4 Transpiration by trees on land with shallow watertables: a survey of the literature suggests that transpiration is affected by soil texture

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Summary

This chapter surveys the literature relating site conditions to wateruse by stands of trees growing above shallow watertables. Analysis of the data suggests that transpiration by stands of trees is affected by E_{pan}, depth of the watertable, planting density and soil texture.

4.1 Introduction

Across the mediterranean agricultural region it is generally accepted that rising watertables have resulted from increased deep drainage after clearing of native vegetation and its replacement with crops and pastures that use less than the incident rainfall.

As far as we are aware, the first suggestion that revegetation of the landscape with trees may reverse the trend of rising watertables is comparatively recent. Greenwood and Beresford (1979) suggested that secondary salinisation (resulting from watertable rise) could be ameliorated using a variety of options including: (a) complete re-afforestation, (b) strategically placed plantations of salt-tolerant ground cover or deep-rooted trees, (c) conventional plantations of commercial softwoods, and (d) more widely spaced plantations to allow agriculture to be combined with forestry (agroforestry).

Intuitively, the arguments of these authors in favour of revegetation appear obvious and uncontestable. However, to implement this agenda in the more arid parts of Australia, two practical challenges must be addressed: (i) revegetation must occur while maintaining and enhancing agriculture (after all, the costs of revegetation will be met primarily from the profits of farming enterprises), and (ii) trees must be planted in such locations that they achieve the greatest salinity abatement benefit for the investment made.

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Until now, the main focus of research in revegetation for salinity abatement has been in improving the targeting of trees to points in the landscape in which more water must be used (eg. Farrington and Salama 1996). As a result of these efforts, there are now several case studies where the planting of trees has been shown to reduce deep drainage and alleviate salinity (eg. Engel 1988; George 1990).

This chapter stems from inquiry in another direction. In particular, we have been concerned with how site conditions affect the ability of trees to use water. Until recently the bulk of the evidence on transpiration by trees has been of questionable integrity, being based either on extrapolation from limited daily observations using ventilated chambers, or on watertable drawdown (reviewed by Raper (1997)).

However, recent technical developments in the ‘heat pulse’ technique (Durham and Hatton 1989) now enable the continuous measurement of transpiration in trees for periods of months or years. This technique therefore provides an increasing body of data which can be used to assess the impact of site conditions on tree wateruse.

4.2 Materials and Methods

Sites

The literature relating to annual transpiration by stands of trees in mediterranean environments is relatively small. Recent reviews by Thorburn (1996) and Raper (1997) list 18 and 11 studies, respectively. In these previous works, the approach has been synthetic or inclusive in nature. In contrast, we have taken an analytical approach and have only adopted data from studies that satisfy critical ‘quality criteria’. Specifically, studies have been adopted where:

1 Transpiration has been measured using the heat pulse technique. Thus, we have not used studies where annual transpiration has been estimated from limited numbers of daily readings of

transpiration using ventilated chambers (Greenwood et al. 1981, 1982, 1985). Neither have we included studies where annual transpiration has been estimated from groundwater monitoring (Hookey et al. 1987; George 1990).

2 Transpiration has been measured for sufficient period to allow a reasonable estimation of annual transpiration.

3 Data are available (or calculable) for pan evaporation, soil texture, and average depth and salinity of the groundwater.

4 Data are applicable to stands of trees, not isolated trees (eg. Greenwood et al. 1981, 1982) or stands with an unmeasured understorey (eg. Dunn and Connor 1993; Farrington et al. 1994).

5 Data from trees grown on waterlogged sites (average watertables less than 1 metre) have not been considered.

On the basis of these criteria, transpiration data have been gathered from seven sites using published sources and our own unpublished data. These investigations are summarised below.

