

Transpiration in two common tree species of Auroville, Tamil Nadu, India, using the calibrated heat pulse method to measure sap flux

Anil Graves, Pedro Berliner* and Israel Gev*

Auroville Greenwork Resource Centre, Auroville 605 101, India

*Jacob Blaustein Institute of Desert Research, Sede Baker 84993, Israel

The community of Auroville since 1968 has been reforesting large tracts of land on the Coromandel Coast near Pondicherry. Well over three hundred species of indigenous and exotic trees have been introduced to the area, as well as shrubs, grasses, and creepers. The groundwater has, however, witnessed a steep decline, yet rainfall patterns have not varied out of the ordinary. Although one of the major reasons for this depletion is the huge increase in borewell-irrigated agriculture, it was posited that the reforestation in Auroville must have played some part in modifying the water balance of the area. The purpose of this research therefore, is to understand in more depth, the role of Auroville's forests on the replenishment of groundwater, with a possible view to managing the forests of Auroville according to the requirements of the area's water balance. The technique employed here to determine transpiration is known as 'the calibrated heat pulse method'.

Measurements started in Auroville in March 1994, on two common tree species, *Acacia auriculiformis* and *Peltophorum pterocarpum*. The trees examined were planted in 1982, and the data, taken for five months between March and July 1994, showed that *P. pterocarpum* transpired more than three times as much as *A. auriculiformis*. Although the results were revealing, it was clearly seen that measurements would be required over a period of at least one year, and on more species of trees, to obtain a detailed hydrological picture of the area.

MEASURING the quantity of water transpired by trees has historically been difficult, cumbersome or both, with questionable data to finish with. Such methods have involved weighing the tree and its soil in a weighing lysimeter and measuring the resulting decrease in weight as the tree transpired or, alternatively, injecting dyes, solubles or radioactive materials to be 'traced', thereby giving the velocity of the sap in the tree. The latter methods in particular, physically harmed the tree and even destroyed it, making it alter its transpiration¹, otherwise, as with the lysimeter, trees were taken out of their natural context and estranged from the complex variables that nature brings into play.

The development of the calibrated heat pulse method overcame some of these problems. It involved minimal

physical damage to the tree, and the equipment being light and easy to install, could be used in field situations.

Tracing heat pulses to determine sap velocity was developed by Marshall¹. He envisaged a two dimensional heat flow in a medium of thermal homogeneity and uniform liquid flux—not likely in a tree, but close enough to reality to make the data valid. Marshall also discovered that the speed of the sap was actually greater than that of the heat pulse and put this down to the disturbance caused by the insertion of thermistors and heater into the tree. Most importantly, what Marshall noted was the constant relationship between the sap velocity and the heat velocity, allowing the difference to be quantified and calculated. Cohen *et al.*², who developed the present method using advanced electronic equipment, confirmed this in an experiment on citrus trees, kept under drought and well-watered conditions, in both cloudy and sunny weather. Results showed that the heat pulse method under-estimated transpiration by a mean value of 55.3% with only a 2.4% coefficient of variation.

Research using the calibrated heat pulse method is currently underway in Auroville, Tamil Nadu, India. The project was started after a seminar led to a discussion over the net effect of trees on the hydrology of the area, especially on the level of the water table which was declining steadily despite the extensive watershed work. Auroville, situated on a plateau, now consists of about 2,500 acres of land, approximately half of which has been reforested since the late 1960s.

Due to experimental constraints, only two tree species were measured with four replicates for each species. *A. auriculiformis*, the most dominant tree in the area, is a very fast growing and relatively hardy and drought-resistant exotic from Australia. The other tree selected was *P. pterocarpum*, a popular tree used primarily as an ornamental and alleyway tree.

In the calibrated heat pulse method, the heat wave velocity is measured after a half second heat pulse has been radially injected as a line source into the tree. The heat is transported by convection with the sap and measurements of the heat wave velocity are made by special microbead thermistors exactly 15 mm downstream from the linear heat source (that is 15 mm higher up the tree (Figure 1)). Each thermistor is capable of measuring at 1 cm increments into the tree for a total of 6 cm (Figure 2). Programme control and measurement of thermistor signals are made by a datalogger (Campbell 21X) through the intermediary of a custom-built thermistor and heat pulse junction box (Ariel).

As the heat wave passes the thermistors, the time to maximum temperature (t_{max}) is recorded by the datalogger, giving the velocity of the heat between the linear heat source and the thermistor. The t_{max} values along with the areas of the presumed concentric rings of

similar sap flux in the tree (Figure 2) are used in the formula modified by Cohen *et al.*² to give volumetric sap flux (for formula see Appendix 1).

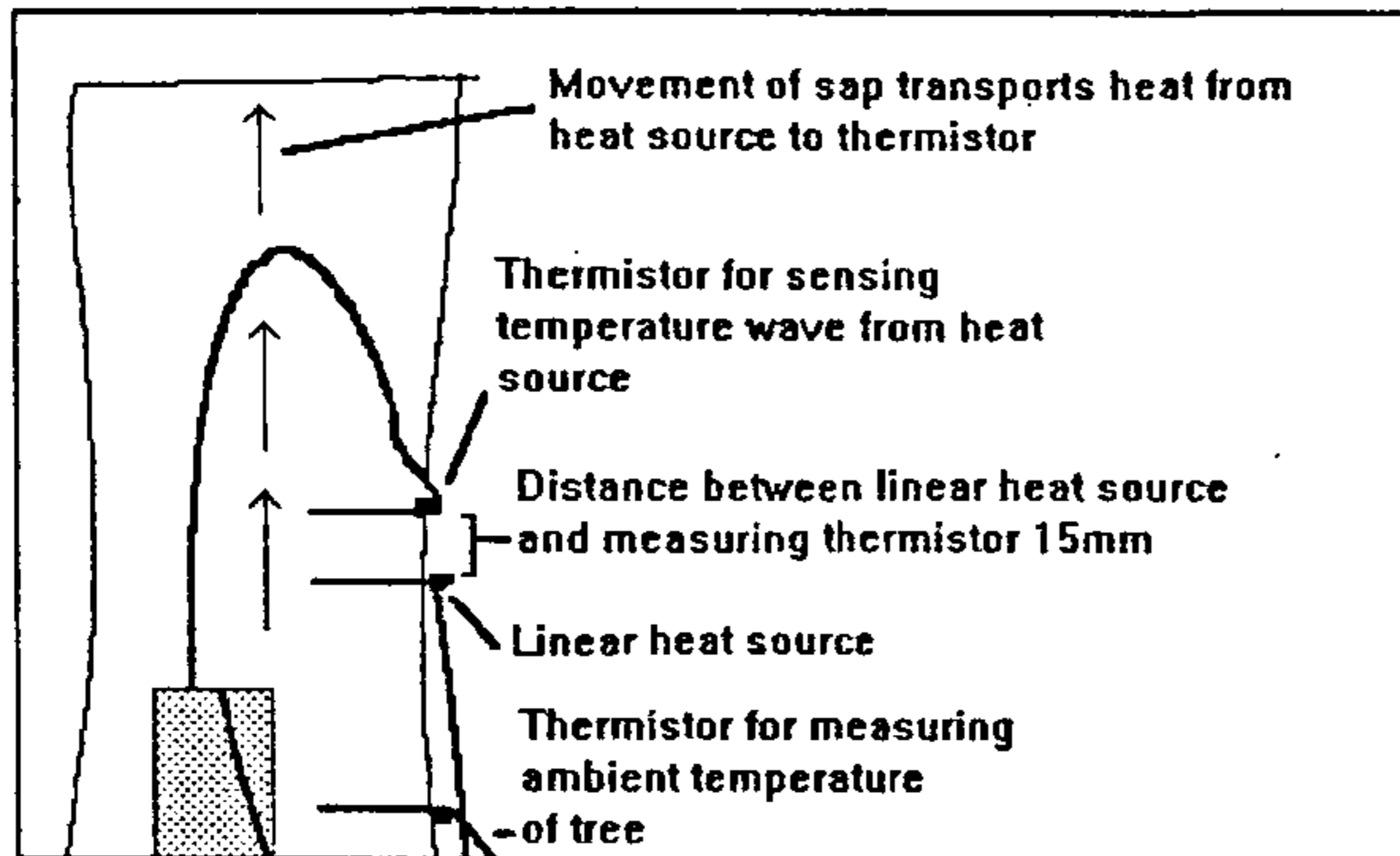


Figure 1. Positions of heater and thermistors in relation to sap stream.

