasonal measurements	Post monsoon period	Pre monsoon period
Evapotranspiration (mm d^{-1})	2.36	1.91

The grassland evapotranspiration during post monsoon period is slightly more than the value for the pre monsoon period. This could be due to the negligible evaporation component during the dry season compared to the post monsoon season as the soil surface starts drying up soon after the rainfall season is over. Besides, the grass also gets dried up during the dry period, contributing very little to transpiration.

Stream flow measurements

Stream flow measurements were made at several points in Chengalar from near its origin down to locations where it joins the Chinnar river at Marayoor. While the Chengalar originates somewhere in the hills of Idallimotta as an underground spring, it passes through the Mannavan Shola, then through the eucalypt planted area, the town of Kanthalloor, the agricultural land down the Kanthalloor town and finally reaches the Chinnar river.

The river was gauged at six locations and the results are shown in Tables 8 & 9. The summary of the results is presented in Table 10. Seasonal measurements at three different times during the project period are presented in the Tables. It is interesting to note that there is no reduction in flow of the river as it flows down from its origin at any location. The observations made at the Kanthalloor Town Bridge Station are especially interesting. At this point, the river flows after passing through the eucalypt plantations in question. Even after passing through the eucalypt plantations, it is noted that there is no reduction in flow; rather the stream flow shows an increase in rate at all the three seasons measured. At the last station, there is a decrease in the flow rate, mainly because most of the agricultural fields are located before this. From the stream flow measurements, it is apparent that there is charging of the river happening at all locations during its course from the high mountains till it joins the Chinnar River at Marayoor.

Table 7. Post monsoon stream flow measurements.

Stream Flow observationat Kanthallur on 16/11/2005

1.Near mannavan sholai

Sl No	Length(m)	Width(m)	Deth of flow(m)	Time(Sec)	Flow rate (m3/sec)
1	3	5.24	0.76	17	0.702776471
2	3	5	0.81	16	0.759375
3	3	4.7	0.89	14	0.896357143
				Average	**0.786169538**

2.Near Grass land

Sl No	Length(m)	Width(m)	Deth of flow(m)	Time(Sec)	
1	2	2.24	0.95	8	0.532
2	2	2	1.16	8	0.58
3	2	2.56	1.21	9	0.688355556
				Average	**0.600118519**

3.Diversion Channel

Sl No	Length(m)	Width(m)	Deth of flow(m)	Time(Sec)	Flow rate (m3/sec)
1	2	0.65	0.35	8	0.056875
2	2	0.65	0.35	8	0.056875
3	2	0.65	0.35	9	0.050555556
				Average	**0.054768519**

At Kanthallur Town Bridge

Sl No	Length(m)	Width(m)	Deth of flow(m)	Time(Sec)	Flow rate (m3/sec)
1	6.5	4.65	0.46	18	0.772416667
2	6.5	4.65	0.4	17	0.711176471
3	6.5	4.65	0.48	20	0.7254
				Average	**0.736331046**

5.At Dindikommbu(Joining point of Theerthamalai Ar)

Sl No	Length(m)	Width(m)	Deth of flow(m)	Time(Sec)	Flow rate (m3/sec)
1	3	4.8	0.95	4.17	3.28057554
2	3	2.95	0.7	6	1.0325
3	3	3.25	0.9	4.5	1.95
				Average	**2.087691847**

6.Theerthamalai Arat Dindikombu((Joining point of Chengal Ar)

Sl No	Length(m)	Width(m)	Deth of flow(m)	Time(Sec)	Flow rate (m3/sec)
1	2	4.3	0.8	5	1.376
2	2	4	0.55	5	0.88
3	2	4.3	1.12	5	1.9264
				Average	**1.394133333**

Table 9. Stream flow observations at Kanthalloor on 21.03.2006

1. Near Mannavan Shola

Sl.No	Length(m)	Widthh(m)	Depth(m)	Time(sec)	Flow(m^3/sec)
1	2.8	2.3	0.23	16	0.092575
2	2.8	2.1	0.27	17	0.093388
3	2.8	1.7	0.31	16	0.092225
				Average	**0.092729**

2. Near Grassland

Sl.No	Length (m)	Widthh (m)	Depth(m)	Time(sec)	Flow(m^3/sec)
1	2	2.24	0.25	11	0.101818
2	2	2	0.22	12	0.073333
3	2	2.56	0.26	11	0.121018
				Average	**0.098723**

3. At Kanthalloor Town Bridge

Sl.No	Length (m)	Width(m)	Depth (m)	Time (sec)	Flow (m^3/sec)
1	6.5	4.65	0.57	24	0.717844
2	6.5	4.65	0.52	26	0.6045
3	6.5	4.65	0.61	22	0.838057
				Average	**0.720134**

4. At Dindikombu(Joining point of Theerthamalaiar)

Sl.No	Length(m)	Width(m)	Depth(m)	Time(sec)	Flow(m^3/sec)
1	3.5	5.2	0.14	12	0.212333
2	3.5	6.7	0.16	4	0.938
3	3.5	6.7	0.13	6	0.508083
				Average	**0.552806**

5. At Dindikombu (Joining point with Chengalar)

Sl.No	**Length(m)**	**Width(m)**	**Depth(m)**	**Time(sec)**	**Flow(m^3/sec)**
1	2.5	5.6	0.17	7	0.34
2	2.5	6.3	0.18	5	0.567
3	2.5	6.3	0.18	6	0.4725
				Average	**0.459833**

Table 10. Summary Table showing the result of stream flow measurements at Kanthalloor during various seasons of the year.