Study 1. Eucalyptus camaldulensis *near Wubin in Western Australia (Marshall et al. 1997; Akilan et al. 1997).* In this study trees were planted on a sandplain seep at a density of about 1100 stems/ha. Water-use measurements were made on two clones at an upslope location and a downslope location. We refer here to the data from the upslope location; the downslope trees are regarded as having been too waterlogged for our purposes. Transpiration measurements were begun when the trees were about 9 years old (May 1991) and continued for one year (April 1992). The trees had mean heights of 15 m and mean trunk diameters of 21 cm (Clone M80) and 18 cm (Clone M66). Depth and salinity of groundwater was measured at three-weekly intervals. Pan evaporation was measured at the Wongan Hills Agricultural Station, about 50 km to the south-east of the site.

Study 2. Eucalyptus camaldulensis *Dehnh. about 160 km east of Brisbane in Queensland (Fraser et al. 1996).* This paper refers to studies at three sites in south-eastern Queensland; however, we focus on ‘Site 2’ where *E. camaldulensis* was planted at a density of 500 stems/ha (G. Fraser, pers. comm., 1998). Transpiration measurements commenced in Spring 1994 (when the trees had an average height of 5.7 m) and continued until Summer 1995 (about 450 days). The site had a clayey texture above the watertable (G. Fraser, pers. comm., 1998).

Study 3. Eucalyptus camaldulensis *Dehnh. near Bakers Hill in Western Australia (Salama et al. 1994).* In this study measurements were made in a 10-year-old plantation growing on a sandy clay lateritic soil. The original plantation had been established at a density of 1111 stems/ha; this was reduced to 580 stems/ha seven years before the start of measurements. The trees in the stand were categorised into three groups (T1, T2 and T3, DBH 18.0, 17.3 and 13.4 cm respectively) on the basis of visual estimates of leaf area. Transpiration measurements were made between October 1990 and March 1992 on one standard tree from each group. The wateruse of the plantation was then estimated based on the relative proportions of T1, T2 and T3 trees in three regions of the plantation (C1, C2 and C3). We focus here on the C1 and C2 regions, for which water-table depth and salinity data are available (C1 – well Y1; C2 – assumed to be the average of wells Y2 and Y3). Pan evaporation at this site was estimated using ESOCLIM, a program that estimates average E_{pan} in Australia based on latitude, longitude and elevation (Ian Foster, pers. comm., 1998).

Study 4. Acacia nilotica *near Tando Jam in Sindh Province, Pakistan (Khanzada et al. 1998).* We refer to two data sets from this study. Site A had a stand of trees established in 1991 at about 800 stems/ha. Transpiration measurements began in March 1994 (when the trees had an average trunk diameter of 10 cm) and continued until February 1995 (when the trees had an average trunk diameter of 12.3 cm). Site B had a stand of trees established in 1991 at 2500 stems/ha. Transpiration measurements commenced in March 1995 (when the trees had a trunk diameter of 9.9 cm) and continued until February 1996 (when the trees had a trunk diameter of 11.5 cm).

Study 5. Eucalyptus camaldulensis *at the Nuclear Institute for Agriculture and Biology Research Station, Pacca Anna, Punjab Province, Pakistan (ACIAR Project 9316, 1996).* In this study, measurements were made on a plantation growing on a sandy loam soil with shallow groundwater of salinity 5 dS/m (J. Morris, pers. comm., 1997). The trees had been planted in 1993 at a density of 2500 stems/ha. Transpiration measurements were made between March 1995 and March 1996 on two plots on which the depth to the watertable differed. Trunk diameters were 3.4 cm (shallow watertable) and 4.1 cm (deeper watertable) at the start of the measurements, and were 5.4 cm (shallow watertable) and 6.2 (deeper watertable) at the end of the measurements.

Study 6. Eucalyptus microtheca *at the Nuclear Institute for Agriculture and Biology Research Station, Lahore, Punjab Province, Pakistan (ACIAR Project 9316, 1996).* We refer to measurements made on a block of trees planted in 1990 at a density of 2000 stems/ha. The groundwater at the site was ca 1.5 m deep and had a salinity of 3 dS/m (J. Morris, pers. comm., 1997). Transpiration was measured between March 1994 and March 1995. Trunk diameters were 7.7 cm at the start of the measurements and 9.1 cm by the end of the measurements.