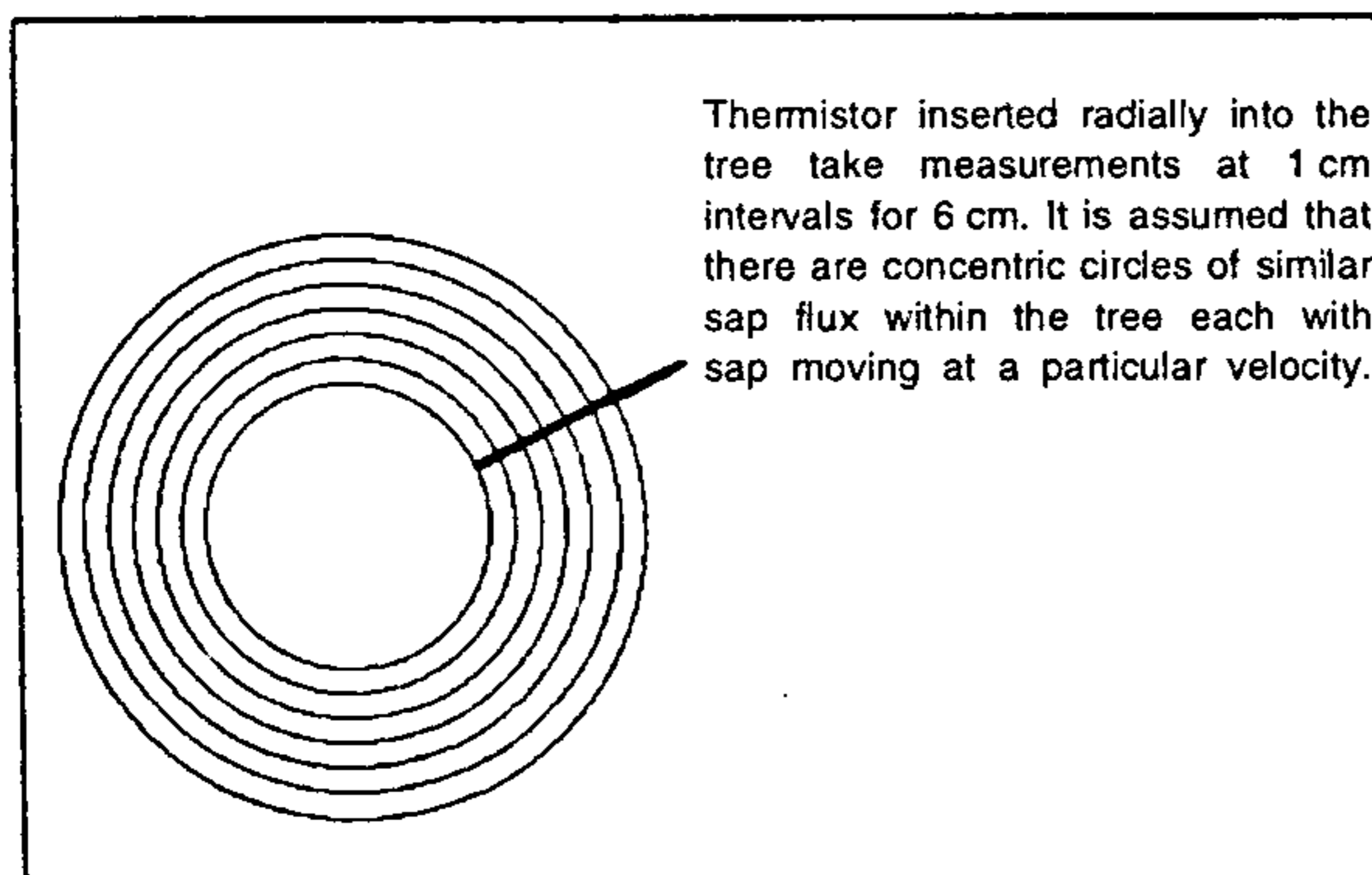


Figure 2. Presumed concentric rings of sap flux movement inside the tree.

When illustrated, the t_{max} values indicate how the tree responds to its environment. Figures 3 and 4 illustrate t_{max} values for *P. pterocarpum* and *A. auriculiformis* respectively, during March 1994. *P. pterocarpum* (Figure 3) responds very rapidly to the onset of light, almost reaching its maximum sap flux in two hours. In addition, all six microbead thermistors register a response. This indicates that sap flux occurs to a depth of 6 cm, possibly more, and that sap flux for all 6 concentric rings must therefore be calculated. A lateral cut through *P. pterocarpum* shows it to be largely composed of sapwood and confirms that sap flux can occur in all the 6 concentric rings that are measured.

A. auriculiformis (Figure 4) responds differently to *P. pterocarpum*. Its t_{max} graph indicates that only the two outermost rings of the tree are conveying sap as indicated by thermistors 1 and 2. This is again evident from a cross-section of the tree, which is largely composed of heartwood, apart from the exterior 1 or 2 cm. The t_{max} values indicate lower sap velocity and the curves are less pronounced. For these reasons it can be expected that *A. auriculiformis* transpires less than *P. pterocarpum*.

The t_{max} values indicate which rings of the tree transpire and during which hours of the day they transpire. Having determined this, it is possible to calculate the volumetric flow of sap in the tree. Sap flux in *P. peltophorum* starts rather abruptly from 0.7 litres between 7.25 h and 8.25 h to 7.2 litres between 8.25 h and 9.25 h (Figure 5). Maximum sap flux occurs between 13.25 h and 14.25 h and is about 12.4 litres. The outermost ring monitored by thermistor 1 conveys the most water during the day (21.8 litres), whilst thermistors 5 and 6 monitoring the innermost rings of the tree show similar sap fluxes of 5.5 and 5.7 litres per day. The total sap flux on March 14 is about 84.6 litres.

