

## Management of windbreaks in the Sahel: the strategic implications of tree water use

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**Abstract.** At sites in the Sahel where windbreaks are used to control wind erosion, management strategies are required to minimise competition for water between trees and crops. Uptake of water by windbreak trees was therefore studied in experiments designed to compare water use among tree species, assess which variables exert most control over transpiration and determine the source of water transpired by windbreak trees. Transpiration and soil-water extraction by *Acacia nilotica*, *Acacia holosericea* and *Azadirachta indica* trees in windbreaks were measured at the ICRISAT Sahelian Centre, Niger. Coupling of windbreaks to the atmosphere was evaluated and a stable isotope technique was used to compare utilisation of groundwater by windbreaks and crops at two sites in Niger with different water table levels. *Azadirachta indica* used least water, probably as a result of lower stomatal conductances, since windbreaks exhibited good physiological control over transpiration. The potential for competition for water was most severe with *Acacia nilotica* and *Acacia holosericea*, as they extracted large quantities of water through lateral roots, and at the location where trees could not access groundwater. At such sites, the effects of competition on crop productivity should be minimised by planting tree species with low water requirements and by using pruning to limit tree transpiration.

### Introduction

Windbreaks are recommended as a means of controlling wind erosion in Sahelian West Africa (Rocheleau et al., 1988) because, when planted perpendicular to prevailing or storm winds, wind speeds near the soil surface are reduced in a sheltered zone in the lee of the trees (McNaughton, 1988; van den Beldt, 1990; Brenner et al., 1995a). Windbreaks also improve the microclimate for crop growth (McNaughton, 1983, 1988; Brenner et al., 1995b) and so crop yields in the Sahel can be higher behind windbreaks than in unsheltered fields (Ujah and Adeoye, 1984; Long, 1989; van den Beldt, 1990; Brenner et al., 1993). However, competition for resources at the tree-crop interface can exacerbate stresses in crop plants and result in lower yields near the trees and a reduction in total crop production (Brenner et al., 1993). Thus, under some conditions, consumption of resources such as water and nutrients by trees in windbreaks (or other agroforestry systems) can detrimentally affect the long-term productivity of land in semi-arid West Africa (Kessler and Breman, 1991).

Agencies planning to establish windbreaks in the Sahel must therefore ensure that, together with other resources for plant growth, water is utilised as effectively as possible by the trees and adjacent crops; as a result, sound strategies are required for managing water resources where windbreaks are planted. Such strategies should be applicable under the widest possible range of conditions and so should be drawn from research into the processes underlying the acquisition of water by trees and crops (Anderson and Sinclair, 1993). Recommendations for reducing losses in crop yields caused by competition for water with windbreak trees should be developed, therefore, from knowledge of the mechanisms driving water use by the trees. Consequently, a series of experiments was undertaken to examine how much water windbreak trees use, from where it is obtained and which environmental and physiological variables control transpiration from windbreak canopies. The results from these investigations were then used to develop a strategy for the deployment of windbreaks in the Sahel that should minimise problems caused by competition between trees and crops for water.

### Materials and methods

The experiments were located at the ICRISAT Sahelian Centre at Sadoré (13°14'N, 2°16'E), about 45 km south of Niamey, Niger, and in the Majjia Valley, near the town of Bouza (14°25'N, 6°03'E), some 400 km north-east of Niamey. At both sites, there is a single rainy season between June and September, with mean annual rainfall of 544 mm at Sadoré and 379 mm at Bouza (Sivakumar et al., 1993). The soil is a deep, sandy alfisol at Sadoré and a loamy inceptisol at the Majjia Valley site. Double-row, 8 m-tall windbreaks of *Azadirachta indica* A. Juss., spaced 100–150 m apart, were used for experiments at Sadoré and in the Majjia Valley. Other experiments were done using hedge windbreaks of *Azadirachta indica*, *Acacia holosericea* A. Cunn. ex G. Don and *Acacia nilotica* subsp. *adstringens* (Schumacher & Thonn.) Roberty at Sadoré, which were arranged in randomised complete blocks. The hedge windbreaks were oriented north-south, were 50 m long with 30 m of cropland between parallel windbreaks, and they were composed of a double row of alternately planted trees, with 1.5 m between rows and 3 m between trees in the same row; the hedge windbreaks were pruned to 2 m from a height of 3–5 m at the end of every dry season. Crops of pearl millet (*Pennisetum glaucum* (L.) R. Br.) were planted between all windbreaks in all years of the study.