Study 7. *Blocks of* Eucalyptus camaldulensis *and* Casuarina cunninghamiana *planted at the Girgarre Evaporation Basin in north-central Victoria (ACIAR Project 9316, 1996).* Measurements were made on large blocks of trees planted in 1989 at a density of 625 stems/ha. The soil was a clay loam with a heavy clay B horizon and a watertable at 1–3 m. Transpiration measurements began in July 1994 (when the *E. camaldulensis* and *C. cunninghamiana* had trunk diameters of 10.5 and 10.2 cm, respectively) and continued until August 1996 (when the *E. camaldulensis* and *C. cunninghamiana* had trunk diameters of 12.7 and 14.5 cm, respectively). Pan evaporation at this site was estimated using ESOCLIM as previously described.

Analysis of data

Stepwise multiple regression analysis (Genstat 5, Rothamsted Experimental Station) was used to determine the effects on the transpiration by stands of trees of: planting density (area per tree), soil variables (texture, depth and salinity of groundwater), and climate (E_{pan}).

4.3 Results

Raw data

Table 4.1 shows the raw data available to us after our screening of the literature (12 points from 7 sites). The data set was not ideal for correlational analysis, being small in size, having a limited range in one critical variable (the salinity of the watertable), and having a partial confounding between the soil texture and planting density variables (discussed below).

Effects of E_{pan}

Following a preliminary viewing (Figure 4.1), it appeared reasonable to pool the data into two soil textural groups: clays; and sands and loams. The accumulated analysis of variance (see Figure 1) showed that transpiration on an areal basis was significantly affected by E_{pan} and soil texture group. However, there was no significant difference (P = 0.191) in the slopes of the relationships between T and E_{pan} for the two soil textural groups (see Figure 1). Visual inspection of the data suggested that the lack of significance of the interaction may have been due to the small size of the data set. We therefore fitted and tested the significance of separate linear

Table 4.1 Rates of tree wateruse (T) measured using the heat pulse method.

Study	Species	T (mm/year)	E_{pan} (mm/year)	T/E_{pan}	Soil texture	Mean water table depth (m)	Mean water table salinity (dS/m)
1	*E. camaldulensis* – clone M66	1334	2032	0.66	sand	1.16	9.0
	E. camaldulensis – clone M80	1680		0.83			
2	*E. camaldulensis*	≈460	2430	0.189	clay	3.0	6.2
3	*E. camaldulensis*	307	2025	0.152	sandy clay	4.5 (Y1)	6.2 (Y1)
		416		0.205		3.0 (mean of Y2 and Y3)	9.0 (mean of Y2 and Y3)[a]
4 (Site A)	*A. nilotica*	1248	2650	0.471	silty loam	1.3	20
(Site B)	*A. nilotica*	2225		0.84		2	1.5
5 (Site A)	*E. camaldulensis*	1181	1646	0.72	sandy loam	1.5	5
(Site B)		1090		0.66		3	5
6 *E. microtheca*		1048	1618[b]	0.65	loam	1.5	3
7 *E. camaldulensis*		340	1350	0.252	clay	2	17
C. cunninghamiana		350		0.259			

[a] These values are from Salama (pers. comm., 1997).
[b] R.H. Qureshi (pers. comm., 1997).

regressions for the two textural groups (Figure 4.1). T-tests on the standard errors of the slopes of these lines showed that the slope of the response of the clay group was not significantly different from zero ($P = 0.779$), whereas the slope of the response of the (sand and loam) group was significantly different from zero ($P = 0.034$).

Effects of the depth and salinity of the groundwater

Previous researchers have noted that the transpiration by trees on areas with shallow watertables should be affected by the depth and salinity of the groundwater (Thorburn 1996; Raper 1997). A multiple regression analysis was therefore conducted to test the significance of these factors. In this analysis, account was taken of the effect of E_{pan} on T by treating T/E_{pan} as the dependent variable. We also considered the possibility that the effects might be due to the lower planting densities (larger areas per tree) in the clay group than in the (sands and loams) group.