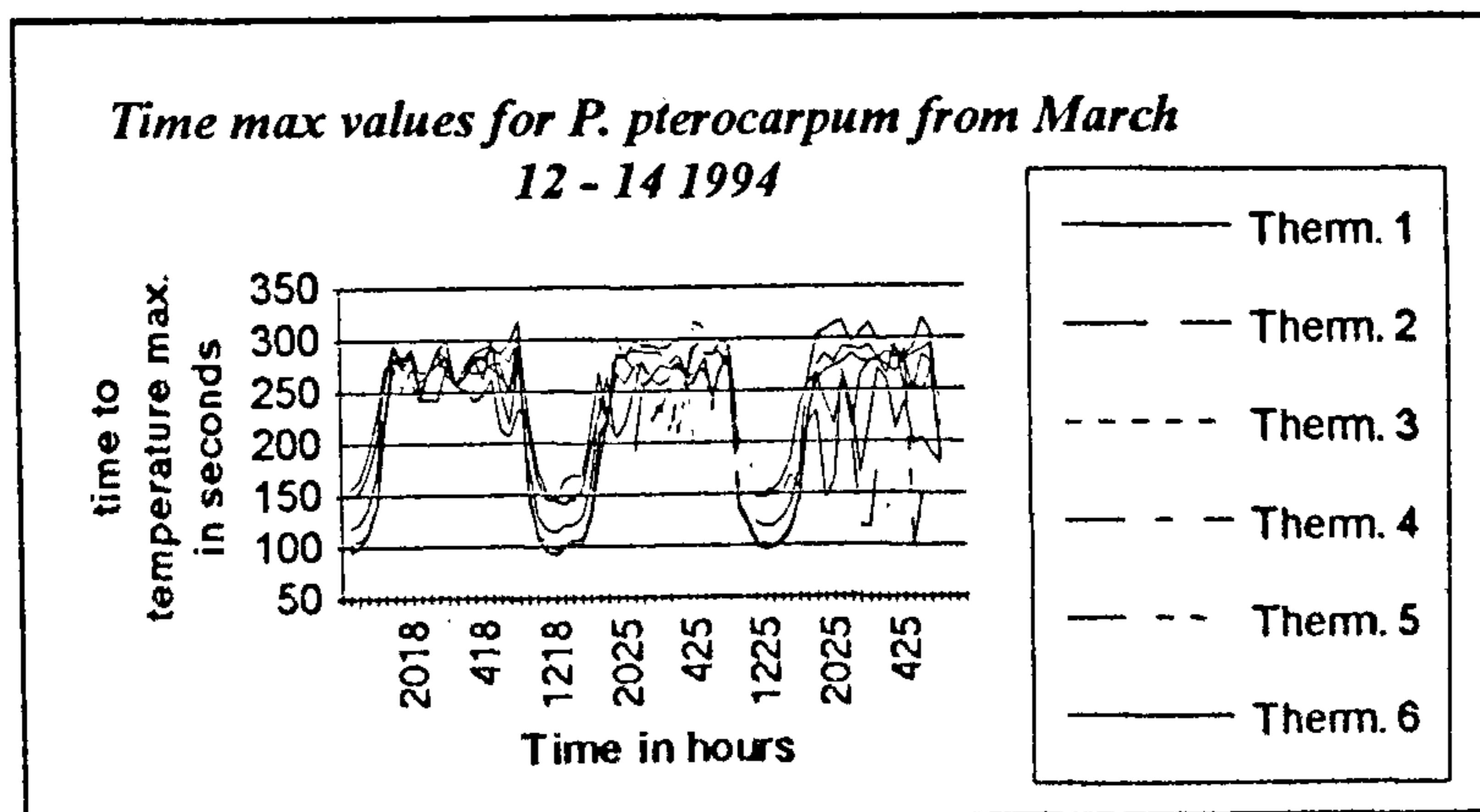


Figure 3. t_{max} values for *P. pterocarpum* in March 1994.

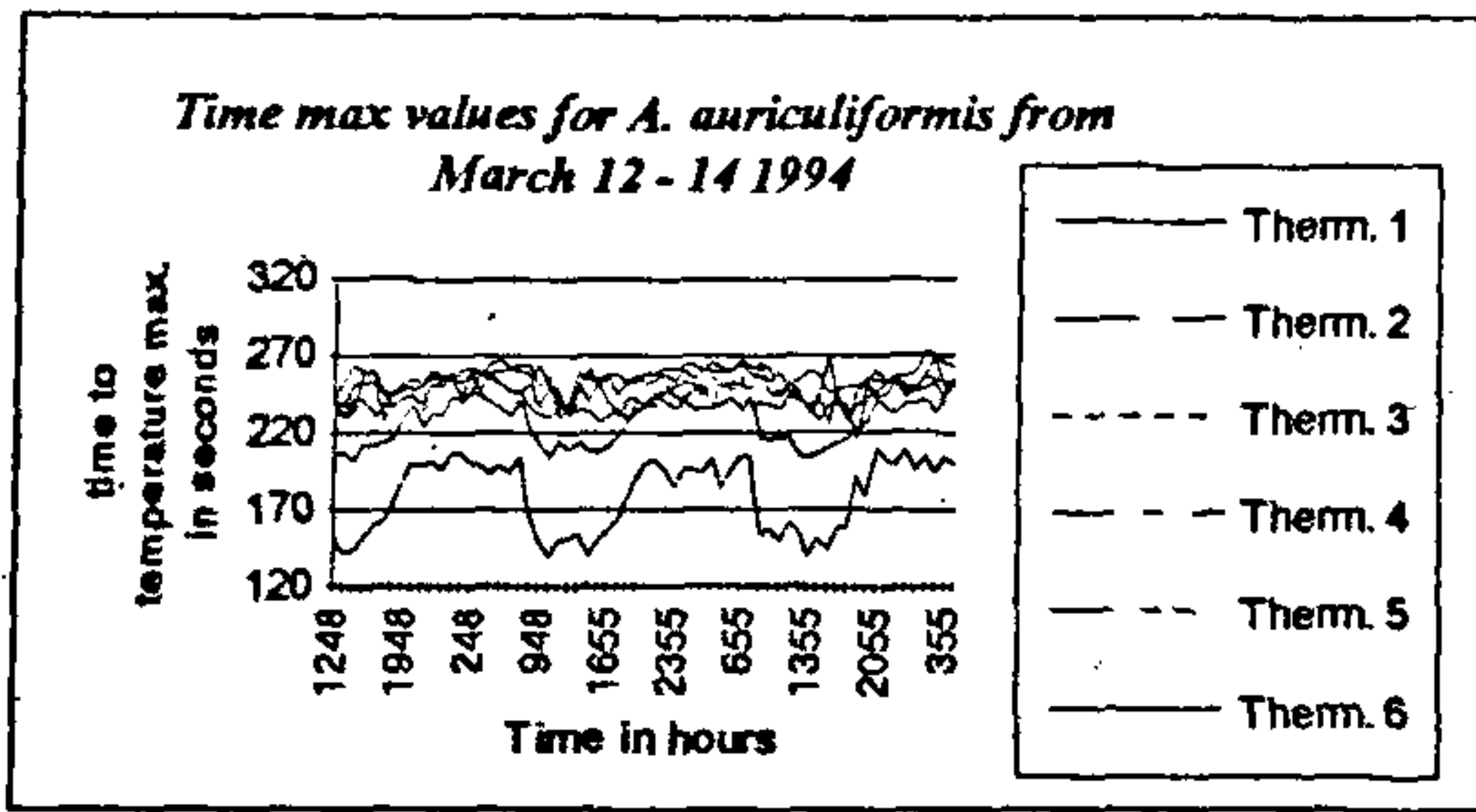


Figure 4. t_{max} values for *A. auriculiformis* in March 1994.

