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Transpiration from a neem windbreak in the Sahel

A. J. BRENNER, P. G. JARVIS

Institute of Ecology and Resource Management, Edinburgh University, Kings Building, Mayfield Road, Edinburgh EH9 3JU, UK

R. J. VANDENBELDT

ICRISAT Sahelian Center, BP 12404, Niamey, Niger

Abstract Windbreaks are being recommended for many areas of dryland Africa, although their effect on the area water balance is unknown. This study shows that a linear relationship exists between the leaf area and stem basal area of young neem trees. The relationship remains linear into the dry season with a constant slope and a changing intercept. Transpiration from individual trees, measured using a heat pulse velocity recorder, was scaled up to a windbreak by normalizing with stem basal area. For the unstressed windbreak calculated transpiration rates were 29.2 $dm^3\ day^{-1}\ m^{-1}$.

INTRODUCTION

Windbreaks are recommended and used for soil conservation and crop protection over much of dryland Africa. Extensive lines of windbreaks have been established in many areas of the Sahel. In northern Nigeria and Niger, windbreaks have been shown to increase crop yields in their lee, decrease soil erosion, and produce wood for fuel and construction (Ujah & Adeoy, 1984). However, if windbreaks are to be established in areas of low rainfall, it is important to know how much water they are likely to transpire. Recent developments of the heat pulse velocity recorder (CUSTOM, 1986), allow relatively accurate measurements of transpiration from individual trees to be made. The question then arises as to how this information on the transpiration of individual trees can be extrapolated to that of a complete windbreak.

Jarvis & McNaughton (1985) developed the idea that transpiration can be separated into two parts, the equilibrium transpiration and the imposed transpiration. The balance between the two components is dependant on the coupling of the vegetation to the atmosphere. Aerodynamically rough vegetation such as a windbreak, in even moderate wind speeds, is well coupled to the atmosphere and so transpiration will be largely dependant upon the water vapour saturation deficit of the atmosphere and the leaf area of the trees. Marchand (1983), and Whitehead *et al.* (1984) have shown that there is a linear relationship between sapwood basal area and leaf area, for a particular tree species at a specific site and Kline *et al.* (1976) have shown that there is a linear relationship between transpiration and sapwood basal area.

This paper presents data on the relationships between leaf area and stem basal area, and transpiration rate and stem basal area, for individual trees over a six month period, for neem trees in a windbreak in the Sahel. It has been assumed that stem basal area is a good approximation to sapwood basal area at the same height. The relationships found allow the calculation of transpiration by the windbreak.

MATERIALS AND METHODS

Site and windbreak description

The work was carried out at Sadoré (13°15'N; 2°17'E), the experimental farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center (ISC), located 45 km south of Niamey, Niger. The windbreaks studied were made up of a double row of six-year-old neem (*Azardirachta indica A. Juss.*) planted 4 m apart in 2-m wide rows on a triangular planting pattern. The average height of the windbreak was about 6 m. The soil is Daybou sand, 2–3 m deep over laterite gravel (West *et al.*, 1984).

The climate is typically Sahelian. The mean annual rainfall at Niamey is 562 mm falling mainly within the four months of June–September, and the annual Penman potential evaporation is 2046 mm, nearly four times the rainfall (Sivakumar, 1987).

Leaf area measurements

Defoliation of neem trees was carried out during November and December 1988 and 1989 (11 and 18 trees respectively) and May 1990 (eight trees). The procedure of defoliation was slightly different in 1988, 1989, and 1990. The tree crowns were divided into a series of sections and the area of a subsample of approximately 5000 cm^2 of leaves from each section was measured using a leaf area meter (LI 3100, LI-COR Inc., Lincoln, Nebraska, USA). After drying for 48 h at 70°C the total dry leaf weights of each section and their subsample were measured. Total leaf areas for each section and each tree were then calculated using the area:weight ratio obtained for the subsamples.

Tree parameter measurements

On all three occasions above, the height of the trees, height to the bottom of the canopy, and the stem diameters at 50 cm above ground level were measured. In 1988 and 1989 diameters were also measured at heights of 100 and 130 cm.

Stem diameters were measured using a 5 m tape measure accurate to ±1 mm. Stem basal area of each tree was calculated at the three heights, and average bark thickness was taken as 4.0 mm.

Heat pulse

The heat pulse velocity recorder used (Custom Electronics, Soil Conservation Service, Aokautere, New Zealand) allowed continuous logging of measurements only on one tree at a time. A sampling strategy was, therefore, adopted that allowed comparative measurements of tree transpiration to be gathered, with only one logging unit. This was done using spare sets of probes installed in a series of trees simultaneously, the logger was then connected to probes in one tree for a period of between 2 and 7 days and then transferred to a second tree for a similar time period. The unit was periodically moved between trees to enable a range of tree diameters to be compared.