#### *Transpiration by windbreaks*

Transpiration by *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* trees in hedge windbreaks was determined by using the heat-pulse technique to measure sap flow (Edwards and Warwick, 1984; Smith and Allen, 1996). Tests of the validity of the heat-pulse method, which were described by Smith

and Allen (1996), showed that observed rates of sap flow needed to be corrected by factors of 1.62 for *Azadirachta indica*, 2.43 for *Acacia holosericea* and 1.85 for *Acacia nilotica*, because of the xylem anatomy of these species (Smith, 1995; Smith and Allen, 1996).

Sap flow was measured in large branches of all three species in three replications between 10 August and 6 September, 1991. Data were recorded at intervals of 20 min using heat-pulse loggers (Custom HP1, Hort Research, Palmerston North, New Zealand). Daily total transpiration was then calculated by integrating sap flows over 24 h. The leaf area ( $A_l$ ) of each branch was estimated non-destructively using allometric relationships between leaf area and the basal cross-sectional area of small branches deriving from the main instrumented branch. These relationships were developed for each species from destructive harvests of leaves from other trees at the site (Smith, 1995). Differences in rates of daily transpiration per unit leaf area among species were then assessed using analysis of variance and protected least significant differences (Snedecor and Cochran, 1980).

In 1992 and 1993, sap flow in the trunks of *Azadirachta indica* and *Acacia holosericea* trees in the windbreaks was monitored over the cropping season, between sowing and maturity of the millet crop. Measurements were made in up to three trees per species, but not on all days over the season. The heat-pulse apparatus was moved to a new tree every three weeks and  $A_l$  was determined by harvesting all leaves from each tree;  $A_l$  was found from the product of the total dry mass of leaves and specific leaf area, which was determined from a subsample of leaves using a leaf area meter (LI-3100, Li-Cor Inc., Lincoln NE, USA). The ground area enclosed by the perimeter of the tree crown ( $A_c$ ) was determined from measurements of the radius of the crown. Stomatal conductances of leaves of *Azadirachta indica* and *Acacia holosericea*<sup>1</sup> were also measured at hourly intervals on several days using a diffusion porometer (LI-1600, Li-Cor Inc., Lincoln NE, USA).

#### *Coupling of windbreaks to the atmosphere*

Jarvis and McNaughton (1986) showed that the Penman-Monteith equation for estimating transpiration ( $E$ ) can be re-written as

$$E = \Omega E_{eq} + (1 - \Omega) E_{imp}, \quad (1)$$

where  $E_{eq}$  is an equilibrium evaporation rate which depends chiefly on net radiation ( $R_n$ ),  $E_{imp}$  is an imposed evaporation rate which depends on ambient vapour pressure deficit ( $D_a$ ) and the surface conductance of the vegetation ( $g_c$ ) and  $\Omega$  is a dimensionless 'decoupling coefficient'.  $\Omega$  has a range of 0 to 1 and is determined from aerodynamic conductances ( $g_a$ ) and  $g_c$  using, for hypostomatous vegetation,

$$\Omega = \frac{(\epsilon + 2)}{(\epsilon + 2 + g_a/g_c)}, \quad (2)$$

where  $\varepsilon = s/\gamma$ , the ratio of the slope of the saturation vapour pressure curve at the canopy temperature ( $s$ ) and the psychrometric constant ( $\gamma$ ). At the limit of  $\Omega = 1$ , a plant canopy would be completely decoupled from the ambient atmosphere, with  $E$  determined by  $R_n$ , so that changes in  $g_c$  have no effect on  $E$ . At the limit of  $\Omega = 0$ , coupling is complete and  $E$  depends on  $D_a$  and  $g_c$ , so that fractional changes in  $g_c$  cause equal fractional changes in  $E$  and stomata have full control over transpiration. Such physiological control over transpiration diminishes as  $\Omega$  increases from 0 to 1 (Jarvis and McNaughton, 1986).