Location	Flow rate (m^3/sec)		
	10/03/2005	**16/11/2005**	**21/03/2006**
Near Mannavan shola	0.0666	0.0786	0.0927
Near grassland	0.0780	0.6001	0.0987
Diversion channel	0.0546	0.0547	---------
Kanthalloor town bridge	0.6440	0.7363	0.7201
At Dindikombu	0.5662	2.0876	0.5528

Discussion

Heat pulse and sap flow technique validation

Cut tree experiments have been used by several workers to validate sap flow estimates of eucalypt trees. Doley and Grieve (1966) applied an early version of the sap flow method (based on surface heating of the stem) to several small *E. marginata* trees and found that sap flow estimates equated to about half the actual tree water uptake. In an application of the technique to several *E. regnans* saplings, Dunn and Connor (1993) obtained sap flow estimates that were within 5% of actual tree water use. Hatton *et al.* (1995) reported a 15% difference between estimated and actual water use in an *E. populnea* tree, and Barrett *et al.* (1995) reported differences of 1-11% in their study examining sap flow behavior in two small *E. maculata* Hook. trees. Olbrich (1991) applied the *in situ* cut tree technique to a 56-m-tall *E. grandis* and found that the sap flow estimate of water uptake was about 12% greater than the actual value. This difference was attributed partly to the use of a flexible reservoir to hold water around the stem. Vertessy *et al.* (1997) found that the sap flow method underestimated cumulative water uptake over 3 days by less than 4%. Estimated sap flow closely tracked actual water uptake throughout the measurement period, except for periods of very low uptake (< 0.05 m^3 day^{-1}) when the sap flow logger recorded no flow. From the above studies, it may be reasonably concluded that the sap flow method is a valid means of determining the water use behavior of a single tree, although the sensitivity of the sap flow sensor needs to be improved if accurate estimates of low sap flows are required.

Stem diameter and its relation with other parameters

In *E. grandis*, we found strong statistical associations between stem diameter and other parameters analyzed. Stem diameter measurements explained 94% of the variation in sapwood area, and more than 90% of the variations in mean daily transpiration by trees. Stem disc analysis indicated that up to an age of 7 years, which is the usual rotation period for *E. grandis* plantation used for pulping, the sapwood ring is more or less uniform, without any buttressing. Hunt and Beadle (1998) in a study on *Eucalyptus nitens* mixed with *Acacia dealbata* in Tasmania using heat pulse velocity method recorded mean daily sap flux ranging from 1.4 to 103.6 l day^{-1}. Stem diameter explained 98% of the variation in sapwood area for *E. nitens* and was determined to be a suitable parameter for scaling water use from the tree to stand level. Roberts *et al.* (2001) measured mean sap velocity of *Eucalyptus sieberi* trees in three plots with differing age in late summer (February-March). It was not significantly different and averaged 9.5 cm h^{-1}. Here also, diameter was a good predictor of sapwood area and leaf area of individual trees. Diameter predicted 94% of the variation in sapwood area and 96% of the variation in leaf area. Stand sapwood area declined with age from 11 m^2 ha^{-1} in the 14-year-old forest, to 6.5 m^2 ha^{-1} in the 45-year-old forest, to 3.1 m^2 ha^{-1} in the 160-year-old forest. LAI was 3.6, 4.0, and 3.4 for the 14, 45, and 160-year-old plots, respectively. Because of the difference in sapwood area, plot transpiration declined with age from 2.2 mm per day in 14-year-old forest, 1.4 mm per day in 45-year-old forest, to 0.8 mm per day in 160-year-old forest.

Because stem diameters are easy to measure, it is possible to make reliable assessments of related stand parameters in large plots with similar geographic and environmental conditions. The strong correlation between stem diameter and mean daily transpiration helps us to extrapolate the stand transpiration by measuring the DBH of the trees in the stand. This has many practical applications, as this would be able to tell us more about the water management possibilities in a catchment by reducing the basal area of the trees. Vertessy *et al.* (1995) report on 50% basal area reduction, reducing mean daily (spring) transpiration by 58% if the biggest trees were felled, or by 42% if the smaller trees were felled in mountain ash (*E. regnans*) forests in Australia. However, forest thinning experiments in mountain ash forests suggest that instantaneous reductions in transpiration and interception would not be converted entirely into stream flow gains (Jayasuriya *et al.* 1993).

Sap flow velocity and water use

In this study, sap velocity variations noticed in the different depths of sapwood in a tree was found to follow the same pattern throughout the days of measurements, namely, the outermost ring of sapwood was showing the maximum velocity compared to the inner rings of sapwood. This uniform pattern makes the calculation of the mean velocity using a regression for arriving at the mean values. It is also interesting to note that the velocity variations between trees were also not very significant within a season.

Since we did not make the sap flow measurements on all days of the year, it is not possible to make any conclusion on the annual evapotranspiration from the plantation. However, from the magnitude of transpiration measured during the post monsoon and pre monsoon period, it is apparent that the transpiration would be much more than what is input as rainfall, which is only less than 1500 mm annually. This means that water must be drawn from deeper layers of the soil or from the phreatic aquifer. Since we have been able to locate roots of the *E. grandis* trees more than 10 m deep in this location, uptake of water from such deep sources cannot be ruled out. Cohen *et al.* (1997), while measuring the water consumption of eucalypts in an arid region in Israel found that the water use by the trees was much beyond what is input in the form of rainfall. They measured an annual consumption of 24.4 m^3 $year^{-1}$ $tree^{-1}$ for a large eucalypt tree and they found that the transpiration was linearly related to potential evapotranspiration. White *et al.* (2002) measured soil water content and water use in a contour-planted belt of trees comprised of *Eucalyptus saligna*, *E. camaldulensis*, *E. leucoxylon*) and *E. platypus*. The tree-belt used 595 mm on a projected crown area basis over a 12-month period. Of this, 440 mm was transpiration, 100 mm interception and 55 mm soil evaporation. Rainfall was 445 mm and was all captured by the upper 2 m of the soil profile. Both soil water measurements and piezometric data from the same site indicated that most of the water was from groundwater flowing under the trees.

What determines the water use?

The results of the present study indicate that the water use during post monsoon and pre monsoon period vary widely. Leaf area of a tree is an important parameter determining the water use. Hubbard *et al.* (2004), in a study done on *Eucalyptus saligna* in Hawaii found that fertilization of the trees increased stand water use by increasing leaf area. Fertilized trees grew more wood and used more water, but fertilization did not change wood growth per unit water use or the WUE did not change.