In total 13 trees were sampled during the period 9 September 1989 to 14 March 1990. Details of sampling dates and tree sizes are given in Table 1.

Table 1 Sampling dates and tree sizes for the heat pulse measurements, ISC, Niger, 1989 and 1990

Tree no.	Date	Diameter (cm)	Basal area at 80 cm (cm^2)	Period
1	9 September	11.0	95.0	1
2	29 October	12.2	116.9	1
3	12 November	11.3	100.3	1
4	29 November	15.6	191.1	2
5	25 November	7.9	49.0	2
6	9 December	11.1	95.9	2
7	18 January	7.0	38.5	3
8	13 January	15.0	176.7	3
9	24 January	13.2	136.9	3
10	3 February	14.1	156.2	3
11	14 March	16.6	216.4	4
12	8 March	12.3	118.8	4
13	8 March	15.8	196.1	4

Calculation of transpiration

Jarvis & McNaughton (1985) consider transpiration as the weighted sum of two limiting conditions, the equilibrium transpiration (λE_{eq}) and the imposed transpiration (λE_{imp}). Since a windbreak is likely to be well coupled to the atmosphere, the transpiration of an individual leaf will tend towards λE_{imp}. Assuming that this is true for leaves within the canopy of the neem trees and that the transpiration of the individual leaves are additive, an estimate of tree transpiration can be gained from multiplying the average transpiration of individual leaves by the leaf area A_l, i.e.:

$$\lambda E_{imp} = (\rho_a \; c_p/\gamma)\, g_s \; D_a \; A_l \qquad (1)$$

where g_s is the average stomatal conductance, D_a is vapour pressure deficit of the air, c_p is the specific heat capacity of air at constant pressure, ρ_a is the density of air and γ is the psychrometric constant.

From equation (1) it can be seen that transpiration of the trees will depend on A_l, g_s and D_a. D_a was measured with an aspirated psychrometer mounted at 8.6 m over a nearby fallow bush site on the ICRISAT farm.

Verification of the heat pulse method

The values of transpiration obtained using the heat-pulse method were compared with transpiration calculated with equation (1). The agreement between the two methods was reasonable although the heat pulse method seemed to underestimate transpiration in the morning, and overestimate it in the afternoon. This is not unexpected because the heat pulse measures the flow of water up the stem of the tree, whereas equation (1) calculates the water vapour flux from the leaves (Waring *et al.*, 1980). There may be a net loss to water storage in the plant at the beginning of the day, and a net gain at the end of the day.

RESULTS

Leaf area

The stem basal area at the three heights measured was regressed against the total leaf area of the tree. The results are presented in Figs 1 and 2. The data for 1988 and 1989 were not significantly different and so have been grouped together in Fig. 1. The linear relationship between tree leaf area and stem basal area at 130 cm, has an intercept that is not significantly different from zero, and a significant positive slope. The correlation is better when using the basal area at 130 cm rather than at 50 cm, despite the more extensive branching of neem at this height. The assumption that stem basal area equals sapwood basal area may be more valid at 130 cm than 50 cm. Figure 2 shows the linear relationships between leaf area and stem basal area at 50 cm in both the dry and wet seasons. The slopes of the two lines are not significantly different and have a combined slope of 0.260, but the intercepts are significantly different at the 1% level.

Sap fluxes

Within each of the four time periods (Table 1), the sap flux data were normalized with respect to stem basal area, which accounted for much of the between-tree variation. Figure 3 shows the sap flux data for three individual trees during the period November/December 1989. When normalized the

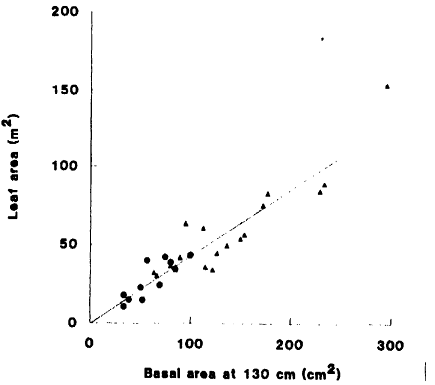

Fig. 1 Leaf area (A_l) as a function of stem basal area at 130 cm. (BA_{130}) for a neem windbreak ISC, Niger, 1988 and 1989 seasons. Post wet-season values for 1988 (●) and 1989 (▲) gave the regression equation $A_l = 0.43\ BA_{130} - 0.58$, $r^2 = 0.87$.

curves converge as shown in Fig. 4. The fluxes normalized with basal area were averaged for the trees within each period, and are shown in Table 2. The fluxes normalized with respect to estimated leaf area are also given in Table 2. Figure 5 shows the average hourly sap fluxes normalized to basal area for the four time periods. There was a decrease of about 20% in the day-time sap fluxes from September/November 1989 to November/December 1989, and a further decrease of around 22% from November/December 1989 to January/February 1990. There was, however, no significant change in the normalized sap flux between January/February 1990 and March 1990.