Values of  $\Omega$  were determined for crowns of *Azadirachta indica* trees in hedge windbreaks at Sadoré during four periods of several days each in different seasons of 1992 and 1993, as described in detail by Smith and Jarvis (1997). Values of  $g_a$  for tree crowns were derived from boundary layer conductances for leaves, which were measured using heated leaf replica pairs (Leuning and Foster, 1990; Brenner and Jarvis, 1995) and scaled to the total leaf area of the trees studied using the scheme described by Smith et al. (1997a). Values of  $g_c$  were calculated from total conductances for vapour transfer from the canopy ( $g_v$ ), on the assumption that  $g_v$  comprises  $g_c$  and the aerodynamic conductance in series, with values of  $g_v$  determined using

$$g_v = \left( \frac{\lambda\gamma}{\rho_a c_p} \right) \frac{E}{(e_s(T_c) - e_a)}, \quad (3)$$

where  $(e_s(T_c) - e_a)$  is the leaf-air vapour pressure difference,  $\lambda$  is the latent heat of vaporisation,  $\rho_a$  is the density of air and  $c_p$  is the specific heat of air at constant pressure.  $E$  was measured at 20 min intervals using the heat-pulse technique and 20 min averages of  $(e_s(T_c) - e_a)$  were measured using leaf thermocouples and an aspirated psychrometer mounted above the windbreak (Smith and Jarvis, 1997). At the conclusion of each period of measurement,  $A_c$  and  $A_l$  were determined for each tree.

#### *Soil-water extraction*

Volumetric soil moisture content ( $\theta_v$ ) in the vicinity of the hedge windbreaks at Sadoré was measured using a neutron probe (model IH II, Didcot Instrument Co., Abingdon, UK) in 1992 and 1993 at approximately weekly intervals during the rainy season and monthly intervals during the dry season. Measurements were made every 0.3 m between 0.1 and 2.5 m below the soil surface in 45 mm-diameter aluminium access tubes at distances of 0, 1.0, 2.5, 5.0 and 10.0 m from the base of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* trees on the western sides of windbreaks in three replications. Differences among species in the influence of the windbreaks on  $\theta_v$  were assessed using a repeated measures analysis of variance (Littell et al., 1991)

### *Utilisation of groundwater*

Utilisation by plants of water from different sources can be distinguished by comparing isotopic ratios in plant sap and water from each source, because isotopic ratios often differ naturally among sources and there is no isotopic fractionation of water during transfer into plant roots or through suberised stems (Dawson and Ehleringer, 1993; Thorburn et al., 1993). Variations in isotopic ratios for oxygen ( $^{18}\text{O}/^{16}\text{O}$ ) were used to compare utilisation of groundwater and soil water by 8 m-tall windbreaks and millet at Sadoré, where the water table was at a depth of 35 m, and the Majjia Valley, where the water table was only 6–8 m below the soil surface. Samples of tree twigs, millet stems, groundwater and soil were collected on several occasions in 1992 and 1993 at both sites (Smith et al., 1997b). Twig and millet samples were each taken from four plants and soil samples were collected from a series of depths between the surface and 3 m, at three positions beneath both the trees and crop. Only mature, suberised twigs were collected and samples of millet stem were wrapped in plastic for several hours before collection to prevent transpiration through stem walls and thus isotopic fractionation of sap. Groundwater samples were taken from wells and boreholes between 100 m and 2 km from the windbreaks at each site.

Isotopic ratios are normally expressed relative to a standard using delta ( $\delta$ ) notation with units of per mil (‰) (i.e. parts per thousand);  $\delta^{18}\text{O}$  is given by

$$\delta^{18}\text{O} = \left( \frac{R_s}{R_{\text{SMOW}}} - 1 \right) 1000, \quad (4)$$

where  $R_s$  and  $R_{\text{SMOW}}$  are the  $^{18}\text{O}/^{16}\text{O}$  ratios for the sample and Standard Mean Ocean Water (SMOW), respectively (Ehleringer and Dawson, 1992). Values of  $\delta^{18}\text{O}$  for water in the samples collected for this study were measured with an isotopic ratio mass spectrometer using the direct equilibration method (Scrimgeour, 1995). The significance of differences in  $\delta^{18}\text{O}$  values among samples was evaluated using Student's *t*-tests.

## **Results and discussion**

### *Differences in water use among species*

Between 10 August and 6 September, 1991, mean daily transpiration per unit leaf area was  $0.63 \pm 0.03 \text{ kg m}^{-2} \text{ d}^{-1}$  for *Azadirachta indica*,  $0.91 \pm 0.04 \text{ kg m}^{-2} \text{ d}^{-1}$  for *Acacia nilotica* and  $1.32 \pm 0.07 \text{ kg m}^{-2} \text{ d}^{-1}$  for *Acacia holosericea*. Water use per unit leaf area was significantly ( $P < 0.05$ ) lower for *Azadirachta indica* than either *Acacia holosericea* or *Acacia nilotica* on most days in this period. Similar differences among species were found in 1992 and 1993, as mean daily transpiration rates, expressed per unit  $A_c$  (i.e.

as a depth equivalent), tended to be higher for *Acacia holosericea* than *Azadirachta indica* (Table 1). The difference in water use between these species was largest in the final stage of the cropping season, even though the ratio  $A_l/A_c$  was higher for *Azadirachta indica* (Table 1); despite higher leaf areas, therefore, *Azadirachta indica* appeared to use less water than *Acacia holosericea*.