Our measurements of the leaf area index (LAI) in the plantation indicated leaf area of 1.4 and 1.32 during post monsoon and pre monsoon periods respectively, thus showing no significant variations. Thus the big difference in transpiration estimates noticed between the two seasons could not be due to the difference in leaf area variations. Dye and Olbrich (1993) in their measurements of water use in *E. grandis* have confirmed that photosynthetically active radiation (Q) and vapour pressure deficit (D) of the atmosphere determine the transpiration rate in the above species. Whitehead and Beadle (2004), in their extensive review on productivity and water use in eucalypts mention that in well-watered conditions, transpiration from *Eucalyptus* forests can be explained largely by leaf area index and vapour pressure deficit of the atmosphere. Measurements of photosynthesis for many *Eucalyptus* species over a wide range of conditions have confirmed the potential for high rates of carbon uptake. Measurements of maximum rates of photosynthesis, A_{max}, maximum rate of carboxylation, Vc_{max}, and the maximum rate of electron transport, J_{max}, for Eucalyptus trees are high in relation to other broad-leaved tree species, but actual rates of photosynthesis are often much lower because of water and nutrient limitations. This results in a wide variation in light-use efficiency ranging from 0.7 to 2.7 g (dry matter) MJ^{-1} (intercepted photosynthetically active radiation between 400 and 700 nm). Several mechanisms for drought avoidance are identified, including low values and large seasonal dynamic changes in leaf area index, near-vertical arrangement of leaves, high stomatal sensitivity to air saturation deficit, deep rooting ability and osmotic manipulation to maintain turgor in leaves. Further evidence from measurements of carbon isotope fractionation at sites along rainfall gradients and estimation of the relationships between leaf area, sapwood cross-sectional area and conductance demonstrate homeostatic adjustment of hydraulic properties in relation to growing conditions. Thus it seems from our work that much of the variation in seasonal changes in water use, namely 1.4 to 7.7 mm day^{-1}, can be attributed to vapour pressure deficit of the atmosphere, which is relatively high during the pre monsoon period. The pre monsoon values of VPD are more than four times the values in post monsoon period. In the absence of any stomatal closure mechanism, the possibility for high water use during this period is evident, especially when the soil is having high water content (as evidenced by high predawn leaf water potentials) and a deep rooting system.

Mielke *et al.* (1999) in a study on *E. grandis* conducted in Brazil reported that water vapour exchange in the tree canopy was strongly dominated by the regional vapour pressure deficit and that canopy transpiration is controlled mainly by stomatal conductance. On a seasonal basis, stomatal conductance and canopy transpiration were mainly related to predawn leaf water potential and, thus, to soil moisture and rainfall. In a hydrological study combining sap flow method and ground water monitoring of *Eucalyptus camaldulensis* plantation in Argentina, Engel *et al.* (2005) reported that the trees used both deep ground water and water from the upper layers giving a transpiration rate of 2-3.7 mm d^{-1}. They also reported that the water consumption by the eucalypts promoted flow from the adjacent grassland into the plantation. Fetene and Beck (2004) have shown that the sap flow in *Eucalyptus globulus* is closely related to the VPD changes in the atmosphere. They reported a transpiration of 45 kg d^{-1} $tree^{-1}$ for the above species.

The water use of 7.7 mm day^{-1} by eucalypts reported in our study might sound quite high. However, Hunt and Beadle (1998) in a study on *Eucalyptus nitens* mixed with *Acacia dealbata* in Tasmania using heat pulse velocity method recorded mean daily sap flux ranging from 1.4 to 103.6 l day^{-1}. Plot transpiration varied from 1.4 to 2.8 mm day^{-1} in mixed 8-year-old plots and was 0.85 mm day^{-1} in a mixed 4-year-old plot. However, from regression models they predicted that, in the absence of acacia competition, plot water use for the 8-year-old stand would approach 5-6 mm day^{-1} during the growing season. Morris and Collopy (1999) reported average single tree water use determined by the heat pulse method varying from less than 10 l day^{-1} in winter to over 30 l day^{-1} in summer. Stand water use averaged 0.9±1.0 mm day^{-1} over 2 years, and was evidently limited by soil water availability. The leaf area index (LAI) of the *E. camaldulensis* stand was estimated as 2.07. Morris *et al.* (2004) monitored tree growth, water use, climate and soil water conditions over 12 months in two 3–4-year-old *Eucalyptus urophylla* plantations on the Leizhou Peninsula of southern China. One of the plantations (Hetou) was established on a sandy soil of sedimentary origin with low water storage capacity, and the other (Jijia) plantation was established on a clay soil formed on basalt. Sapwood area was ~50% higher at latter than at former because of differences in plant spacing (1994 versus 1356 stems ha–1). Annual water use, assessed by heat pulse measurements, was 542 mm at former and 559 mm at latter, with mean sap flux densities of 2772 and 1839 l $m^{-2}day^{-1}$, respectively. Limitations to water use, imposed by climatic and soil factors, were quantified by analysis of daily canopy conductance in relation to daytime vapor pressure deficit (VPD) and soil water content. Similar annual water use at the two sites was a result of higher VPD and soil water availability at Hetou compensating for the greater sapwood area at Jijia. Potential annual water use in the absence of soil water limitation was estimated at 916 mm at Jijia and 815 mm at Hetou. Higher water availability during the dry season and early wet season at Hetou than at Jijia was the result of deep root systems.

Water balance of eucalyptus plantations worldwide

It is interesting to examine the issue of the alleged excess water use by eucalypts from studies done in eucalypt growing countries during the past. Generally, trees tend to use more water than grasses or shrubs because of interception by the large canopy and a relatively deeper root system (Calder 1998). Zhang *et al.* (2001) found an average difference of 345 mm in evapotranspiration between grass and forest for an annual rainfall of 1,500 mm. When exotic trees replaced grasslands or shrub lands, the overall water use by the vegetation increased, leaving less water for the streams (Dye *et al.* 1995). A controversy on the hydrological effects of the reforestation with eucalypts, such as their possible high water use and decreased dry-season water yield in catchment level (Calder *et al.* 1997, Kallarackal and Somen 2008) has risen in many parts of the world since 1980s. In a comparative study on the water use of exotic and native species, Fetene and Beck (2004) have shown that differences in phenology and the proportion of pioneer trees like *Croton macrostachys* (a native species in Ethiopian forest) could bring about significant variation in stand transpiration of this forest. That *Croton* under favourable conditions transpired more than *Eucalyptus* questions the statement by FAO (1985) that *Eucalyptus*, due to high transpiration rates, reduces water yield more than other broad-leaved tree species. Thus the notion that exotic species are less efficient in water use may not hold always true.

To understand the links between eucalyptus plantation and water resources requires a basic knowledge of hydrology and plant physiology, and a good understanding of various environmental processes (Yan 2009). The contribution of plantations to water regimes varies from different regions of the world and from one site to another. Topography, soil type, local climate and species involved and a variety of other factors will exert their own particular influence.