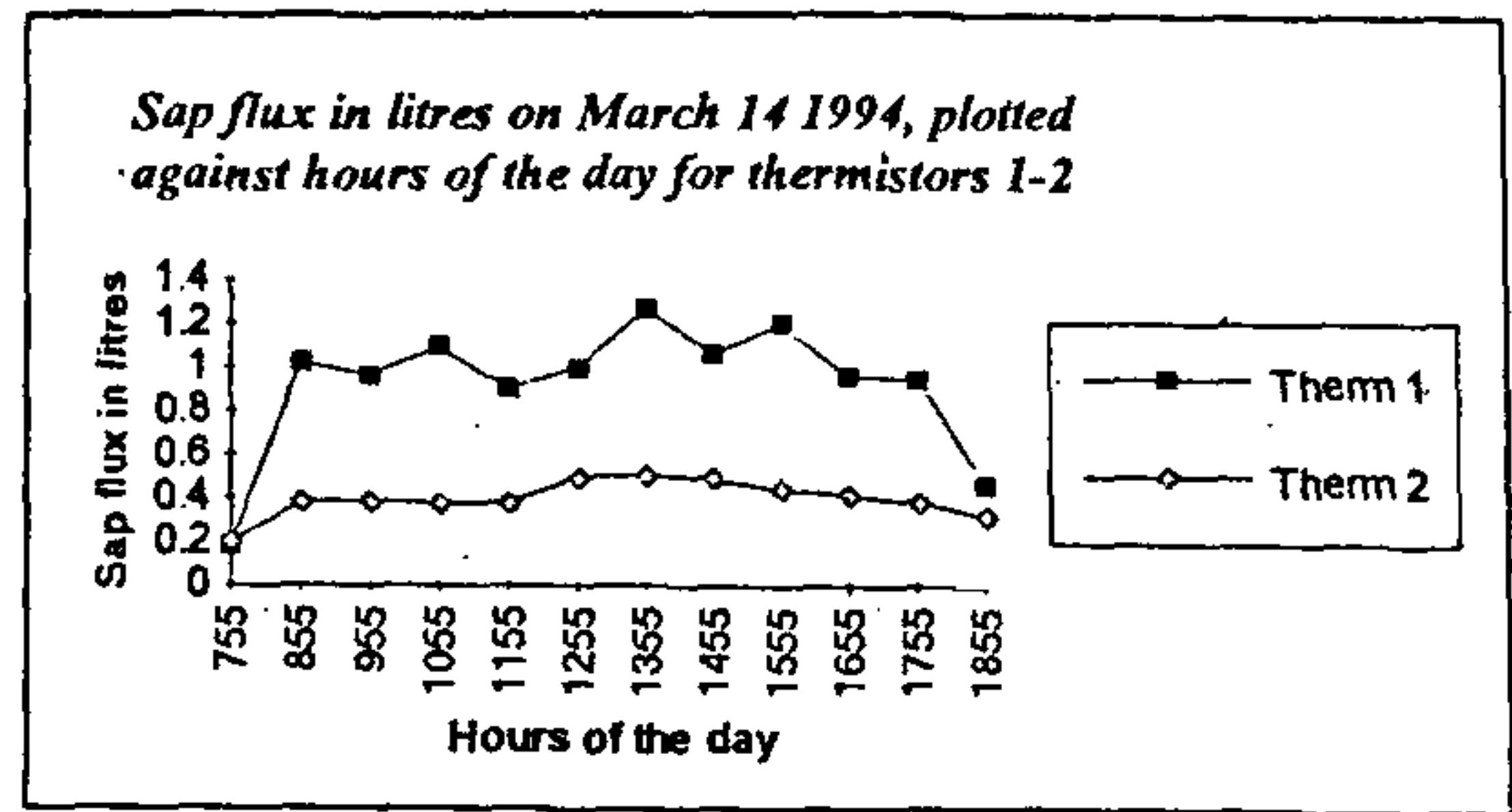


Figure 6. Sap flux for *A. auriculiformis* on March 14, 1994.

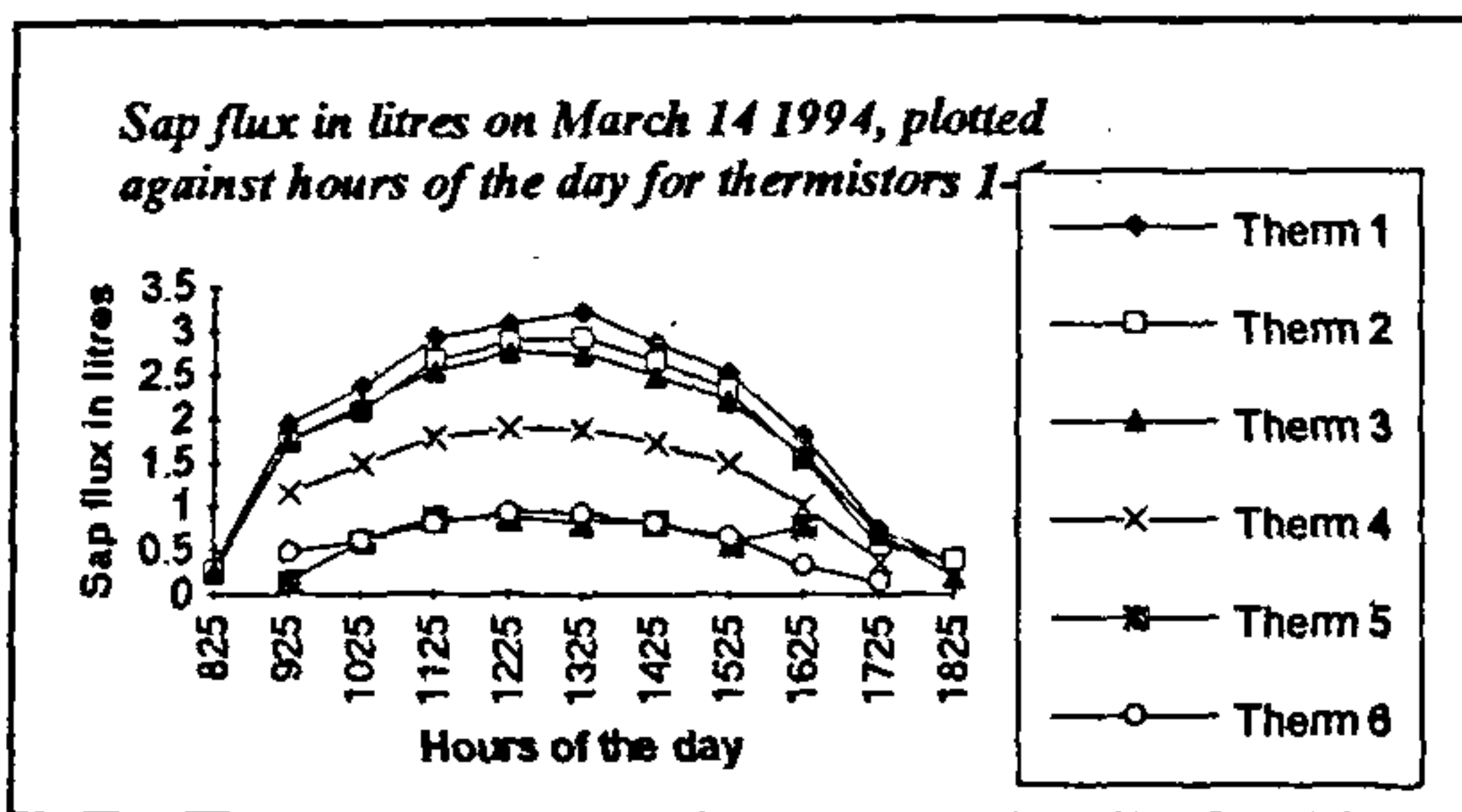


Figure 5. Sap flux for *P. pterocarpum* on March 14, 1994.