The disparity in water use among species may have resulted from physiological differences, as stomatal conductances tended to be lower for leaves of *Azadirachta indica* than *Acacia holosericea*, as shown in Figure 1 for a typical day in the cropping season. This suggests that, if trees in windbreaks are well coupled to the atmosphere, it may be possible to assess relative water use among tree species considered suitable for use in windbreaks by comparing their stomatal conductances.

#### *Physiological control of transpiration by windbreaks*

Values of  $\Omega$  for the hedge windbreaks were close to 0.3 at moderate wind speeds at all times of year except the late dry season, when  $\Omega$  generally had a value of about 0.1 (Figure 2). Thus, the windbreaks had good physiological control over transpiration, as expected because they are aerodynamically rough, unless wind speeds were exceptionally low, when  $\Omega$  tended towards 0.5 and  $E$  more towards  $E_{eq}$  (Figure 2). Changes in  $g_c$  therefore effectively regulate water loss from windbreak canopies, particularly during the driest times of the year when control over transpiration is most critical.

Management strategies designed to influence  $g_c$  can, consequently, be used to control demand for water by windbreak trees and alleviate stresses caused by competition for water between trees and crops. As  $g_c$  depends on stomatal conductance and leaf area, farmers and land-use planners can limit water use by windbreaks, if required, by using tree species that tend to have low stomatal conductances or leaf areas, or by pruning the trees to restrict their leaf areas.

*Table 1.* Mean values of  $A_l/A_c$ , the ratio of leaf area and the area enclosed by the perimeter of the crown, for *Azadirachta indica* and *Acacia holosericea* during the early, middle and late thirds of the cropping season; mean daily transpiration per unit projected crown area for days in the 1992 and 1993 cropping seasons in Niger when measurements were made concurrently in both species; and mean ( $\pm 1$  s.e) additional water use by *Acacia holosericea* relative to *Azadirachta indica* ( $\Delta_T$ ). The cropping season, defined as the dates between sowing and maturity of the millet crop, extended from May 26 to September 15 in 1992 and from June 6 to September 21 in 1993.

Stage of season	$A_l/A_c$		Transpiration (mm d <sup>-1</sup> )		$\Delta_T$ (mm d <sup>-1</sup> )
	<i>Az. ind.</i>	<i>Ac. hol.</i>	<i>Az. ind.</i>	<i>Ac. hol.</i>	
Early	2.0	1.7	2.2	2.6	0.4 $\pm$ 0.15
Middle	2.3	2.2	2.3	2.2	-0.1 $\pm$ 0.22
Late	4.6	3.8	2.8	3.6	0.9 $\pm$ 0.19

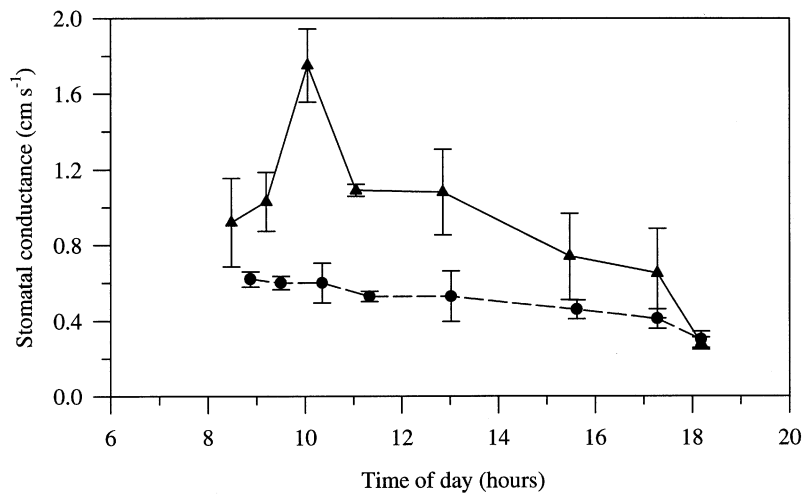


Figure 1. Stomatal conductances ( $n = 3$ ), on the basis of single-sided leaf area, for *Azadirachta indica* (●) and *Acacia holosericea* (▲) on 2 July 1993 in Niger. Error bars show  $\pm 1$  s.e.