Windbreak transpiration

The windbreak studied was 196 m long, with a mean height of 6.5 m and a mean basal area at 50 cm of 130 cm^2. The total basal area of the windbreak at 80 cm was 11 786 cm^2. Using the relationship between the daily transpiration and basal area per tree (Table 2), the amount of water transpired by the windbreak was calculated as approximately 5722, 5095, and 3857 dm^3 day^{-1}, over time periods September/November 1989, November/December 1989 and January/February 1990, respectively. This corresponds to 29.2, 26.0, and 21.1 dm^3 day^{-1} m^{-1} of windbreak, over

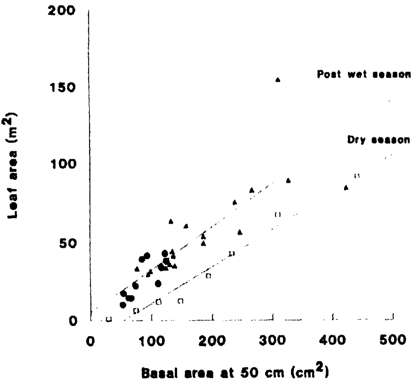

Fig. 2 Leaf area (A_l) as a function of stem basal area at 50 cm. (BA_{50}) for a neem windbreak ISC, Niger, 1988 and 1989 seasons. Post wet-season values for 1988 (●) and 1989 (▲) gave the regression equation $A_l = 0.27\ BA_{50} + 5.30$, $r^2 = 0.70$. Dry season values (□) gave a regression equation of $A_l = 0.24\ BA_{50} - 12.81$, $r^2 = 0.97$.

September/November 1989 and November/December 1989 and an average of January to March 1990.

DISCUSSION

Leaf area-basal area relationship

The linear relationship between stem basal area and leaf area is likely to be valid only while the area of non-conducting heartwood is insignificant. Much work has been carried out that shows good correlations between sapwood basal area and leaf area for specific species at particular sites. Kaufmann & Troendle (1981) found values for the slope of the regression (*b*) varying from 1.88 with subalpine fir (*Abies lasiocarpa*) to 0.19 in aspen (*Populus tremuloides*). Marchand (1983) found a considerably lower value of 0.673 for balsam fir (*Abies balsamifera*), and red spruce (*Picea rubens*) 0.167. Whitehead & Jarvis (1981) suggest that a wide range of values for *b* should be expected, since it is dependant on species, age, site, and permeability of the wood.

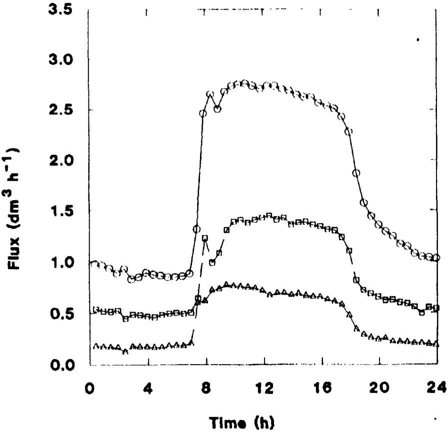

Fig. 3 Hourly sap flux measurements for tree 4 (O), tree 5 (Δ), and tree 6 (□), during November/December 1989, ISC, Niger.

Some of the variability in *b* values may be accounted for by differences in wood permeability (Whitehead *et al.*, 1984). Climatic conditions may also influence *b* since the higher the average transpiration rate at a site, the smaller is the leaf area that would be supplied per unit sapwood basal area. A value of 0.65 was quoted for a mature teak plantation in Nigeria (Whitehead *et al*, 1981). The value of 0.429 found in this study may have resulted from the lower rainfall conditions under which the trees grew or from differences between the species. In a more mature neem windbreak, sapwood basal area rather than stem basal area would need to be estimated in order to give a linear relationship with leaf area.

Leaf area does not generally remain constant with time (Pook, 1984). However, the data obtained here during the wet and dry seasons tend to indicate that although the relationship does not remain the same throughout the year, the relationship remains linear, and can be used as a predictor of leaf area in each time period. The similarity of the slopes of the lines at the different sampling times suggests that the loss of leaves during the dry season is independent of stem diameter or canopy size.