In Brazil, eucalypt plantations have the highest growth rates recorded for woody vegetation (Whitehead and Beadle 2004). Most commercial eucalypt plantations have been established in areas of tropical and subtropical sub-humid climate rather than high rainfall, humid areas. Soares and Almeida (2001) in a detailed hydrological study on the eucalypt plantations of *E. grandis* in Brazil has shown that annual transpiration was 1,116 mm and evapotranspiration was 1,347 mm where annual rainfall was 1,396 mm. Another study done in Brazil in the Aracruz experimental catchment of *Eucalyptus grandis* plantations and Atlantic rainforest showed that eucalypt plantations consumed water more efficiently than the native trees over six years of measuring a eucalyptus forest and stands of neighbouring native species (Almeida *et al.* 2007). The annual average precipitation was 1,147 mm and average evapotranspiration was 1,092 mm. Because of high soil infiltration and the flat topography where the trees are planted, runoff was only 3% of the precipitation.

Australia with approximately 156 million hectares of natural forest and woodland has about 80% of the forested area dominated by the genus *Eucalyptus* with several hundred species. Most eucalypt plantations have been established in areas with annual rainfall between 650 mm - 900 mm (UNDP 2006). A study done at a 1,100 mm annual rainfall region in Western Australia (Sharma 1984), showed that eucalypts extracted water from depths down to 6 m, creating soil water deficits of up to 450 mm, compared to a water deficit of <150 mm under annual pasture, under similar conditions. It was concluded that both interception as well as water extraction from deep soil horizons, were the major factors responsible for high rates of water loss from eucalypt communities.

China has a fairly large area of eucalypt plantations, mostly located in southern China. A ten-year study was conducted by Zhou *et al.* (2002) in a degraded area of coastal western Guangdong Province to quantify the effectiveness of eucalyptus and subtropical mixed forest for ameliorating microclimate and reducing surface runoff and erosion. Mean annual rainfall in the region is approximately 1,500 mm, with distinct dry (October to March) and wet (April to September) seasons. The results showed that eucalyptus and mixed forest used much more soil moisture than bare land. Water table depth averaged 30 cm deeper beneath mixed forest and 80 cm deeper beneath eucalyptus forest, compared with bare land. In another study conducted in a catchment covered by 4-5-year-old eucalypt plantations in Gaoyao, Guangdong, south China (Xu *et al.* 2007), tree growth, water use and water balance in the watershed were studied. Annual transpiration by 4-5-year-old eucalypt plantation was 431 mm in 2005 and 402 mm in 2006. The stream flow was 565 mm in 2005, and 772 mm in 2006 due to the higher rainfall in that year. It was found that transpiration rate by eucalypt plantations in southern China was much lower than that in semi-arid climate, and usually less than 600 mm annually. Annual evapotranspiration in eucalypt plantations was between 900-1,200 mm. In 1999, monthly, seasonal and annual water balance of *Eucalyptus urophylla* plantations on the Leizhou Peninsula, Guangdong Province were estimated in contrasting soil types (Morris *et al.* 2004). It was found that annual water use of the 3-4-year-old plantation of *E. urophylla* assessed by heat pulse was 542 mm at Hetou and 559 mm at Jijia, respectively. Estimates of the water balance at the two sites found the annual evapotranspiration ranged from 969 - 1,150 mm and the difference in total evapotranspiration between the sites was partly attributable to higher soil evaporation at Jijia (finer soil texture) than at Hetou (Lane *et al.* 2004). In this study it was concluded that eucalyptus plantations did not pose a threat to water resources in that region.

India has the largest area of eucalypt plantations in the world. Several hydrological researches were carried out by the Karnataka Forest Department and Mysore Paper Mills Ltd in a low rainfall zone (800 mm per annum) in the State of Karnataka, southern India since 1987 and in Kerala by the Kerala Forest Research Institute since 1989. The major findings from Karnataka studies are summarized by Calder *et al.* (1992). According to the above investigators, the water use of a young *E. camaldulensis* plantation on a medium depth soil was no greater than that of the indigenous, semi-degraded, dry deciduous forest. The annual water use of eucalyptus and the indigenous, semi-degraded, dry deciduous forest approximated the annual rainfall. The water use of forest was about two times that of a commonly grown annual agricultural crop, ragi (*Eleusine coracana*). At sites where the soils were deeper, there were indications that the water use, over the three years of measurement, was greater than the rainfall indicating that soil water storage was being depleted due to “mining” by deep rooting.

Sikka *et al.* (2003) made a hydrological study on the response of watersheds due to conversion of natural grasslands into blue gum (*Eucalyptus globulus*) plantations. Conversion of natural grasslands into blue gum plantations has resulted in decreased low flow volume as well as peak flow, which in turn increased the soil moisture losses. These effects were more pronounced during the second rotation (i.e. first coppiced growth) as compared to the first rotation. Significant reduction in low flow as a result of decline in base flow could be predicted with LFI decreasing by 2.0 and 3.75 times, in the first and second rotation, respectively. Moderation in peak discharge rates was also observed as a result of blue gum plantation. Probability plots of peak discharge tend to suggest that the effect of blue gum plantation on peak flows become insignificant for the floods with higher return periods. The authors suggest that caution needs to be exercised while planning large scale conversion of natural grasslands into blue gum plantations in the catchments of hydro-electric reservoirs in the Nilgiris which adversely affects water availability especially during lean flow period.

The results of the studies done in *E. tereticornis* and *E. grandis* in comparison with certain indigenous trees such as *Tectona grandis* and other introduced and exotic trees such as *Acacia auriculiformis* and *Anacardium occidentale* (Kallarackal 1993, Kallarackal and Somen 1997a, 1997b, 1998, 2008) in different locations in Kerala have shown that eucalypts showed a transpiration / reference evapotranspiration (Et/Et_o) ratio of approximately 1.5 indicating that the transpiration is much more than the reference evapotranspiration for the area. However, in the other species also, this value was not much different except for *A. auriculiformis*, where the pre-monsoon ratio was below one. *Tectona grandis* certainly had the advantage of the trees shedding their leaves during the pre monsoon period, thereby almost no transpiration. However, the same species had a *Et/Eto* ratio of 2.0 during the post monsoon period. They arrived at the conclusion that instead of giving more importance to the annual transpiration, the seasonal transpiration, especially the summer season transpiration should be compared when choosing trees for a catchment, where water conservation is also intended.