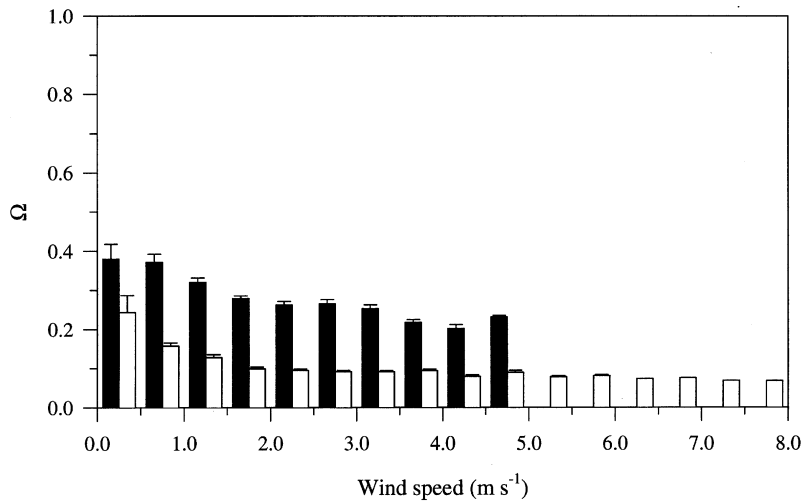


Figure 2. Mean values of the decoupling coefficient,  $\Omega$ , for classes of wind speed over the measurement periods in the early dry season and middle and late rainy seasons (solid bars) and the late dry season (open bars) in Niger. Error bars show 1 s.e.

#### Extraction of soil water by windbreak trees

The effect of water use by windbreak trees on adjacent crops depends not only on the amount of water used, but also from where it is obtained. Soil moisture data from the vicinity of windbreaks of *Acacia nilotica*, *Acacia holosericea* and *Azadirachta indica* are shown in Figure 3 for a typical day in the rainy

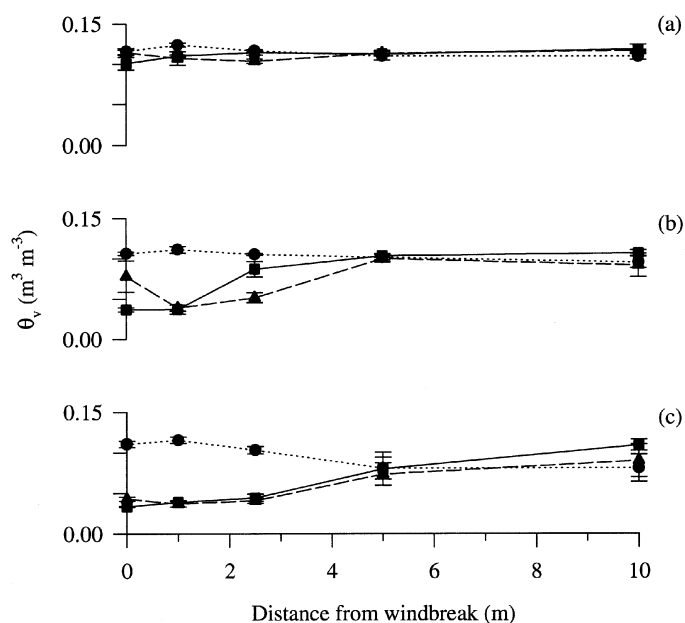


Figure 3. Volumetric moisture content ( $\theta_v$ ) of soil at (a) 0.4 m, (b) 1.0 m and (c) 1.6 m below the soil surface between 0 and 10 m from the trunks of *Acacia nilotica* (■—■), *Acacia holosericea* (▲---▲) and *Azadirachta indica* (●.....●) trees in hedge windbreaks at Sadoré, Niger on 20 August 1993. Error bars show  $\pm 1$  s.e.

season. Soil near the surface was uniformly moist because 45 mm of rain had fallen over the preceding three days, suggesting that interception losses and redistribution of rainfall was similar for the canopies of all species. At greater depths, however, soil near windbreaks of *Acacia holosericea* and *Acacia nilotica* was significantly ( $P < 0.01$ ) drier than soil near *Azadirachta indica* windbreaks as far as between 2.5 and 5.0 m into the crop from the base of the trees. Values of  $\theta_v$  adjacent to *Acacia holosericea* and *Acacia nilotica* barely increased at depths of 1.0 m and below from values recorded in the dry season (Smith, 1995); infiltration through the top layers of the soil was thus slower near these species. A similar observation was made in 1992 (Smith, 1995). *Acacia holosericea* and *Acacia nilotica* therefore extracted more water than *Azadirachta indica* from shallow layers of the soil through lateral roots, suggesting that millet growing near *Acacia holosericea* and *Acacia nilotica* windbreaks is more likely to suffer water stress; thus, *Azadirachta indica* is less competitive with neighbouring crops.