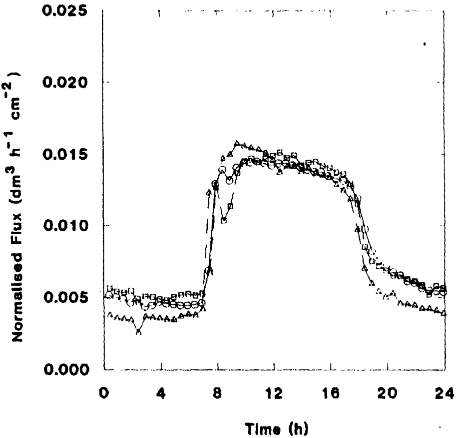

Fig. 4 Hourly sap flux measurements normalized with respect to stem basal area for tree 4 (o), tree 5 (Δ), and tree 6 (□), during November/December 1989, ISC, Niger.

Table 2 Average maximum hourly and cumulative daily sap fluxes from neem normalized with respect to basal area and leaf area. Standard errors (SE) are also shown. ISC, Niger, 1989 and 1990.

Period	*Hourly flux (dm^3 h^{-1} m^{-2}): Maximum*	*SE*	*Daily flux (dm^3 day^{-1} m^{-2}): Cumulative*	*SE*
BASAL AREA				
September-November 1989	*0.01818*	*0.0012*	*0.485*	*0.078*
November-December 1989	*0.01483*	*0.0003*	*0.432*	*0.023*
January-February 1990	*0.01158*	*0.0007*	*0.327*	*0.032*
March 1990	*0.01190*	*0.0015*	*0.373*	*0.064*
LEAF AREA				
September-November 1989	*0.052*	*0.0037*	*0.689*	*0.109*
November-December 1989	*0.043*	*0.0021*	*0.622*	*0.021*
January-February 1990	*0.031*	*0.0027*	*0.470*	*0.055*
March 1990	*0.034*	*0.0039*	*0.521*	*0.085*

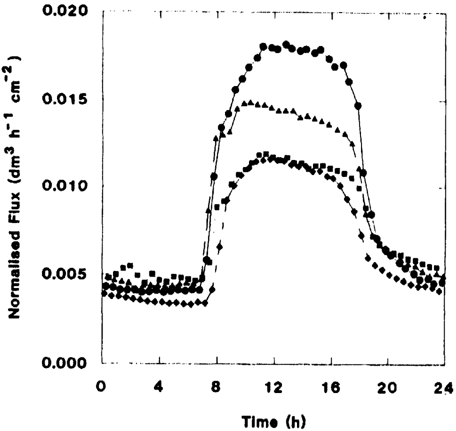

Fig. 5 Average hourly sap flux measurements normalized with respect to stem basal area for time periods September/November 1989, (●), November/December 1989 (▲), January/February 1990 (♦), and March 1990 (■), ISC, Niger.

Tree transpiration

Sapwood basal area has been used to scale up from a series of individual tree measurements to a forest canopy in both temperate coniferous stands (Kline *et al.*, 1976), and tropical rain forests (Jordan & Kline 1977). Assuming that the heartwood is insignificant stem basal area normalized measurements of tree transpiration would be similar to sapwood basal area normalized transpiration measurements. This normalization is useful as a scaling factor, however it is of limited value for comparative measurements.

Leaf area normalized measurements of transpiration are more applicable to other situations. The average maximum hourly transpiration rates per unit leaf area of the neem windbreak were 0.052, 0.043, 0.031, and 0.033 $dm^3\ h^{-1}\ m^{-2}$ in September/November 1989, November/December 1989, January/February 1990 and March 1990 respectively. Doley (1981) presents some values of leaf transpiration per unit area for semiarid trees and shrubs, which he divided into species from the Cerrado of north Brazil and the drier Caatinga. Many of the Cerrado species had higher normalized transpiration rates of 0.07 to 0.11 $dm^3\ h^{-1}\ m^{-2}$ than found in this study, but *Anacardium occidentale* had a value of 0.059 $dm^3\ h^{-1}\ m^{-2}$ in the dry season. The rates observed in this study correspond better to the those found in the Caatinga zone. Transpiration from *Jatropha phyllacantha* leaves decreased from 0.090 to 0.048 $dm^3\ h^{-1}\ m^{-2}$ from early to late dry season. Leaves from *Maytenus rigida* showed decreases of 0.079, 0.052, 0.041 $dm^3\ h^{-1}\ m^{-2}$ over the same time period, similar to the results found in the present study with neem.

CONCLUSIONS

Very little work has been done on the transpiration of windbreaks, even though they are being recommended for areas with limited rainfall, or water reserves. Since windbreaks are very well coupled to the atmosphere, transpiration can be calculated on the basis of imposed rates (equation (1)). In any one time period the major differences in transpiration rates between trees is a result of differences in leaf area and stomatal conductance. Since leaf area is linearly related to sapwood basal area, and in young trees to stem basal area, a measurement of stem basal area allows extrapolation of the transpiration of a sample of single trees to that of a complete windbreak.

The data presented here are limited to a young double row neem windbreak. However, scaling up from single tree measurements to wind breaks on the basis of sapwood basal area should be possible for other species in other environments.

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