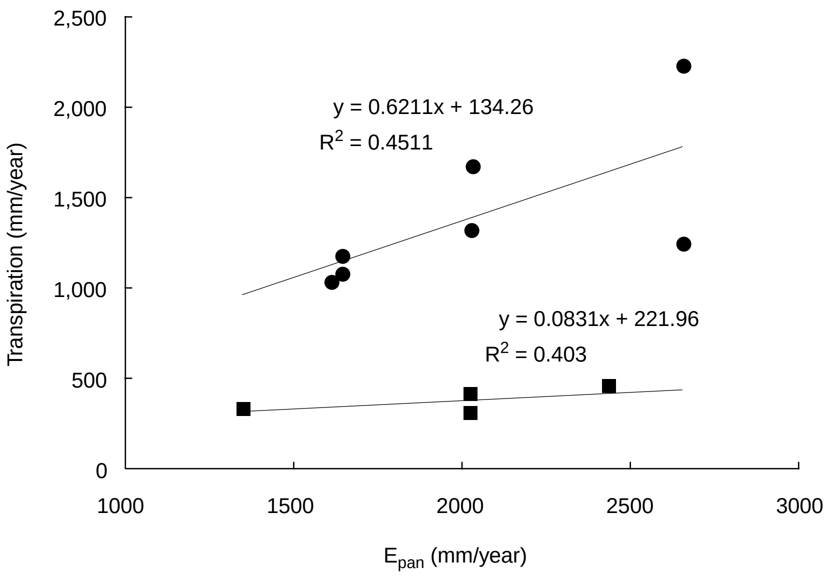
The correlation coefficients for the linear relations between T/E_{pan}, depth of the watertable, salinity of the groundwater and area per tree are shown in Table 4.2. T/E_{pan} was significantly affected by the depth of the watertable ($P < 0.05$) and the planting density ($P < 0.01$). However, there was no significant effect of the salinity of the groundwater; this was presumably because of the narrow range of groundwater salinities in our data set (previously alluded to).

Table 4.2 Correlation coefficients (r) for the interactions between T/E_{pan}, depth of the water table (m), salinity of the groundwater (dS/m), and area per tree (m^2). Superscript letters denote the levels of significance as follows: ns = not significant; * = significant at the 95% level; ** = significant at the 99% level.

Interaction	T/E_{pan}	Depth of water table	Salinity of groundwater	Area per tree
T/E_{pan}	1.000	–	–	–
Depth of water table	-0.635^{*}	1.000	–	–
Salinity of groundwater	-0.414^{ns}	-0.254^{ns}	1.000	–
Area per tree	-0.919^{**}	0.478^{ns}	0.498^{ns}	1.000

Figure 4.1 Effect of soil texture on the relationship between transpiration by stands of trees and E_{pan}. Textures are: sands and loams, ●; clays, ■. The outcomes of the accumulated analysis of variance were as follows:

Dependent variable: transpiration	df	variance ratio	P-value
+ E_{pan} (overall slope)	1	12.69	0.007
+ Soil texture group (different intercepts)	1	33.62	‹0.00 1
+ E_{pan}*Soil texture group	1	2.04	0.191



Effects of soil texture group, area per tree and depth of the groundwater

In the accumulated analysis of variance, the significance of variables depended on the order in which ‘soil texture group’ was added to the model. When ‘soil texture group’ appeared after ‘depth of watertable’ and ‘area per tree’, there were significant effects from the addition of ‘depth of watertable’, ‘area per tree’ and ‘soil texture group’ (Table 4.3a). In contrast, if ‘soil texture group’ was added to the model first there were no significant effects of ‘area per tree’ or ‘depth to watertable’ (Tables 4.3b and c). This suggests that there was partial confounding between ‘soil texture group’ and ‘area per tree’ and ‘depth of the watertable’. Nevertheless, there were significant effects of ‘soil texture group’ that were not caused by variation in either of these other variables.