Based on the studies carried out in Brazil, Australia, southern China and the previous studies done in several locations in Kerala and elsewhere in southern India it appears that the eucalypt plantations at Kanthalloor show more transpiration at least during the pre monsoon period. This can be attributed to the availability of abundant ground water and the prevailing high vapour pressure deficit of the atmosphere. However, from the ecophysiological behaviour of other species already noticed in Kerala (Kallarackal and Soman 2008), plantation species such as *Tectona, Anacardium* or *Acacia* could behave in a similar way. It is interesting to note that the stream flow is not getting reduced after passing through the eucalypt growing area. Probably, the stream is supplied by the spring originating at higher elevations, whereas the eucalypt plantations are getting ground water from other hills located in the surroundings.

From a general analysis of the global data, it becomes apparent that the water use by eucalypt species need not be excessive when compared to other tree species. In Kanthalloor, where the major plantation species is *E. grandis*, the question arises as to what other tree species could be planted. A comparison of the eucalypt transpiration with the evapotranspiration measured in the adjacent grassland shows that grasslands certainly consume much less water compared to eucalypt trees. Hence, any afforestation programmes replacing grasslands with trees should be avoided if water conservation is an important consideration. As long as the plantations in this location are owned by private land owners, the species to be planted will be decided by them based on economic viability. As an area with a cool climate, the land is probably suitable for growing other horticultural crops such as apple, pear, cherry, etc., there is a good possibility to encourage these items, especially in Kerala which is very much tropical. The results also imply that water use by plantations on soils with high water availability and in areas of high VPD may be reduced by establishment at wider spacing (Kallarackal and Somen 1997a, Morris *et al.* 2004). The environmental cost of water use by plantations must be weighed against their economic and environmental values to determine an appropriate mix of forestry, agriculture and other land uses in regions where water resources are limited.

Site specific water use by eucalypts

The next question to be answered in this study is whether the eucalypt trees planted at Kanthalloor and the surrounding hills are a threat to the water flow in the Chengalar river. This can be further answered from the stream flow measurements made during different seasons. There is no doubt that the water flow in the Chengalar river is very normal during the wet season or the post monsoon season. However, there is a reduction in the flow of water during the summer season. Is this reduction in flow during the summer season due to the eucalypt plantations at the uphill regions? To answer this question, it is important to trace the origin of the Chengalar river. It has been noted that the Chengalar river originates as an underground spring in a hill at much higher elevation than Kanthalloor. As this spring continues its journey down the hill, it passes through several forested areas of Mannaval shola, a very virgin forest in this location. Hence during the summer season much water is used by this natural forest from the spring. We could not notice any other springs or canals active in Mannavan shola during the dry period. Hence the entire source of water for the Chengalar river during the summer period is the spring at the top of the hill in this region.

It is interesting to note that as the water flows down through the eucalypt plantations and the river reaches Kanthalloor town, there is not much reduction in stream flow. This is a good evidence that the eucalypt trees are not consuming excessive amount of water. As the river flows further down, much of its water is diverted for rice cultivation down the hill. It is after this that the Chengalar joins the Chinnar in Marayoor town.

Since most of the *E. grandis* plantations were located downhill the Mannavan shola, there is a very good chance for the eucalypt trees located at this elevation to take up the water coming as stream flow. In fact, eucalypts are well known to consume more water if available in the soil. In the above locality, since there is a continuous stream flow from the Mannavan shola, and the eucalypts are located downhill the shola, the trees must be getting good water supply even during the dry period. This could certainly reduce the flow of water downhill. However, stream flow measurements do not indicate any substantial reduction in flow. It is possible that the eucalypts are using another source of subsurface ground water coming from the Mannavan Shola located above the eucalypt plantation. The surface water flowing through the Chengalar river is not affected by this consumption.

Conclusions

The question whether the eucalypts planted in Kanthalloor and surrounding areas cause water shortages in Marayoor has been analysed by studying the stream flow in the river coming from the area as well as from water consumption of the eucalypts planted in the area. The Chengalar originating in the hills is supplied from a natural spring, which reaches Marayoor and joins the Chinnar. The stream flow of this river is not reduced substantially as it passes through the eucalypt growing areas in Kanthallor. Although the water consumption of eucalypts is considerably high during the summer period, the water used by the trees does not seem to be from the Chengalar, rather an alternate subsurface water is probably available to them. Although eucalypts are giving a reasonable income to the landowners now, they should be encouraged to plant more temperate fruit trees and vegetables, as this would improve the food security of the State. Moreover, areas with a temperate climate is very scarce in the State, this area could very well be used for growing such food crops. However, the natural grasslands in the area should not be replaced with any other plantation programmes, as the water consumption by grass is much less than any tree species.

References

Almeida, A.C., Soares, J.V., Landsberg, J.J. and Rezende, G.D. 2007. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production, Forest Ecology and Management (251):10-21.

Alsheimer, M., B. Köstner, E. Falge and J.D. Tenhunen. 1998. Temporal and spatial variation in transpiration of Norway spruce stands within a forested catchment of the Fichtelgebirge, Germany. Ann. des Sci. For. 55:103-193.

Barrett, D.J., Hatton, T.J., Ash, J.E. and Ball, M.C. 1995. Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest and eucalypt forest species of south-eastern Australia. Plant Cell Environ. 18:463--469.

Calder, I. R. 1998. Water use by forests: limits and controls. Tree Physiology, 18,p.625-631.

Calder, I.R., Rosier, P.T.W., Prasanna, K.T. and Parameswarappa, S. 1997. Eucalyptus water use greater than rainfall input - a possible explanation from southern India. Hydrol. Earth Syst. Sci. 1, 249-256.

Calder, I.R., Swaminath, M.H., Kariyappa, G.S., Srinivasalu, N.V., Srinivasa Murty, K.V. and Mumtaz, J. 1992. Measurements of transpiration from Eucalyptus plantation, India using deuterium tracing. *In:* Calder, I.R., Hall, R.L. and Adlard, P.G., (Ed) 1992. Proc. Int. Symp. on the Growth and Water Use of Forest Plantations. Bangalore, 7-11 February 1991, Wiley, Chichester, p.196-215.