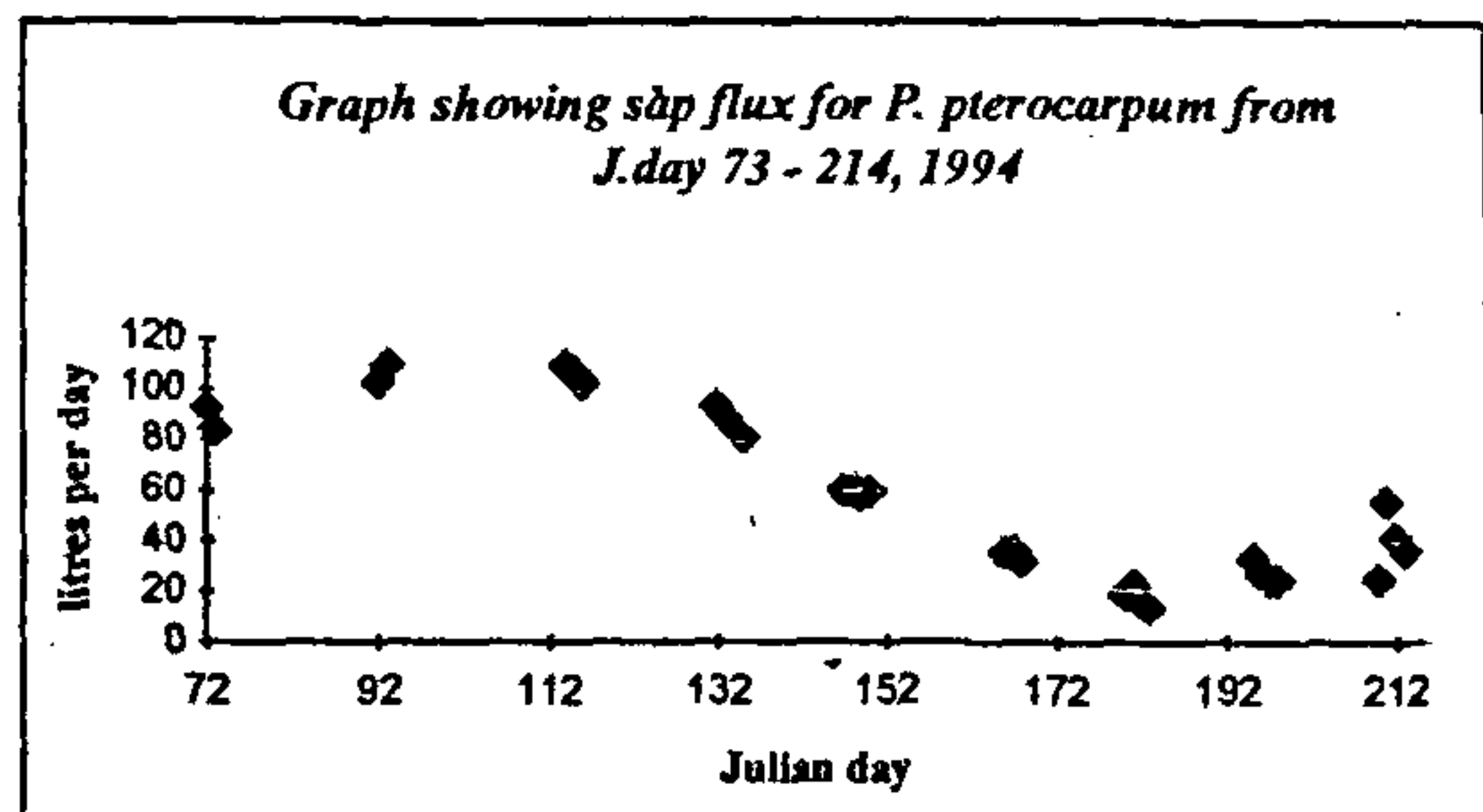


Figure 7. Sap flux for *P. pterocarpum* between March and July 1994. Each square indicates daily sap flux.

The case is rather different for *A. auriculiformis* (Figure 6) as only the 1st and 2nd thermistors indicate sap flux. The 4 inner rings show 'diffusivity' (the movement of heat through the woody material, without convective transport by sap) and indicate zero or very low sap flux. The calculations for sap flux therefore need to be made only for the outer 2 rings monitored by the 1st and 2nd microbead thermistors. It is evident that in *A. auriculiformis*, sap velocity is much lower than in *P. pterocarpum*. The curve is correspondingly less pronounced, showing that it is less responsive to light. Sap flux commences at about 7.55 h and during the first hour is about 0.9 litres. It reaches a maximum of 1.9 litres between 13.55 h and 14.55 h, declining to a stop at about 18.55 h. Total sap flux for 24 hours is about 16 litres.

The presence or absence of sunlight stimulates sap flux, particularly in *P. peltophorum* which is literally 'switched' on and off by sunlight, exhibiting a strong biological rhythm. Other variables, however, are also important in influencing sap flux, notably soil moisture and the physiological status of the tree (i.e. whether it is in leaf or bare).

Figures 7 and 8 show total daily sap fluxes for *P.*

pterocarpum and *A. auriculiformis*, from mid March to July (Julian days 73-214). In *P. pterocarpum* (Figure 7) sap flux increases from about 85 litres per day in mid March (Julian day 73) to about 110 litres per day by the latter half of April (Julian day 112). This is partially attributable to increasing leaf cover density (*P. pterocarpum* loses its leaves between December and February, but by February, March and April is in the process of leafing again), and the greater transpirative surface that is thereby created. Additionally, transpirative demand is also increased, as summer progresses and net radiation and dry bulb temperature rise. Sap flux therefore increases to whatever extent is permitted by the level of moisture in the soil. Thereafter total daily sap flux declines steadily due to decreasing soil moisture, as the rainless days of summer progress and the available soil moisture evaporates, percolates or is transpired by the tree. By the end of June (Julian day 181), sap flux is reduced to about 15 litres per day. After this, it starts to increase again, as the first rains of the SW summer monsoon augment soil moisture.

The pattern is different for *A. auriculiformis* (Figure 8). As the tree is almost evergreen, there is little influence of increasing leaf density on sap flux. Instead,

there is a steady decline from 14 litres per day in mid March (Julian day 72), to about 4 litres per day by the end of April (Julian day 112), as soil moisture brought by the 1993 NE winter monsoon declines. This basic level of sap flux remains unaffected by the first showers of the 1994 SW monsoon that started on Julian day 160.

Figures 9 and 10 show how these two trees respond to a sudden increase in soil moisture caused by an 11 mm rainfall at about 21.00 h on Julian day 210 (July 29). The t_{max} values for *P. pterocarpum* (Figure 9) on Julian day 210 before the rain falls, indicate maximum sap velocity at 14.03 h with a minimum t_{max} value of 166 sec. After the rain, the t_{max} values on Julian day 211 decrease from 166 sec to 122 sec at 12.09 h on Julian day 211, indicating a dramatic increase in the velocity of the sap. Of further note is that the 5th and 6th thermistors (5 and 6 cm deep) do not indicate sap flux during Julian day 210. However, the rain on Julian day 210 allows the 5th thermistor to start conveying sap once again on Julian days 211 and 212. (Note that during March when soil moisture was high, all 6 thermistors were indicating sap flux (Figure 3).) The decrease in t_{max} values at 21.06 h on Julian day 210 indicates that the tree might have absorbed water at night and that some sap flux is perhaps taking place although there is no transpiration. This may be due to an increase in the soil moisture potential after the rainfall, which has allowed water to move into the tree. The effect of the rain is short lived, as a steady decrease in sap flux is indicated by the increasing t_{max} values for Julian days 212 and 213. By Julian day 213, the 5th thermistor once again indicates absence of sap flux altogether.