4.4 Discussion

The analysis presented here suggests that water-use by stands of trees on land with shallow watertables is affected by E_{pan}, depth of the watertable, planting density and soil texture. The responses to E_{pan}, depth of the watertable and planting density are not surprising, having been foreshadowed by previous researchers (eg. Thorburn 1996; Raper 1997). The cause of the soil texture effect cannot be confirmed based on the available data. Nevertheless, it is of interest that in regressions of T versus E_{pan} (Figure 4.1), the slopes for sands and loams appeared to be greater than for clays. The inability of clays to yield greater amounts of water in the face of higher evaporative demand, reflects the fact that for clays there is a greater resistance to the movement of water to the root surface than for sands and loams. The rate of water flow through soil pores is proportional to the fourth power of the diameter of the pores (Russell 1973, p. 429). In general, pore sizes are largest in sands and smallest in clays. Rates of water flow to the root are therefore: sands > loams >> clays.

Until now, tree planting for salinity abatement has been driven primarily by hydrogeological necessity; that is, hydrogeologists have recognised a local cause of salinity, and trees have been planted in such a manner as to address that challenge. However, the

Table 4.3 Effect of changing the order of addition of ‘soil texture group’ to the outcomes of the accumulated analysis of variance.

Dependent variable: T/E_{pan}	df	Variance ratio	P-value
(a) Variables introduced in order: ‘depth of water table’, ‘area per tree’, and ‘soil texture group’			
+ Depth of water table	1	34.57	0.004
+ Area per tree	1	42.06	0.003
+ Soil texture group	1	1.95	0.235
+ Salinity of the groundwater	1	1.71	0.261
+ Depth of water table*soil texture group	1	0.03	0.874
+ Salinity of the groundwater*soil texture group	1	1.27	0.323
+ Area per tree*soil texture group	1	0.10	0.766
(b) Variables introduced in order: ‘soil texture group’, ‘area per tree’ and ‘depth of water table’.			
+ Soil texture group	1	74.31	‹0.00 1
+ Area per tree	1	3.18	0.149
+ Depth of water table	1	1.09	0.355
+ Salinity of the groundwater	1	1.71	0.261
+ Depth of water table*soil texture group	1	0.03	0.874
+ Salinity of the groundwater*soil texture group	1	1.27	0.323
+ Area per tree*soil texture group	1	0.10	0.766
(c) Variables introduced in order: ‘soil texture group’, ‘depth of water table’ and ‘area per tree’.			
+ Soil texture group	1	74.31	‹0.00 1
+ Depth of water table	1	0.33	0.599
+ Area per tree	1	3.95	0.118
+ Salinity of the groundwater	1	1.71	0.261
+ Depth of water table*soil texture group	1	0.03	0.874
+ Salinity of the groundwater*soil texture group	1	1.27	0.323
+ Area per tree*soil texture group	1	0.10	0.766

data presented in this paper suggest that optimisation of the water-using systems may also require an understanding of the capacity of soils to yield water to tree roots. Farmers will increasingly be faced with multiple hydrogeological challenges. They will need to invest their money in such a way as to get the greatest financial return for their investment in terms of tree growth, water used and land saved from salinity.

More research is needed to confirm the conclusions of this paper and further quantify the relationships between wateruse, soil texture and groundwater. The present analysis has been compromised to some extent by the partial confounding of soil texture with planting density (area per tree). Furthermore, it has not been possible to consider the issues of soil texture in anything but the broadest qualitative terms. Data sets with more balanced combinations of key site parameters (area per tree, depth of watertable, salinity of watertable, soil texture) must be developed to ensure that the confounding of factors is avoided. In addition, there is a need to measure the, probably critical, parameters associated with soil texture that cause the lower rates of transpiration by trees on clays. We have noted above that decreased transpiration on clays may be associated with increased resistance in water flow to roots. Confirmation of this suggestion would require the collecting of data that related tree transpiration to soil hydraulic conductivity, pore size distribution and the presence of macropores.

4.5 Acknowledgments

We are grateful for the cooperation of our Pakistani colleagues in ACIAR Project 9316. Our analysis would have not been possible without access to their unpublished results.