Cohen, Y., Adar, E., Dody, A. and Schiller, G. 1997.Underground water use by *Eucalyptus* trees in an arid climate. Trees 11:356-362.

Doley, D. and Grieve, B.J. 1966. Measurement of sap flow in a eucalypt by thermo-electric methods. Aust. For. Res. 2:3--27.

Dunn, G.M. and Connor, D.J. 1993. An analysis of sap flow in mountain ash (*Eucalyptus regnans*) forests of different age. Tree Physiol. 13:321--336.

Dye, P.J. and Olbrich, B.W. 1993. Estimating transpiration from 6-year-old *Eucalyptus grandis* trees: development of a canopy conductance model and comparison with independent sap flux measurements. Plant, Cell and Environ. 16:45-53.

Dye, P.J., Olbrich, B.W. and Everson, C.S. 1995. The water use of plantation forests and montane grassland in summer-rainfall forestry regions in South Africa. Proceedings of the Seventh South African National Hydrological Symposium.Institute for Water Research, Grahamstown.

Engel, V., Jobba´gy E. G., Stieglitz, M., Williams, M. and Jackson, R.B. 2005. Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas, Water Resour. Res., 41, W10409, doi: 10.1029/2004WR003761.

FAO,1985. The ecological effects of *Eucalyptus*. Forestry Paper No.59. FAO, Rome.

Fetene, M. and Beck, E.H. 2004. Water relations of indigenous versus exotic tree species, growing at the same site in a tropical montane forest in southern Ethiopia. Trees 18:428–435.

Hatton, T.J., Moore, S.J. and Reece, P.H. 1995. Estimating stand transpiration in *Eucalyptus populnea* woodland with the heat pulse method: method errors and sampling strategies. Tree Physiol. 4:219--227.

Hubbard, R.M., Ryan, M.G., Giardina, C.P. and Barnard, H. 2004. The effect of fertilization on sap flux and canopy conductance in a *Eucalyptus saligna* experimental forest. Global Change Biology 10: 427–436.

Huber, B. 1932. Observations and measurements of sap flow in plants. Deutsche Bot. Gesellschaft, Beriche 50: 89-109.

Huber, B. and Schmidt, E. 1937. Eine Kompensationsmethode zur thermoelektrischen Messung Langsamer Saftstrome. Ber. dt. Bot Ges 55: 514-529.

Hunt, M.A. and Beadle, C.L. 1998.Whole-tree transpiration and water-use partitioning between *Eucalyptus nitens* and *Acacia dealbata* weeds in a short-rotation plantation in northeastern Tasmania. Tree Physiology 18:557-563.

Jayasuriya, M.D.A., Dunn, G., Benyon, R. and O'Shaughnessy, P.J. 1993. Some factors affecting water yield from mountain ash (*Eucalyptus regnans*) dominated forests in south-east Australia. J. Hydrol. 150:345-367.

Kallarackal J. and Somen, C.K. 1998. Water relations and rooting depth of selected eucalypt species. KFRI Research Report No.136. KFRI, Peechi.

Kallarackal, J. 1993. Studies on water use, photosynthesis and growth of eucalypts. KFRI Research Report No.88, KFRI, Peechi, Kerala, India.

Kallarackal, J. and Somen, C. K. 1997a. An ecophysiological evaluation of the suitability of *Eucalyptus grandis* for planting in the tropics. Forest Ecology and Management 95: 53-61.

Kallarackal, J. and Somen, C. K. 1997b. Water use of *Eucalyptus tereticornis* stands of differing density in southern India. Tree Physiology 17: 195-204.

Kallarackal, J. and Somen, C.K. 2008. Water loss from tree plantations in the tropics.Current Science 94 (2): 201-210.

Kallarackal, J. and Somen, C.K. 2008. Water loss from tree plantations in the tropics. Current Science 94:201-210.

Kelliher F. M. ; Whitehead D. ; Mcaneney K. J. and Judd M. J. 1990. Partitioning evapotranspiration into tree and understorey components in two young *Pinus radiata* D. Don stands. Agri. For. Meteor. 50: 211-227.

Köstner, B., Biron, P., Siegwolf, R. and Granier, A. 1996b. Estimates of water vapour flux and canopy conductance of Scots pine at the tree level utilizing different xylem sap flow methods. Theoret. Appl. Climatol. 53: 105-114.

Köstner, B., Falge, E.M., Alsheimer, M., Geyer, R. and Tenhunen, J.D. 1998a. Estimating tree canopy water use via xylem sapflow in an old Norway spruce forest and a comparison with simulation-based canopy transpiration estimates. Ann. Sci. For. 55: 125-139.

Köstner, B., Granier, A. and Cermak, J. 1998b. Sapflow measurements in forest stands: Methods and uncertainties. Ann. Sci. For. 55: 13-27.

Köstner, B., Schulze, E.D., Kelliher, F.M., Hollinger, D.Y., Byers, J.N., Hunt, J.E., McSveny, T.M., Meserth, R. and Weir, P.L. 1992. Transpiration and canopy conductance in a pristine broad-leaved forest of *Nothofagus*: an analysis of xylem sap flow and eddy correlation measurements. Oecologia 91: 350-359.

Lane P.N.J., Morris, J., Zhang, N.N., Zhou, G.Y., Zhou, G.Y. and Xu, D.P. 2004. Water balance of tropical eucalypt plantations in south-eastern China. Agricultural and Forest Meteorology 124:253-267.

Marshall, D.C. 1958. Measurement of sap flow in conifers by heat transport. Plant Physiology 33: 385-396.

Mielke, M.S., Oliva, M.A., de Barros, N.F., Penchel, R.M., Martinez, C.A. and de Almeida, A.C. 1999. Stomatal control of transpiration in the canopy of a clonal *Eucalyptus grandis* plantation. Trees 13:152–160.

Morris, J., Zhang, N.N., Yang, Z.J., Collopy, J. and Xu, D.P. 2004. Water use by fast-growing *Eucalyptus urophylla* plantations in southern China, Tree Physiology 24:1035-1044.

Olbrich, B.W. 1991. The verification of the heat pulse velocity technique for measuring sap flow in *Eucalyptus grandis*. Can. J. For. Res. 21:836--841.

Poore, M.E.D. and Fries, C. 1985. The Ecological Effects of *Eucalyptus*. FAO Forestry Paper No.59. FAO, Rome. p. 75.