#### Sources of water transpired by windbreak trees and crops

At Sadoré and the Majjia Valley, both the windbreak trees and millet utilised water from the top of the soil profile when it was wet after recent rain. For



example, on the day after 44 mm of rain had wetted the top of the soil profile in the Majjia Valley (Figure 4a (inset)), values of  $\delta^{18}\text{O}$  for millet and tree sap were not significantly different ( $P < 0.05$ ), but they were significantly higher ( $P < 0.05$ ) than the value for groundwater (Figure 4a). Both values coincided with  $\delta^{18}\text{O}$  values for shallow soil water, indicating that both the trees and crop were obtaining the bulk of their water from the top 1 m of the soil profile. Similarly, on the day after 45 mm of rain at Sadoré, the surface layers of the soil were wet (Figure 4b (inset)) and values of  $\delta^{18}\text{O}$  for tree and millet sap

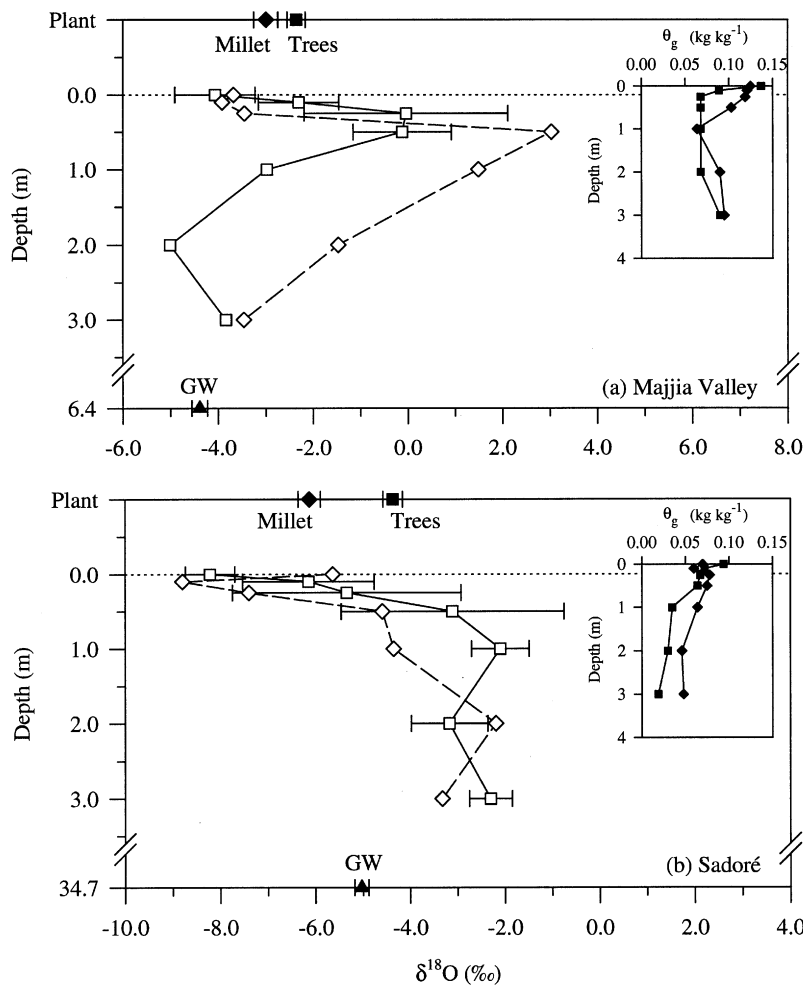


Figure 4. Values of  $\delta^{18}\text{O}$  for the sap of *Azadirachta indica* trees in windbreaks (■) and adjacent millet (◆), and for groundwater (GW) (▲) and soil water beneath the trees (□—□) and millet (◇—◇) on days after rainfall at (a) the Majjia Valley (27 August 1992) and (b) Sadoré (31 August 1992), Niger. Inset: the gravimetric moisture content ( $\theta_g$ ) of soil beneath the windbreaks (■—■) and crop (◆—◆). Error bars show  $\pm 1$  s.e.

coincided with values for soil water from the top 1 m of the soil profile (Figure 4b). Although Figure 4b suggests that the groundwater at Sadoré may have contributed to uptake by the trees, this is improbable, as there was no indication that the trees at Sadoré had access to groundwater, 35 m below the surface, even during the driest periods of the year (Smith et al. (1997b)). Thus, *Azadirachta indica* trees can utilise water in the surface layers of the soil when it is abundant, regardless of the proximity of the water table.