A. auriculiformis (Figure 10), on the other hand, shows no such response to the rainfall on Julian day 210. Only the first thermistor shows a slight decrease in t_{max} values from around 180 sec on Julian day 210, to about 175 sec on Julian day 211, almost negligible when sap flux is calculated. The t_{max} values seem to show that sap flux is altogether absent, with only thermal 'diffusivity' occurring. Calculations with these values, however, still indicate small quantities of sap flux (Figure 8).

It should be emphasized that the discussion above revolves around only 2 of the 8 trees studied (1 for each species), and that intra-species t_{max} values (and thus intra-species sap fluxes) are not necessarily identical to the two examples used. This is illustrated in Table 1 which summarizes the total monthly sap fluxes (in litres) of all four *A. auriculiformis* and all four *P. pterocarpum* monitored between March and July 1994. The trees examined in the discussion above are indicated in the table as Aa3 and Pp3. The average sap flux for *P. pterocarpum* over the 5 months of measurements comes to 8.1 m³, whilst for *A. auriculiformis*, average sap flux over 5 months comes to 2.3 m³.

From the data in Table 1, it is evident that all four *A. auriculiformis* together transpired about 9.4 m³ of water between March and July 1994, whilst all four *P. pterocarpum* together transpired about 32.6 m³ of water over the same period. Rainfall in Auroville in 1994 was 1.15 m³ per m². Sap flux between March and July for *A. auriculiformis* as a percentage of the rainfall received

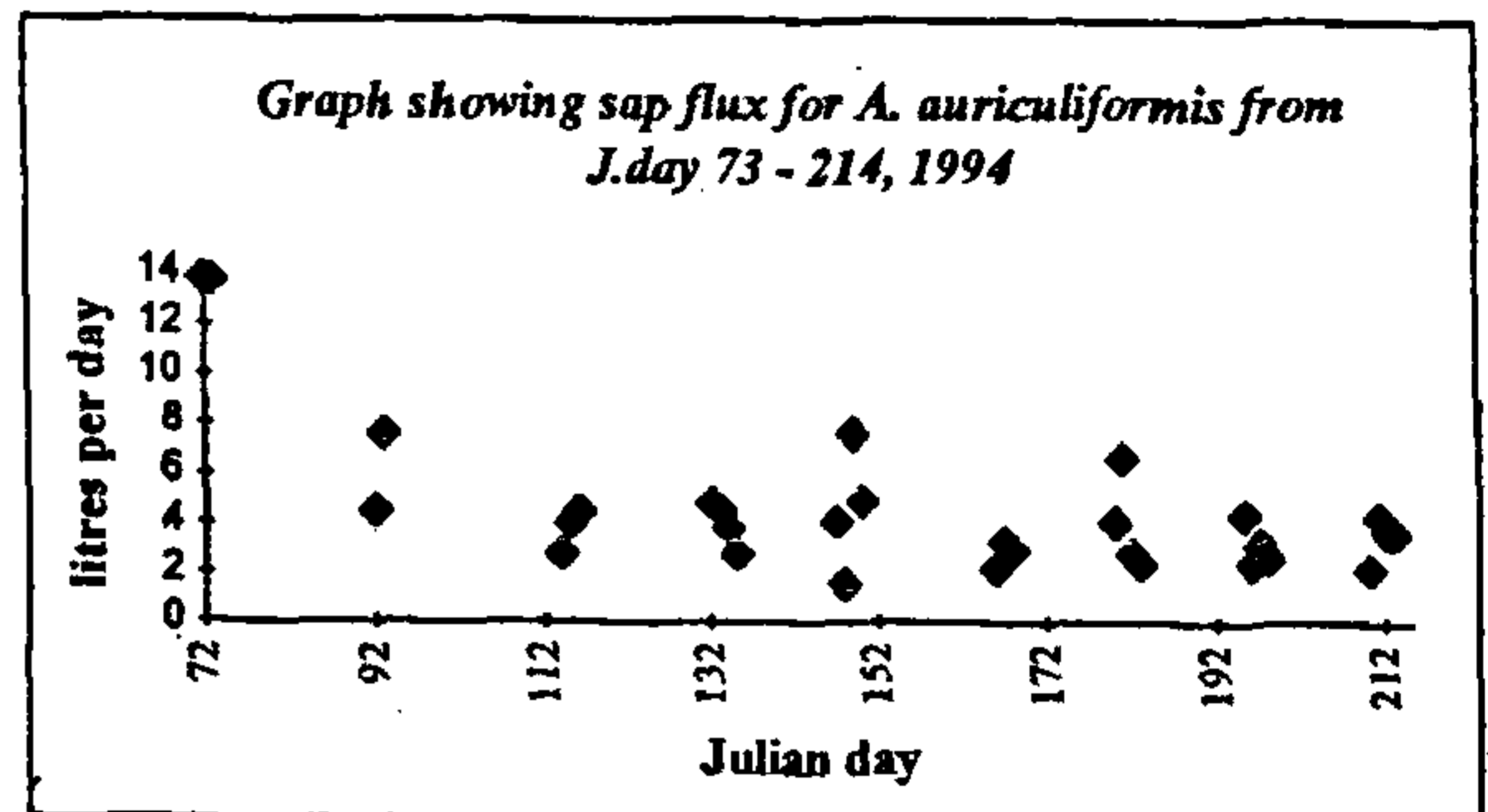


Figure 8. Sap flux for *A. auriculiformis* between March and July 1994.