Roberts, J. 1977. The Use of Tree-cutting Techniques in the Study of the Water Relations of Mature *Pinus sylvestris* L. J. Exp. Bot. 28: 751-767.

Roberts, S. Vertessy, R. and Grayson, R. 2001. Transpiration from *Eucalyptus sieberi* (L. Johnson) forests of different age. Forest Ecology and Management 143:153-161.

Schulze, E.-D., Cermak, J. Matyssek, R., Penka, M., Zimmermann, R., Vasicek, F., Gries, W. and Kucera, J. 1985. Canopy transpiration and water fluxes in the xylem of the trunk of Larix and Picea trees – a comparison of xylem flow, porometer and cuvette measurements. Oecologia 66: 475-483.

Sharma, M.L. 1984. Evapotranspiration from a *Eucalyptus* community, Agricultural Water Management (8):41-56

Sikka, A.K., Samra, J.S., Sharda, V.N., Samraj, P. and Lakshmanan, V. 2003. Low flow and high flow responses to converting natural grassland into bluegum (*Eucalyptus globulus*) in Nilgiris watersheds of South India. Journal of Hydrology 270:12–26.

Soares, J.V. and Almeida, A.C. 2001. Modeling the water balance and soil water fluxes in a fast growing *Eucalyptus* plantation in Brazil. Journal of Hydrology.(253):130-147.

Swanson, R H. 1974. A thermal flow meter for estimating the rate of xylem sap ascent in trees. *In*, Dowell, R B (ed.), Flow - Its Measurement and Control in Science and Industry. pp.674-652. Instrument Society of America, Pittsburgh.

Swanson, R H. 1983. Numerical and experimental analyses of implanted-probe heat pulse velocity theory. PhD Thesis, University of Alberta, Edmonton, Alberta, Canada.

Swanson, R H; Whitfield, D W A. 1981. A numerical analysis of heat pulse velocity theory and practise. Journal of Experimental Botany 32: 221-239.

UNDP, 2006. Environmental and social impact analysis Stora Enso plantation projectin Guangxi, China. Beijing, 5 February, 2006.

Vertessy, R.A., Hatton, T.J., Reece, P. O'sullivan, S.K. and R. G. Benyon, R.G. 1997. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. Tree Physiology 17: 747-756.

Vertessy, R.A.,Benyon, R.G., O'sullivan, S.K. and Gribben, P.R. 1995. Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest.Tree Physiology 15: 559-567.

White, D.A., Dunin, F.X., Turner, N.C., Ward, B.H. and Galbraith, J.H. 2002. Water use by contour-planted belts of trees comprised of four *Eucalyptus* species. Agricultural Water Management 53:133–152.

Whitehead, D. and Beadle, C.L. 2004. Physiological regulation of productivity and water use in *Eucalyptus*: a review. Forest Ecology and Management 193:113–140.

Xu, D.P., Zhang, N.N., Qiao, Z.J., Zhang, G.Y., Yang, Z.J. and Shi, Z.J. 2007. Waterbalance in a catchment covered by 4-5 years-old eucalypt plantation in Gaoyao, south China. *In:* Conference on Eucalypts and diversity: balancing productivity and sustainability 22 - 26 October 2007, Durban, South Africa.

Yan, D. 2009. Spatial distribution of water use by eucalyptus plantations in a small catchment in Guangxi, South China: *a modelling and GIS approach.* Ph.D. Thesis submitted to the University of Helsinki.

Zhang, L. Dawes, W.R. and Walker, G.R. 1999. Predicting the effect of vegetation changes on catchment average water balance. Technical Report 99/12, CRC for Catchment Hydrology, Canberra, Australia.

Zhang, L., Dawes, W.R. and Walker, G.R. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Res. 37: 701–708.

Zhou, G.Y., Morris, J.D., Yan, J.H., Yu, Z.Y. and Peng, S.L. 2002. Hydrological impacts of reafforestation with eucalypts and indigenous species: a case study in southern China. Forest Ecology and Management 167: 209-222.