With a drier soil surface in the Majjia Valley (Figure 5a (inset)), only the

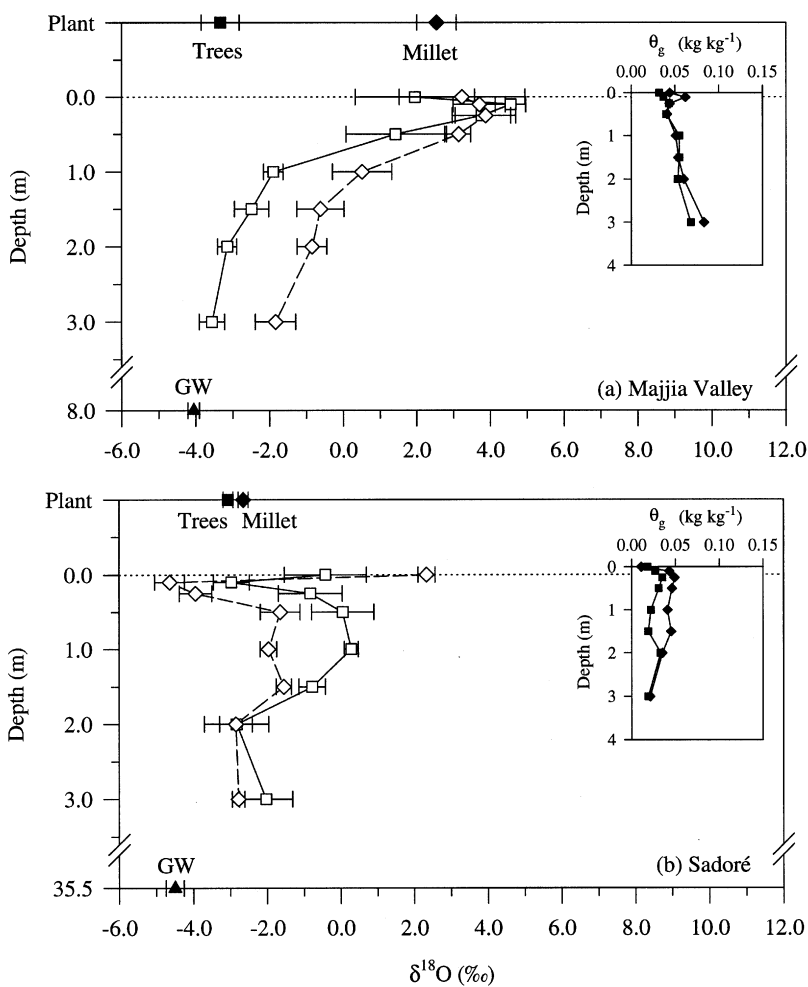


Figure 5. Values of  $\delta^{18}\text{O}$  for the sap of *Azadirachta indica* trees in windbreaks (■) and adjacent millet (◆), and for groundwater (GW) (▲) and soil water beneath the trees (□—□) and millet (◇—◇) during a dry spell in the middle of the 1993 rainy season at (a) the Majjia Valley (27 July 1993) and (b) Sadoré (2 August 1993), in Niger. Inset: the gravimetric moisture content ( $\theta_g$ ) of soil beneath the windbreaks (■—■) and crop (◆—◆). Error bars show  $\pm 1$  s.e.

$\delta^{18}\text{O}$  values for millet sap coincided with values for soil water near the surface (Figure 5a); the  $\delta^{18}\text{O}$  value for tree sap coincided with values for soil water from below 2 m and was not significantly different ( $P < 0.05$ ) from the value for groundwater. Thus, when water was not abundant near the soil surface, windbreak trees in the Majjia Valley were able to extract water from below 2 m, probably including some groundwater, while the millet crop relied on water from near the top of the soil profile. By contrast, at Sadoré during a similar dry spell, the  $\delta^{18}\text{O}$  values for millet and tree sap were not significantly different ( $P < 0.05$ ) and both coincided with values from the top 2 m of the profile (Figure 5b), where the soil was wettest (Figure 5b (inset)). Thus during dry periods, the windbreaks and millet in the Majjia Valley used spatially distinct sources of water, while at Sadoré, they probably competed for water in the rooting zone of the crop; spatial complementarity between windbreaks and crops is consequently enhanced when the trees have access to groundwater.