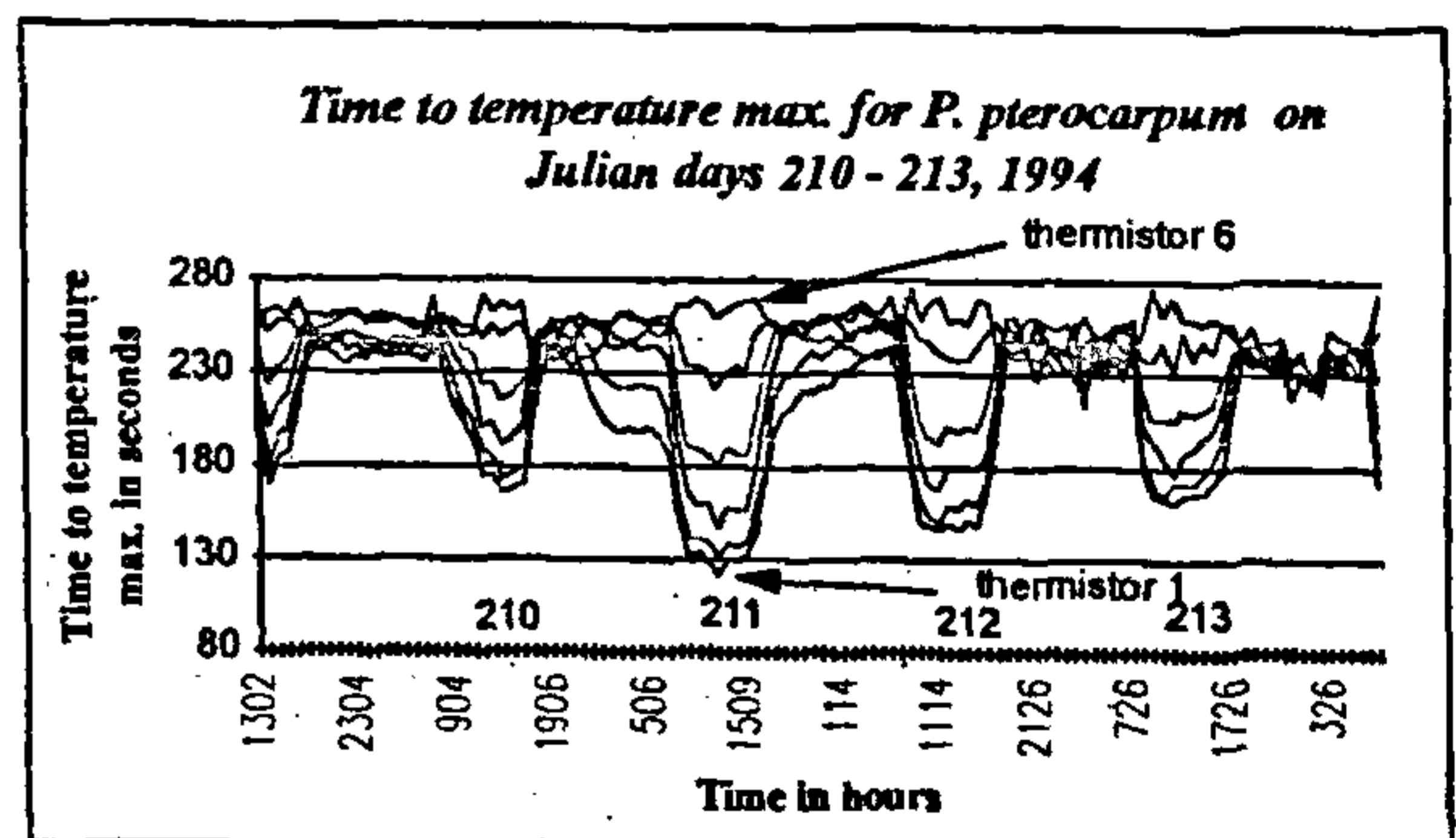


Figure 9. t_{max} values for *P. pterocarpum* in July 1994.

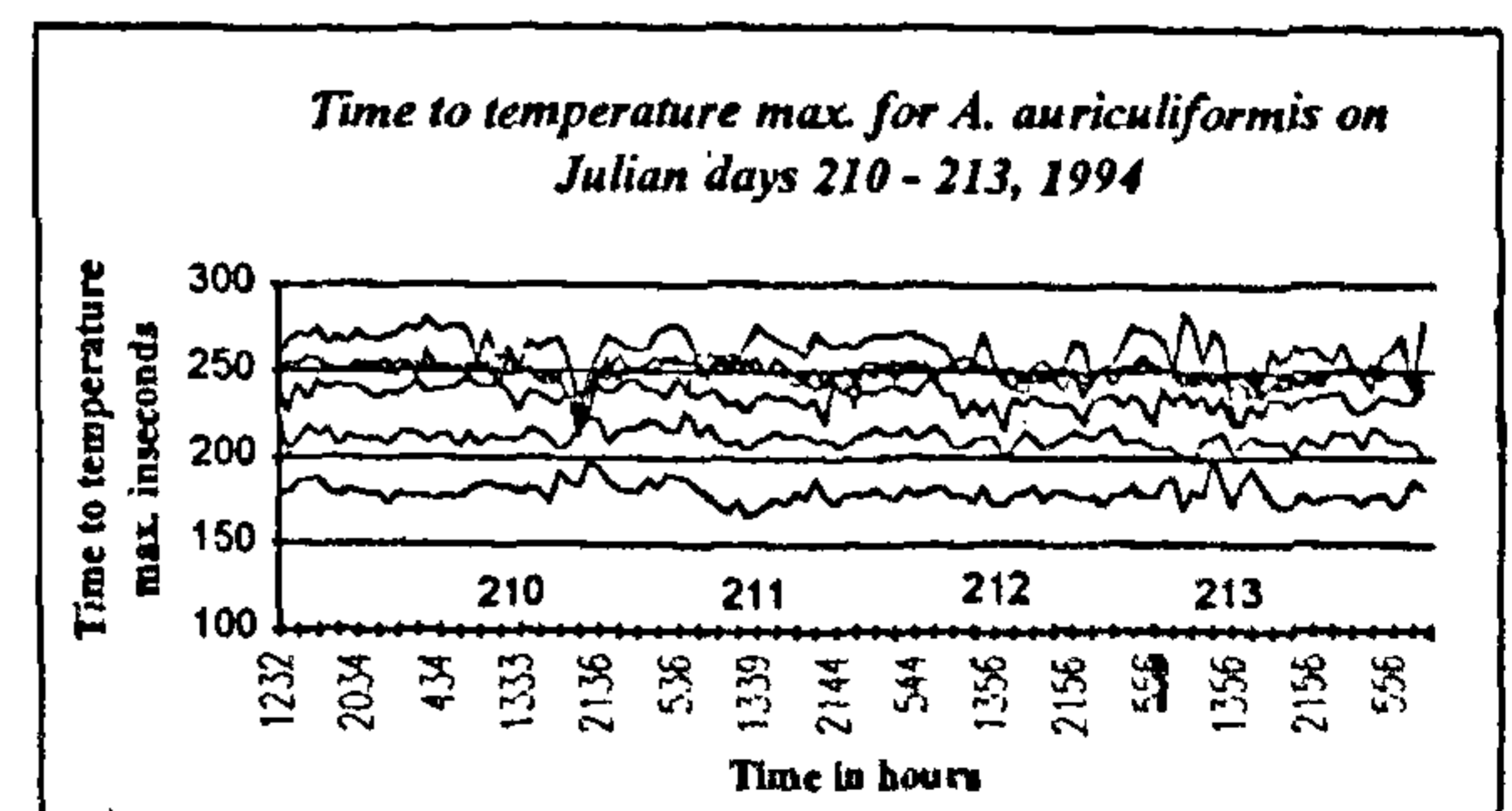


Figure 10. t_{max} values for *A. auriculiformis* in July 1994.

RESEARCH COMMUNICATIONS

Table 1. Total monthly sap fluxes for the eight trees monitored between March and July 1994

Tree no.	March (in litres)	April (in litres)	May (in litres)	June (in litres)	July (in litres)	For 5 months (in m ³)
Aa1	597	511	398	186	159	1.85
Aa2	745	753	321	381	237	2.44
Aa3	705	429	405	306	189	2.05
Aa4	1334	954	300	291	159	3.04
Average	845	662	356	291	186	2.34
Pp1	1338	2192	1326	1326	1329	7.82
Pp2	450	938	750	282	264	2.68
Pp3	2751	3568	2625	720	912	10.58
Pp4	1410	3128	3045	1701	2198	11.48
Average	1487	2457	1937	1007	1176	8.14

upon the canopy area of all eight trees (276 m²) is therefore about 2.9%. For *P. pterocarpum* the figure is about 10.4%. During the five-month study, the eight trees together transpired about 13.3% of the rainfall that fell upon their canopies in 1994.

Assuming that the seven unmeasured months might give equivalent values, these eight trees would, during 1994, transpire 31.1% of the rainfall falling on their canopies. This figure is naturally unrealistic. *P. pterocarpum*, for example, sheds its leaves during winter putting a stop to transpiration altogether, whilst soil moisture and transpirative demand undergo extensive changes during the monsoons.