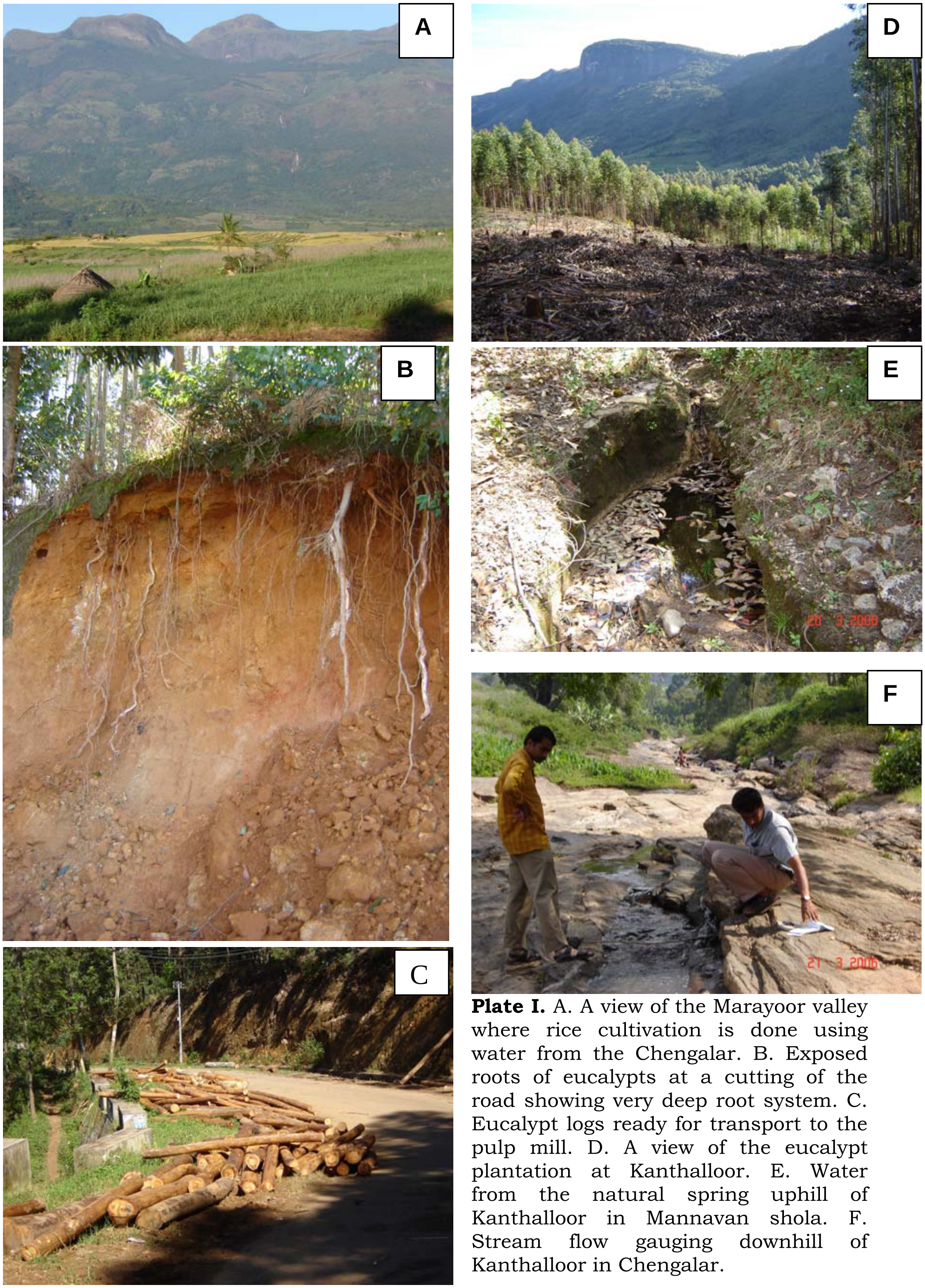


Plate I. A. A view of the Marayoor valley where rice cultivation is done using water from the Chengalar. B. Exposed roots of eucalypts at a cutting of the road showing very deep root system. C. Eucalypt logs ready for transport to the pulp mill. D. A view of the eucalypt plantation at Kanthalloor. E. Water from the natural spring uphill of Kanthalloor in Mannavan shola. F. Stream flow gauging downhill of Kanthalloor in Chengalar.

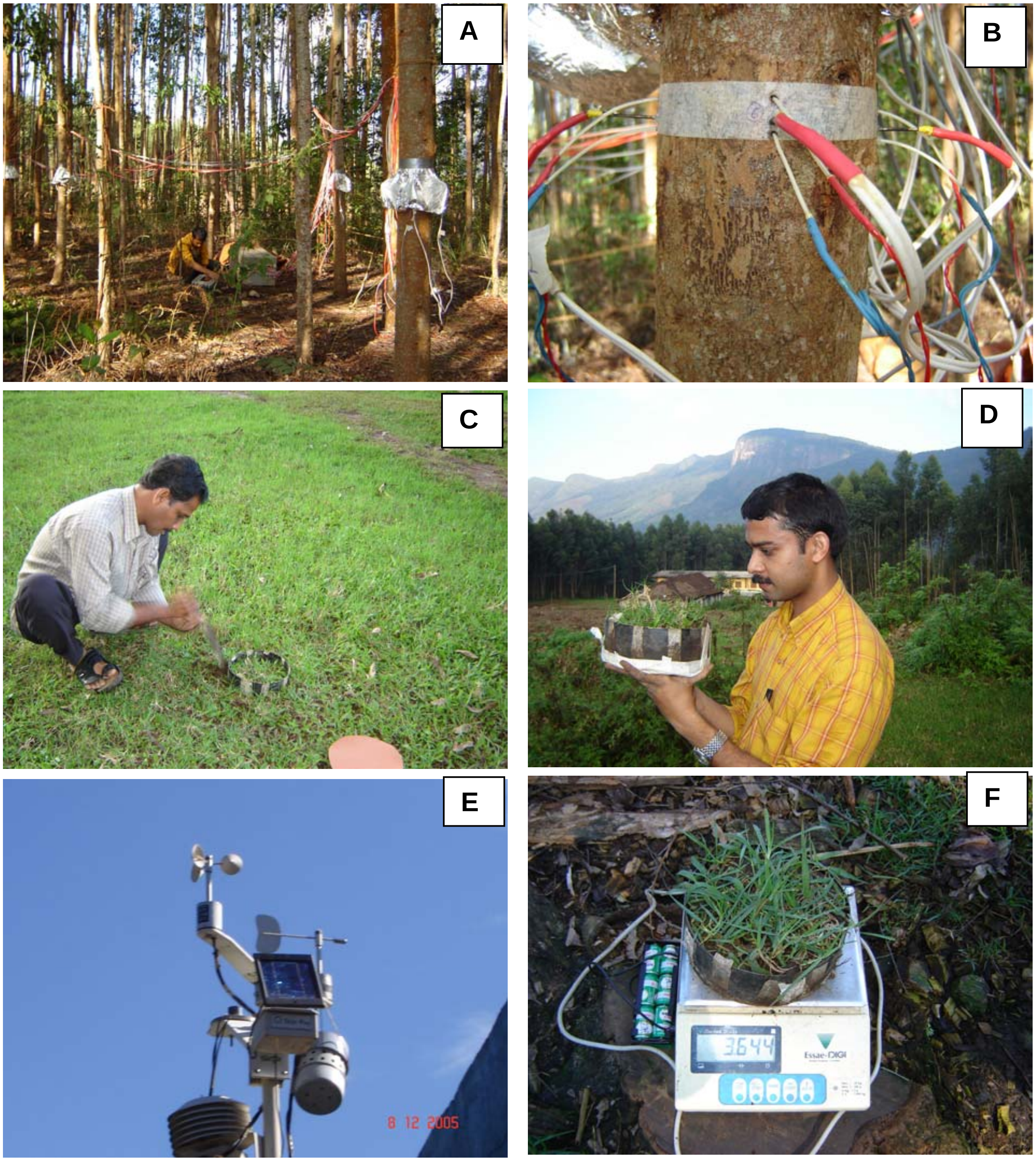


Plate II. A. Sap flow of eucalypt trees being measured using the sap flow sensors. B. Close up of a tree trunk fixed with sap flow sensors and the heaters. C. Fixing a small weighing lysimeter in the grassland at Kanthalloor. D. A weighing lysimeter with a patch of grassland in it. E. An automated weather station installed near the eucalypt plantation at Kanthalloor. F. The small lysimeter being weighed on a field electronic balance.