Proximity of the water table to the surface therefore has important implications for the severity of competition for water between trees and crops when windbreaks are established in the Sahel. Where trees have access to groundwater, as in the Majjia Valley, they are only likely to obtain large proportions of their water from surface layers of the soil during periods when water there is plentiful, for example after rain, so that competition for water is unlikely to have a large effect on the crop. Where access to groundwater by trees is not possible, the evidence from Sadoré indicates that competition for water could be severe during dry periods, possibly causing a reduction in the productivity of adjacent crops. Thus, the observation of improved complementarity between windbreaks and crops where groundwater is accessible to tree roots may help to explain why Long (1989) and others (see van den Beldt (1990)) found increases in millet production of 20–25 % in fields in the Majjia Valley sheltered by windbreaks, while Brenner et al. (1993) found that windbreaks at Sadoré had little effect on millet production.

#### *A strategy for windbreak deployment in the Sahel*

When assessing how water use by windbreaks is likely to affect crop productivity at a particular location, land-use planners should evaluate how much water the trees are likely to demand and from where it is likely to be supplied. Because windbreak canopies are well coupled to the atmosphere, the amount of water transpired by windbreaks depends chiefly on ambient vapour pressure deficit and the surface conductance. Control of vapour pressure deficit is not possible and so efforts to limit demand for water by windbreaks should be directed towards restricting the surface conductance. The source of water used by windbreak trees depends on root architecture and the accessibility of groundwater and deep reserves of soil water. Competition for water is likely to be severe only at locations where trees must, like adjacent crops, rely on water from the top of the soil profile. The severity of this competition depends

on the quantity of water demanded by the trees and the distance to which lateral roots extend into the rooting zone of the crop.

On the basis of these conclusions, it is possible to suggest strategies for windbreak deployment that should minimise problems caused by competition between trees and crops for water:

1. Where windbreaks have access to groundwater or deep reserves of soil water, strategies for limiting transpiration by the trees are not crucial determinants of the effects of the windbreaks on crop productivity. At these locations, planners can use an array of tree species to provide local people with a broad range of tree products, thus maximising the economic value of the windbreaks. Two notes of caution are required, however: first, the tree species selected must have rooting habits that enable them to reach the groundwater; second, the trees must not use so much water that groundwater levels decline in the long term, as this could result in wells running dry, a disastrous outcome for communities in the Sahel.
2. Where groundwater or deep reserves of soil water are not accessible to windbreak trees, it is vital that management strategies are employed to reduce water use by the trees, otherwise crop productivity is unlikely to profit fully from the benefits offered by shelter and may be depressed. Planners of windbreak systems at these locations must first choose tree species that have low demand for water. This selection should be made on the basis of knowledge of actual water use by species under relevant conditions or by comparing typical values of stomatal conductance and leaf area under these conditions. Planners should select species with root systems that do not spread laterally for large distances near the soil surface or could, if warranted by the returns on labour invested, recommend pruning of lateral roots by trenching (Onyewotu et al., 1994; Schroth, 1995). Finally, planners must decide how to manage windbreak canopies once they are established. A major tool for reducing demand for water by windbreak trees at critical times of year should be pruning of the canopy. Planners must decide on the timing and severity of pruning and the desired shape of the canopy; the goal of pruning windbreaks should be to minimise demand for water by the trees while maximising the amelioration of crop microclimate and control of wind erosion.

As the effects of pruning windbreak canopies on interactions between tree water use, erosion control and crop microclimate have not yet been quantified, the effectiveness of strategy (2) would be enhanced by field or modelling experiments in the future. The objective of such experiments should be to define optimum practices for pruning windbreaks.

## Conclusions

By improving knowledge of the processes controlling transpiration and the uptake of water by trees in windbreaks, it has been possible to recommend a

strategy for managing competition between windbreak trees and neighbouring crops in the Sahel. This strategy should be used by researchers to help them design field experiments for testing management practices at specific locations and by planners to guide their decision making at sites in the Sahel where new windbreak systems are being established. The approach used in this study can be used generally in agroforestry research and practice, regardless of climate or which resource for plant growth is limiting; the processes controlling demand for resources by trees and crops should be compared with supplies available from all possible sources, so that strategies for manipulating demand and enhancing complementarity in resource utilisation can be devised.

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### Note

1. Foliar elements of *Acacia holosericea* are phyllodes, or modified petioles, rather than true leaves, but are referred to as leaves in this paper for simplicity.

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