As runoff from the research plot is minimal, it can be assumed that the 68.9% of the rain not transpired by the trees infiltrates into the soil and percolates. What proportion of this reaches groundwater and what proportion of this is evaporated directly from the soil or is transpired by understorey vegetation remains to be seen.

Attempts to quantify the hydrological impact of reforestation in Auroville on the water balance of the local soil and groundwater should ideally include measuring runoff and evaporation from 'bare' as well as reforested areas. It is also important to evaluate with advanced research methods, what proportion of the sap flux comes directly from groundwater sources and what proportion of it comes from soil moisture³.

In conclusion, the study has allowed sap fluxes in two tree species, *P. pterocarpum* and *A. auriculiformis*, to be quantified, showing that sap flux in *P. pterocarpum* is significantly higher than in *A. auriculiformis* (Table 1). Changes in daily sap flux between March and July 1994, were evident for both *P. pterocarpum* (Figure 7) and *A. auriculiformis* (Figure 8). In *P. pterocarpum* the onset of the SW monsoons stimulated an increase in sap flux. In *A. auriculiformis* no such response occurred

presumably because the necessary soil moisture level had not yet been attained by the time measurements ended in July.

To some extent the study has also unveiled the inner dynamics of water movement in *P. pterocarpum* and *A. auriculiformis*. When soil moisture was plentiful, sap flux in *P. pterocarpum* occurred to a depth of 6 cm (Figure 3) and in all 6 concentric rings (Figure 2), whilst in *A. auriculiformis* sap flux occurred to a depth of only 2 cm (Figure 4) and was confined to the outer 2 concentric rings (Figure 2). This pattern changed as soil moisture decreased during the rainless summer months. In *P. pterocarpum*, sap flux stopped in the 2 innermost concentric rings and occurred in only the 4 outermost concentric rings (Figure 9). In *A. auriculiformis*, only thermal 'diffusivity' in the 2 outer sap conveying rings occurred during the dry summer months (Figure 10), indicating that ideally more sensitive equipment is needed to measure sap flux at such low velocities.

With further research on other tree species, it will be possible to know how reforestation as a land use compares with agricultural or domestic land use, or with just leaving the ground bare. In particular, it will be possible to know which trees and how many trees to introduce into which hydrological situations. In an area with scarce water resources for example, it might be more beneficial to introduce trees which are frugal users of water, like *A. auriculiformis*, whilst trees with high transpirative capabilities like *P. pterocarpum* might be better utilized in areas prone to water logging. Concerning Auroville and coastal areas in general, where urbanization and population are rapidly increasing and salt water intrusion and falling groundwater levels threaten to bring environmental catastrophe, trees selected for their transpirative characteristics and planted in strategically chosen areas could do much to redress the hydrological balance.

Appendix 1

Marshall's formula as modified by Cohen *et al.*² is quoted below:

'The temperature elevation, T , produced by the heat pulse after time, t , and at a distance $r = (x^2 + y^2)^{0.5}$ from the line heater, is given by (Marshall¹).

$$T = H/4\pi pck \exp((x-Vt)^2 + y^2)/4kt, \quad (1)$$

where H is the heat output per unit length of the heater, and p , c , and k are the density, specific heat, and the thermal diffusivity of wet wood, respectively. The heat wave convective velocity, V , is defined as:

$$V = (p_1 c_1 / pc) J_1, \quad (2)$$

The function defined by equation (1) has a maximum occurring at t_{\max} when the first derivative of eq. (1) is equal to zero. This condition yields,

$$V = (r^2 - 4kt_{\max})^{0.5}/t_{\max} \quad (3)$$

For a given value of r , and with known physical and thermal properties of the live wood, the measurement of t_{\max} in eq. (3) allows the computation of the water flux J_1 , in eq. (2). The only property that is difficult to determine is the thermal diffusivity, k of the live wood. With $V=0$, eq. (3) yields,

$$k = r^2/4t_{\max} \quad (4)$$

Consequently, k can be determined when no convective transport is taking place. In order to determine the volumetric flow, F , the water flux, J_1 must be integrated over the cross-sectional area of the stem,

$$F = fJ_1 ds, \quad (5)$$

where ds is the element of stem area in which J_1 has been determined.'

1. Marshall, D. C., *Plant Physiol.*, 1958, 33, 385-396.
2. Cohen, Y., Fuchs, M. and Green, G. C., *Plant, Cell Environ.*, 1981, 4, 391-328.
3. Adar, E. M., Gev, I., Berliner, P. and Issar, A. S., *J. Arid Land Studies*, 1995, 5, 259-262.

ACKNOWLEDGEMENTS. I am grateful to David Nagel, Ed Giordano, Silvie Rousseau, Yaap den Hollender, Rauf Ali, Carston, Steve, Bernard Borg, Robby, Bobby and Goupie for their inputs and to all the Aurovillians who have helped out. I thank the anonymous referee for his extensive inputs.

Received 23 April 1996; revised accepted 6 December 1996

Bioleaching of copper from chalcopyrite ores coated with polyaniline film

S. A. Mallick* and A. K. Dasgupta**

Regional Agriculture Research Section, S.K. University of Agricultural Sciences and Technology, R. S. Pura, Jammu Tawi 181 102, India
**Department of Biochemistry and Biophysics, University of Kalyani, Kalyani 741 235, India

A simple method of extracting copper and iron from chalcopyrite ore using the bacterium *Thiobacillus ferrooxidans* is reported. By surface modification of the ore and using a thin polyaniline film, the rate of bioleaching can be increased considerably. The film acts as a coating to the heterogeneous ore surface, leaving the catalysable sites more frequently exposed to microbial attack. The inhibitory effect is due to formation of jarosites, and is found reduced in the coated ore samples. This may be due to ferric hydroxide formed within the film coat during leaching.

SEVERAL reports pertaining to improvement of bioleaching process have appeared in the literature. The effect of detergents^{1,2} and passing of mild electric current^{3,4} etc. have been reported to be beneficial for the recovery process. On the other hand, the adverse effect of detergents⁵ has also been reported. Leaching primarily involves a direct pathway⁶⁻⁹, wherein *Thiobacillus ferrooxidans* attacks the ore mineral causing leaching. Thus an alteration of the ore-bacteria interface would affect

leaching rate either positively or negatively. Murr and Berry¹⁰ observed no preferential adhesion of cells of *T. ferrooxidans* to specific surface features such as steps or dislocations, needed both for molybdenum sulphide and chalcopyrite. However, higher growth rate was observed at the inclusions. As the surface of the ore dictates the rate-determining factors of leaching, in the present work premise the dislocation sites were artificially exposed to microbial attack. Another reason for following this procedure was that gangue material containing oxides of magnesium, calcium and aluminium may be inaccessible to microbial populations, and by preventing the catalytically inactive growth, one could arrest the extent of precipitation of jarosites (precipitation of ferric hydroxide complex associated with growth of *T. ferrooxidans*).

The microorganism, *T. ferrooxidans*, is a chemolithotrophic bacteria deriving its energy from ferrous oxidation reaction utilizing carbon dioxide as the main carbon source. The strain of *T. ferrooxidans* in ATCC19859d (supplied by Dr David Holmes, USA) was repeatedly subcultured in 9 k medium¹¹ (ammonium sulphate, 3 g;

Table 1. Composition (proportion-wise) of polyaniline coated chalcopyrite ore samples

Sample	Aniline (M)	Ammonium persulphate (M)	Chalcopyrite ore (g)
1	0.1	0.73000	0.5
2	0.1	0.07300	0.5
3	0.1	0.00073	0.5
4	0.5	0.07300	0.5

*For correspondence